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ON DECOMMISSIONING

European Radiation Survey and Site Execution Manual

(EURSSEM)

Final Report
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ABSTRACT

The European Radiation Survey and Site Execution Manual (EURSSEM) provides information and guidance on strategy, planning, stakeholder involvement, conducting, evaluating and documenting radiological, environmental and facility (surface) surveys based on best practices for demonstrating compliance with dose or risk-based regulations or standards, remediation, reuse, short-term and long-term stewardship on radioactively contaminated and potentially radioactively contaminated sites and/or groundwater.

EURSSEM is a consensus document the first draft of which was developed by the "Co-ordination Network on Decommissioning of Nuclear Installations" funded by the European Community and with the support of private companies and persons.

The objective of EURSSEM is to describe a consistent approach to and execution of strategy, planning, stakeholder involvement, performing, assessing radiologicaly contaminated soil surface and groundwater (final) status surveys to meet established dose- or risk-based release criteria, and/or remediation, restoration, reuse and stewardship objectives, while at the same time encouraging effective use of human, raw material and financial resources.

DISCLAIMER

The first draft of this manual was prepared by the “Co-ordination Network on Decommissioning of Nuclear Installations” which was funded by the European Commission. New drafts and improvements may be prepared by institutes, companies and individual persons.

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1 Introduction

1.1 Background

Radioactive materials have been produced, processed, used, and stored at thousands of sites in Europe and all over the world. Many of these sites - ranging in size from nuclear activities, e.g., power production, weapons-production facilities covering tens of square kilometres, industrial sites, to the nuclear medicine departments of small hospitals, research institutes (sometimes accidental) - were at one time, or are now radioactively contaminated.

The owners and managers of a number of sites would like, or are obliged to determine if these sites are radioactively contaminated, to remediate the sites if contaminated, and to release the sites for restricted use or for unrestricted public use.

In most countries different national agencies are involved in these processes and are responsible for the release of sites following clean-up. These involvements and responsibilities apply to facilities under the control of institutes or private/national companies or national agencies like Department of Defences.

To provide a consistent guidance and best practices to involved participants (stakeholders), important documents have been produced by different organisations, like:

- The International Atomic Energy Agency (IAEA), (www.iaea.org).
- The SAFEGROUNDS Learning Network (www.safegrounds.com) that uses participatory approaches to develop and disseminate good practice guidance for the management of contaminated land on nuclear and defence sites in the United Kingdom.
- The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM), which is the product of a multi US agency workgroup with representatives from the U.S. Environmental Protection Agency (EPA), the U.S. Nuclear Regulatory Commission (NRC), the U.S. Department of Energy (DOE) and the U.S. Department of Defence (DOD), (www.marssim.com). In the mission of these agencies is stated that they have:
    - To improve, preserve and protect the quality of the environment, on both national and global levels.
    - To ensure adequate protection of public health and safety, security, and the environment in the use of certain radioactive materials.

The different approaches caused by the various missions of the above organisations can be recognised in their documents.

EURSSEM incorporates information provided in the documents of the above mentioned organisations and acknowledges the importance and the quality of the information and know-how presented in their documents. In EURSSEM, references are included to these documents as consistent as possible and all documents are mentioned in the Section “References”.

1.2 Purpose and scope of EURSSEM

The *European Radiation Survey and Site Execution Manual (EURSSEM)* has been developed to provide a consistent consensus approach and guidance to conduct all actions at radioactively contaminated and potentially radioactively contaminated sites and/or groundwater up to their release for restricted or unrestricted (re)use. This approach and guidance should be both scientifically rigorous and flexible enough to be applied for a diversity of site (surface) clean-up conditions.

The title EURSSEM includes the term “survey” because it provides information on control, planning and conducting surveys, and the term “execution” because the processes outlined in the manual allow interested persons/organisations to execute planned actions.

The EURSSEM guidance focuses on the demonstration of compliance with regulations and standards during all stages of such a project.

The EURSSEM guidance includes as well the general functional approach “what has to be done or what should be required” as detailed guidance “how it can be done or how it can be demonstrated that requirements are met”, but the guidance provided is not intended and never had the intention to be prescriptive. A consensus approach is advocated, however.

The EURSSEM guidance is primarily written from rendering a service point of view according to the best available practice.

An important step in understanding the Radiation Survey and Site Investigation Process is accomplished by understanding the scope of this guideline, the applied terminology and concepts. As the guidance set out in EURSSEM is based on important documents that have been produced by:

- the International Atomic Energy Agency (IAEA), (www.iaea.org),
- the SAFEGROUNDS Learning Network (www.safegrounds.com),
- the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM),

the same terminology has been adopted to present a consistent approach. In the case of different terms for the same object/purpose preference is given to terms defined by the IAEA.

1.3 The EURSSEM approach

Five principles have been identified for the development of a consistent approach and guidance to conduct all actions at radioactively contaminated and potentially radioactively contaminated sites and/or groundwater up to their release for restricted or unrestricted (re)use:

1. Protection of people and the environment.
2. Stakeholder involvement.
3. Identifying the preferred site management option.
4. Immediate action.
5. Archiving for future referencing.

These principles apply at various stages in site and groundwater management and are explained in more detail in Section 2, “Development of a contaminated land strategy”.

This guidance on the management of a radioactively or suspected radioactively contaminated sites and/or groundwater has five interrelated parts and two major topics of concern. In practice, depending on case by case bases, the individual parts (in whole or partially) of the management process will be iterative.

The five interrelated parts of EURSSEM are indicated in Figure 1.1:

I. *Decide whether EURSSEM guidance or part(s) of EURSSEM guidance applies:* Assistance is provided with the aid of flowcharts to decide which part(s) of EURSSEM guidance is applicable.

II. *Development of a Contaminated Land Strategy:* Ensuring a clear context and objectives, effective external participation - stakeholder involvement - whether it is required by organisational policy or regulatory frameworks, to meet stakeholder expectations, or to improve decision-making [1]. The part includes two major topics of concern:

1. *Stakeholder involvement*: ensuring an effective external participation, in order to improve the decision-making process, to develop approaches that can be implemented with community support, to improve transparency, to build trust and to take better decisions.

2. *Archive for future referencing*: this archive has not to be seen as a special part of the project file, but as an archive that will contain information that can be consulted in the nearby and long-term future for answering questions dealing with the former radioactive contaminants present at the site and/or groundwater.

III. *Characterisation of Radioactively Contaminated Sites and/or groundwater:* Measuring site-specific data on the levels and distribution of radioactive contamination and residual radioactive contamination, as well as levels and distribution of radio-nuclides present as background, by employing suitable field and/or laboratory measurement techniques[1]. Decide whether the data obtained from sampling do support the assertion that the site meets the release criterion, within an acceptable degree of uncertainty, through application of a statistically based decision rule [2].

IV. *Remediation and Restoration;* Decide about reuse and environmental restoration, selection of remediation technologies [3].

V. *Reuse and Stewardship:* Monitoring, maintenance, information management, record keeping, archiving for future referencing, land use controls and other mechanisms necessary to protect the public and the environment from legacy waste deemed impractical, unsafe, or too costly remediate to unrestricted release [4] now and in the future [5].

EURSSEM presents comprehensive guidance on all 5 topics mentioned in Figure 1.1 for radioactively contaminated soil and/or groundwater. The guidance describes a performance-based approach for demonstrating compliance with a dose- or risk-based regulation. This approach includes processes that identify data quality needs and may reveal limitations that enter into conducting a survey. The data quality needs stated as Data Quality Objectives (DQOs) include performance measures and goals in relation to a specific intended use of the data.

Data Quality Objectives must be developed on a site-specific basis. However, because of the large variability in the types of radiological contaminated sites and/or groundwater, it is impossible to provide criteria that apply to every situation. As an example, EURSSEM presents methods for planning, implementing, assessing, and making decisions about regulatory compliance at sites with radioactive contaminants in surface soil and/or groundwater

Therefore, EURSSEM provides standardized and consistent approaches for developing a strategy, planning, conducting, evaluating, and documenting environmental radiological surveys, with specific focus on the final status surveys that are carried out to demonstrate compliance with clean-up and release regulations.

It is evident that the described approaches may not be applicable for each specific site so that the Data Quality Objectives will be met. Other methods may be used to meet site-specific Data Quality Objectives, as long as an equivalent level of performance can be demonstrated[2].

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1 Measurements include field and laboratory analyses; however, EURSSEM leaves detailed discussions of laboratory sample analyses to other manuals or guidelines.

2 The authors and organisation that have developed EURSSEM would like to be informed about possible other methods and their specifications, so that they can be taken into account in future versions of EURSSEM.

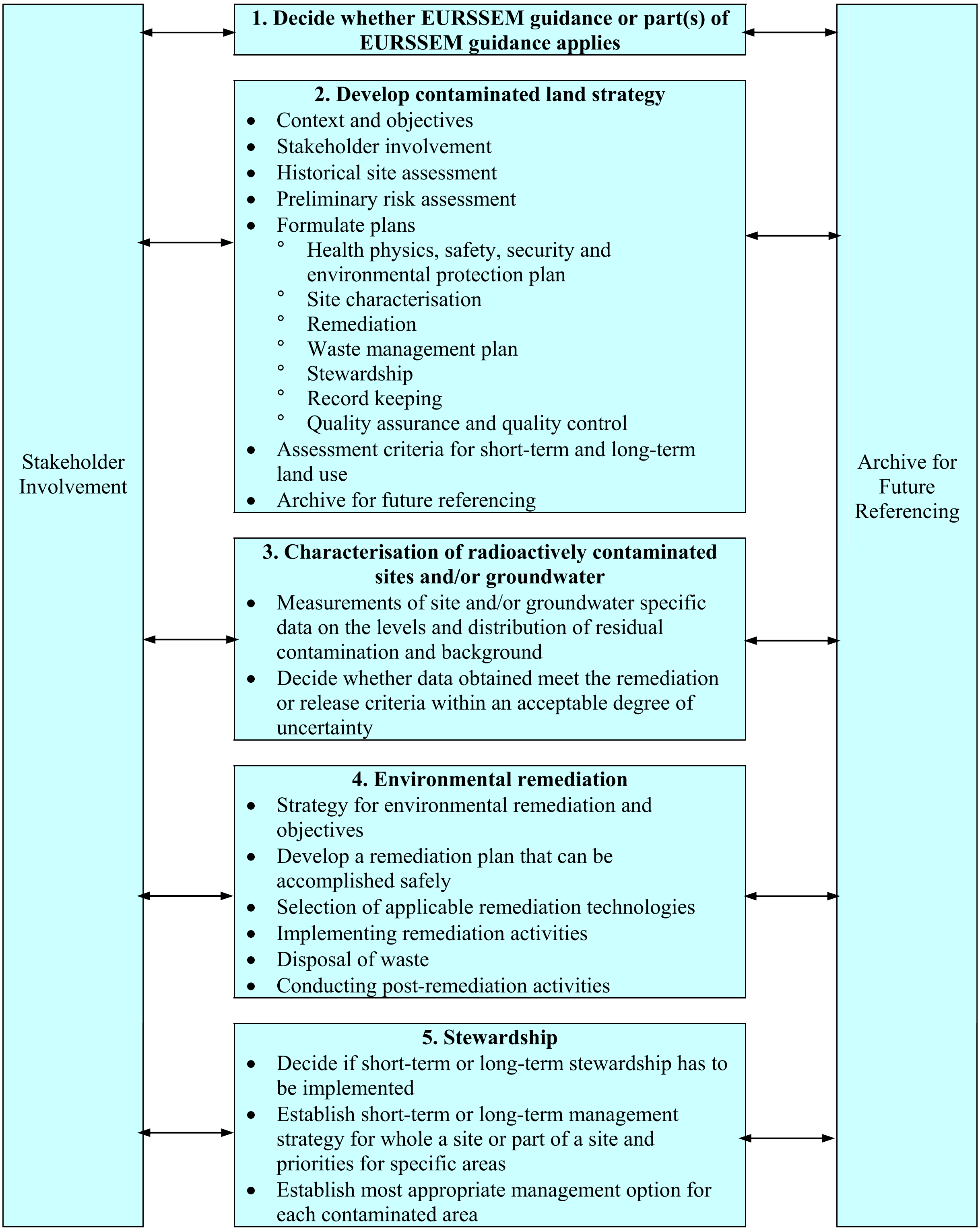

Figure 1.1 The five interrelated parts of EURSSEM

For simplicity, in Figure 1.1 the iterative issue has been omitted.

Table 1.1, at the end of this section, summarizes the scope of EURSSEM. EURSSEM can be applied to surveys performed at vicinity properties, but the decision to apply the EURSSEM at vicinity properties is outside the scope of EURSSEM. EURSSEM main focus is on the release of sites, e.g., restricted or unrestricted (re)use, taken all radioactive contaminants into account and to give guidance to all stakeholders in this process.

EURSSEM is written to develop and to disseminate good practice guidance from rendering a *service point (not a regulatory point)* of view to support clean-up efforts and the management of radiological contaminated sites.

1.4 Structure of the manual

EURSSEM begins with the "Development of a contaminated land strategy" in Section 2 and focuses on the strategy to be applied, e.g., describing the two major topics, e.g., stakeholder involvement in this process and the requirements/set up of an archive for future referencing, in detail, as these two topics are linked to all actions in this process. Presented guidelines, the formulation of the necessary plans at a generic level, e.g., dose or risk assessments, health physics plan, waste management plan, etc., are dealing with soil as well as with groundwater.

In Section 3, the focus is on the radiological characterisation of a site and on the processes involved in how actually doing this, e.g., measuring site and/or groundwater contaminant concentration levels, how to decide if data obtained meet the remediation or release criterion within an acceptable degree of uncertainty, etc.

Remediation and post-remediation activities (restoration) guidelines are presented in Section 4. These guidelines are focusing on the development of a remediation plan that can be accomplished safely, but also on the selection of applicable remediation techniques as well as on implementing remediation and post-remediation (restoration) actions.

Section 5 provides information and guidelines on "Reuse and Stewardship". It is evident that not all radiological contaminated sites and/or groundwaters can be cleaned and released for unrestricted use in an acceptable time scale. Sometimes this is also not needed, like for industrial areas. Therefore, guidelines are set-up for deciding and the implementation of short-term or long-term stewardship.

In each section, flowcharts will summarize the steps and decisions taken in the process, if needed. EURSSEM also contains several appendices to provide additional guidance on specific topics:

- 0: Development of a decision rule and specification of the limits on decision errors.
- 0: Field survey and laboratory analysis equipment for radioactive material concentrations and radiation levels.
- 0: Derivation of the alpha scanning detection limit calculations.
- 0: Supporting information for interpreting survey results and tables of statistical data.
- 0: Glossary of specific terms applied in site characterisation, remediation and restoration processes.
- 0: Examples of report formats, checklists and files.

EURSSEM is presented in a modular format, with each module containing guidance on conducting specific aspects of, or activities related to, the process. Followed in the related order, each module leads to the generation and implementation of a complete plan. Although this approach may involve some overlap and redundancy in information, it will also allow many users to concentrate only on those portions of the manual that apply to their particular needs or responsibilities. The procedures within each module are listed in order of performance and options are provided to guide a user past portions of the manual that may not be specifically applicable to the user's area of interest. Where appropriate, checklists condense and summarize major points in the process. The checklists may be used to verify that every suggested step is followed or to flag a condition in which specific documentation should explain why a step was not needed.

EURSSEM, which is based on a graded approach that many users of radioactive materials may be able to employ - with the approval of the responsible regulatory agency - to demonstrate compliance with the release criterion. Sites that may qualify for simplified release procedures are those in which the radioactive materials used were: 1) of relatively short half-life (e.g., $t_{1/2}$ # 120 days) and have since decayed to insignificant quantities; 2) kept only in small enough quantities so as to be exempted or not requiring a specific license from a regulatory authority; 3) used or stored only in the form of non-leaking sealed sources; or 4) combinations of the above.

EURSSEM supports existing programs and approaches to expedite site clean-ups and the integrating of EURSSEM with other remediation and survey site designs. These approaches can save time and resources by reducing sampling, preventing duplication of effort, and reducing inactive time periods between steps in a clean-up process. EURSSEM is based on six principal steps; although these steps are described sequentially, EURSSEM is not intended to be a serial process that would slow site clean-ups. Part of the significant emphasis on planning in EURSSEM is meant to promote saving time and resources. Where appropriate, EURSSEM will provide information about these alternate programs and approaches.

1.5 Use of the manual

Potential users of this manual are companies, government agencies and other parties that can be described as stakeholders involved in processes to remediate or restore radioactively contaminated sites for restricted or unrestricted (re)use.

The manual is intended for a technical as well as a non-technical audience. However, having knowledge of radiation health physics and understanding of statistics as well as experience with practical applications of radiation protection is recommended.

Understanding of instrumentation and methodologies and expertise in planning, approving, and implementing surveys of environmental levels of radioactive material is assumed. This manual has been written so that individuals responsible for planning, approving, and implementing radiological surveys will be able to understand and apply the guidance provided here. Certain situations and sites may require consultation with more experienced personnel.

EURSSEM provides guidance for developing a strategy, conducting radiation surveys and site investigations. EURSSEM uses the word “should” as a recommendation that ought not to be interpreted as a requirement. The reader does not need to expect that every recommendation in this manual should be taken literally and applied at every site. Rather, it is expected that the documentation will address how the guidance will be applied on a site-specific basis.

As previously stated, EURSSEM supports implementation of dose- or risk-based regulations. Guidelines are incorporated how to translate the regulatory dose limit to a corresponding concentration level. Therefore, the guidance in this manual is applicable to a broad range of regulations, including risk- or concentration-based regulations. The terms dose and dose-based regulation are used throughout the manual, *but these terms are not intended to limit the use of the manual.*

Note that (national) governmental agencies that can approve a demonstration of compliance may support requirements that differ from what is presented in this version of EURSSEM. *It is essential*, therefore, *that the persons carrying out the process remain in close communication with the (proper) national and local government throughout the compliance demonstration process*.

Table 1.1 Scope of EURSSEM

Within Scope of EURSSEM		**Beyond Scope of EURSSEM**	
Guidance	EURSSEM provides technical, performance-based guidance on developing a contaminated land strategy, stakeholder involvement, conducting radiation surveys and site investigations, remediation and restoration, and reuse and stewardship.	*Regulations*	EURSSEM does not set new regulations or non-technical issues (e.g., legal or policy) for site clean-up. Guidance in the calculation of release criteria is provided; however, applied methods and results should be approved by involved regulators.
Tool box	EURSSEM can be thought of as an extensive tool box with many components – some within the text of EURSSEM, others by reference.	*Tool box*	Many topics are beyond the scope of EURSSEM, for example: - packaging and transportation of wastes for disposal; - decontamination and stabilization techniques for waste; - training.
Stakeholder involvement	The guidance given in EURSSEM is general and based on internationally reported experiences in literature.	*Procedure*	Suggested points of concern and approaches in EURSSEM depend on a site-specific need - there are no set of general applicable procedures to set-up an effective stakeholder-involvement.
Measurement	The guidance given in EURSSEM is performance-based and directed towards acquiring site-specific goals.	*Procedure*	The approaches suggested in EURSSEM vary depending on the various site and/or groundwater data needs - there are no set of general applicable procedures for sample collection, measurement techniques, storage and disposal of waste established in EURSSEM.
Modelling	The interface between environmental pathway modelling and EURSSEM is an important survey design consideration addressed in EURSSEM.	*Modelling*	Environmental pathway modelling and ecological endpoints in modelling are beyond the scope of EURSSEM.
Soil, subsurface soil, surface or subsurface water (and buildings)	The main media of interest in EURSSEM are contaminated surface soil, subsurface soil, surface or subsurface water (and building surfaces).	*Other media*	EURSSEM does not cover other media, including construction materials, equipment, biota, air, sewers, sediments or volumetric contamination.
Final status survey	EURSSEM gives guidance on final status survey as this is the deciding factor in judging if the site meets the restricted or unrestricted release criteria.	*Materials or equipment*	EURSSEM does not recommend the use of any specific materials or equipment or methods - there is too much variability in the types of radiation contaminated sites and/or groundwater - some information will be within the text of EURSSEM, others by reference.
Radiation	EURSSEM only considers and focuses on radiation-derived hazards.	*Chemicals*	EURSSEM does not deal with any hazards posed by chemical contamination - this information will be in other documents.
Data Quality Objective process	EURSSEM presents a systemised approach for designing surveys to collect data needed for making decisions such as whether or not to release a site.	*Data Quality Objective process*	EURSSEM does not provide prescriptive or default values of Data Quality Objectives.
Data Quality Assurance	EURSSEM provides a set of statistical tests for evaluating data and lists alternate tests that may be applicable at specific sites.	*Data Quality Assurance*	EURSSEM does not prescribe a statistical test for use at all sites.
Remediation (restoration) method	EURSSEM assists in determining a remediation-restoration method when sites are ready for a final status survey and provides guidance on how to	*Remediation methods*	EURSSEM does not discuss selection and evaluation of remedial-restoration alternatives, legal considerations and policy decisions related to planning.

Within Scope of EURSSEM		Beyond Scope of EURSSEM	
	determine if remediation was successful.		
Radioactive waste	EURSSEM provides some general information and guidance on management and transport.	*Procedure*	The set-up of detailed guidance and implementation on radioactive waste management and transport are beyond the scope of EURSSEM.
Post-remediation activities	The presented guidance and assistance in EURSSEM is to prevent this type of activity; however, it cannot be excluded. Therefore, EURSSEM provides assistance in post-remediation activities.	*Post-restoration method*	EURSSEM does not discuss selection and evaluation of post-remediation alternatives, legal considerations and policy decisions related to planning.
Reuse-stewardship	In the case of restricted reuse, EURSSEM provides guidance in implementing short-term or long-term stewardship.	*Stewardship management and strategy*	EURSSEM does not prescribe to implement stewardship or discuss selected stewardship management or strategy.
Archive for future referencing	EURSSEM gives guidance to set-up such an archive and its content.	*Content of archive for future referencing*	EURSSEM does not provide prescriptive or default contents of an archive for future referencing.

2 Development of a strategy, implementation and execution programme to remediate radioactively contaminated sites

2.1 Context and objectives

As indicated in Section 1, the European Radiation Survey and Site Execution Manual (EURSSEM) has been developed to provide a consistent consensus approach and guidance to conduct all actions at radioactively contaminated and potentially radioactively contaminated sites and/or groundwater up to their release for restricted use or for unrestricted use.

The term 'site' means land together with any buildings or structures being considered for release from regulatory control [6]. Buildings or other structures are not subject of this document. However, techniques used for the characterisation, decontamination and remediation and reuse of buildings and structures might also be used for the characterisation, remediation and reuse of sites.

Mixed contamination sites generally result from waste disposal practices, unintentional releases from waste or material storage facilities, accidental spills during transportation or operations at facilities that manage hazardous and radioactive materials, and mining [7]. They can also derive from smelting operations and incineration of radioactive and hazardous wastes when air emissions are deposited on land. Releases of hazardous and radioactive contamination to the environment can have an impact on surface soil and the vadose zone, groundwater, surface water and sediments.

The word 'soil' has a variety of different meanings depending upon its relevance to the society [8]. Farmers consider it as the part of the earth's surface containing decayed and organic material in sufficient quantity to grow plants and crops. Geologists take it as the residual (left over) material from underlying parent rock that supports root growth. To the engineer, soils include all earth materials overlying the rock crust and contain particles of minerals, gasses, and liquids.

In general, soil is a living system that represents a finite resource vital to life on earth. It forms the thin skin of unconsolidated mineral and organic matter on the earth's surface. It develops slowly from various parent materials and is modified by time, climate, macro- and microorganisms, vegetation, and topography.

Soils are complex mixtures of minerals, organic compounds, and living organisms that interact continuously in response to natural and imposed biological, chemical, and physical forces. Vital functions that soils perform within ecosystems include: sustaining biological activity, diversity, and productivity; regulating and partitioning water and solute flow; filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials, including industrial and municipal by-products and atmospheric depositions; storing and cycling nutrients and other elements within the earth's biosphere; and providing support for socio-economic structures and protection for archaeological treasures associated with human habitation.

Different views about soil quality exist. For people active in production agriculture, it may mean highly productive land, sustaining or enhancing productivity, maximizing profits, or maintaining the soil resource for future generations. For consumers, it may mean plentiful, healthful, and inexpensive food for present and future generations. For naturalists, it may mean soil in harmony with the landscape and its surroundings, and for the environmentalist, it may mean soil functioning at its potential in an ecosystem with respect to maintenance or enhancement of biodiversity, water quality, nutrient cycling, and biomass production. In general, soil quality may be defined as*:* the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation.

Soil quality is therefore related to how well the soil does what we want it to do. This means that we need to have the complete information about the specific kind of soil or the soil characteristics which in fact are always subjected to fluctuations due to changes in management, changing rainfall patterns (including acid rain), changing water table levels and vegetation cover and other environmental factors. These changes in turn disturb the chemical equilibrium pattern in soil. In other words, soils are not material specific, many of their properties are not single valued, many are transient, and many are not randomly distributed but rather systematically time and spatially dependent.

Soil quality can be affected or disturbed by any of the factors described above and when a disturbance is due to the presence of substances in such concentrations which affect or tends to affect the role the soil plays in the ecosystem, it is known as contaminated soil, and the substances involved in this process are called soil contaminants. The standards or the thresholds that are fixed for the various soil contaminants through the national/international legislations provide specific definitions of soil contamination, as contamination here refers to the exceeding of the threshold limiting values prescribed in such legislations.

External contaminants entering a soil body through wet or dry precipitation, such as radionuclides, trace elements or organic compounds behave differently with regard to each soil type according to the absorption properties, texture, density, humidity, and other factors. As these properties are not homogeneously developed in a certain soil bed and soil properties change largely with stratigraphy it is extremely difficult to collect soil samples from a sampling area for chemical analysis in such a way that representativity is assured.

Groundwater is considered to be the water in the subsurface, in both the unsaturated and saturated zone, of a region, being an integral part of the larger hydrologic cycle of the region (Figure 2.1) [9]. Interactions between groundwater and surface water bodies (recharge and discharge zones) provide one of the major pathways through which site and/or groundwater contaminants interact with humans and the wider terrestrial environment. These interactions can be beneficial by diluting the contaminated groundwater which can be a major factor in the reduction of the impact of groundwater contamination.

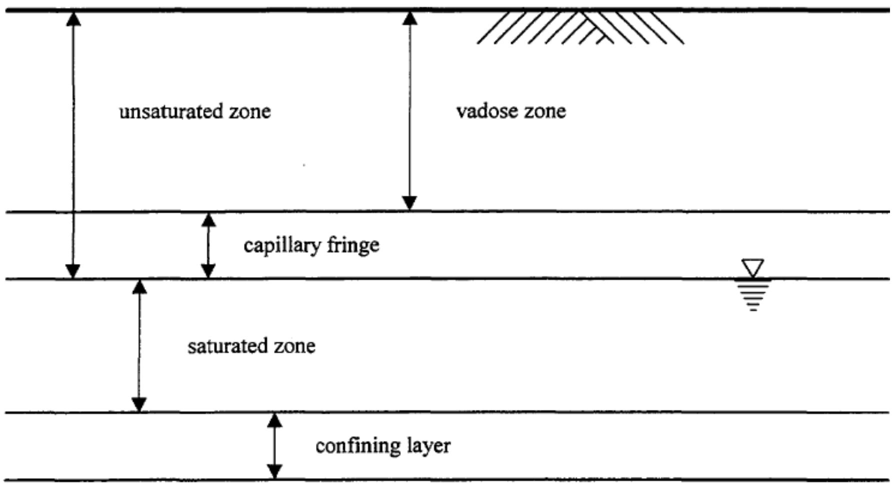

Figure 2.1 Generalized overview of the subsurface environment

Alternatively, contamination may become concentrated in bottom sediments through precipitation and sorption processes, or may be taken up and accumulated in plants and animals. Contaminants may also be transported to become deposited some distance from the point of discharge, usually at some interface, such as when suspended particulates are deposited when a river flows into a lake. Changes in water chemistry can occur downstream in a river system or where two rivers meet, as may the anaerobic conditions when a polluted river flows into a clean river or where effluents such as sewage are discharged into a water course. All of these processes and others can influence the way in which contaminants interact with man and the environment.

As a result, any programme intended to assess and remediate contaminated sites and/or groundwater should start with the development of a structured conceptual model that embodies geology, hydrogeology, toxicology, radiology, and affected populations.

Five principles have been identified for the development of a consistent approach and guidance to conduct all actions at radioactively contaminated and potentially radioactively contaminated sites and/or groundwater up to their release for restricted use or for unrestricted use [10]. These principles apply at various stages in site and groundwater management. They are:

- **Principle 1: Protection of people and the environment**
  The fundamental objective of managing a radioactively contaminated site and/or groundwater that is going to be reused should be to achieve a level of protection of people and the environment that is conform to the existing views of health physics and ALARA.

  The term "managing a radioactively contaminated site and/or groundwater" includes all actions to control, to characterise and to remediate (wholly or partially) the radioactive contamination, to restore the site, to install if necessarily short-term or long-term stewardship, as well as the associated decision-making processes.

  This definition excludes the management of radioactively contaminated sites and/or groundwater that are still in operation conform its original intent and license, e.g., the site of an operational nuclear power plant, the site of a radioactive waste disposal facility, etc..

  The intent of Principle 1 includes that it should not be tied to a moment in time, but should be applicable now and in the future, so that new developments, such as in the field of control, characterisation, remediation, etc., can be taken into account. Therefore, the fragment "conform existing views of health physics" is included in this principle.

  The International Commission on Radiological Protection (ICRP) stipulates that [21]:

  > "*Remediation measures shall be justified by means of a decision aiding process requiring a positive balance of all relevant attributes relating to the contamination. In addition to the avertable annual doses, both individual and collective, other relevant attributes shall be assessed.*"

  Remedial actions at a radioactively contaminated site have direct and lasting effects on the level of contamination and thus on the level of stewardship required at the site.

  The International Atomic Energy Agency defines that [14]:

  > "*Remediation shall (a) reduce the doses to individuals or groups of individuals being exposed; (b) avert doses to individuals or groups of individuals that are likely to arise in the future; (c) prevent and reduce environmental impacts from the radionuclides present in the contaminated area*."

  The International Atomic Energy Agency formulated in an IAEA Safety Guide the criteria for the release of sites from regulatory control upon the termination of practices [6]. Though strictly speaking this guide applies only to the decommissioning of authorized practices, sites where past practices or accidents have led to contamination in the the ground would have to comply with most of the criteria set out there.

  > "*The restrictions should be designed and implemented to provide reasonable assurance of compliance with the dose constraint for as long as they are necessary… Therefore, existing regulatory limits on the institutional control time frames should be taken into consideration in deciding whether to release a site for restricted use.*"

The term ALARA (As Low As Reasonably Achievable) is included to emphasize that economics are an integral part of the management of radioactively contaminated sites and/or groundwater. By explicitly integrating economics in the management of a radioactively contaminated site and/or groundwater, the managing becomes site specific and will depend on the economical strength of the area (country) in which the radioactively contaminated site and/or groundwater is located.

- **Principle 2: Stakeholder involvement**
  The legal entity responsible for the management of a radioactively contaminated site and/or groundwater should involve stakeholders.

  The intent of Principle 2 is to ensure effective participation of stakeholders in the management of a radioactively contaminated site and/or groundwater, whether it is required by the regulatory framework or included in the organisational policy, to meet stakeholder's expectations and/or to improve decision-making processes.

- **Principle 3: Identifying the preferred site management option**

  The legal entity responsible for the management of a radioactively contaminated site and/or groundwater should identify the preferred reuse option (or options) for the remediated and restored radioactively contaminated site.

  The intent of Principle 3 is to make it unambiguous clear that the responsibility for defining the reuse option of a radioactively contaminated site lays by the legal entity that is responsible for the site. How the responsible legal entity has performed the decision-making process to come to a preferred reuse option is not important and is out of the scope of this guidance. However, it is evident that if in the decision-making process factors are taken into account that are of concern to stakeholders, including health, safety and environmental impacts and various technical, social and financial factors, the chance of acceptance by stakeholders of the preferred reuse option will be greater.

- **Principle 4: Immediate action**

  The legal entity responsible for the management of a radioactively contaminated or suspected radioactively contaminated site and/or groundwater should perform all measures so that Principle 1, Protection of People and the Environment, is fulfilled.

  The intent of Principle 4 is to make it unambiguous clear that the legal entity has to act and will be kept (socially and financially) responsible for any damage, e.g., social, health, environmental impacts, etc., by any negligence.

- **Principle 5: Archive for Future Referencing**

  The legal entity responsible for the management of a radioactively contaminated or suspected radioactively contaminated site and/or groundwater should set-up an "Archive for Future Referencing".

  The intent of Principle 5 is that from each formerly radioactively contaminated or suspected radioactively contaminated site and/or groundwater, the information is available that can be consulted for assessing the eventual risk of any remaining radioactive contamination according to risk-assessments developed in the future.

  The content of the "Archive for Future Referencing" has to contain information about what is present, what is not present and what has never been present.

2.2 Designing a remediation programme for radiological contaminated sites

2.2.1 Major steps in a remediation programme

Environmental remediation should commence with a planning stage [3]. Matters which should be considered first, i.e., at the very beginning of the planning stage, should include the following:

- Potential human health and ecological impacts;
- Public perception and response to the problem;
- Likely permanence of adverse effect of contamination;
- Potential for spread of contamination;
- Established radiological and other criteria;
- Potential for trans-boundary effects;
- Availability of technological solutions and resources;
- Financial capability;
- Lessons learned.

The preparation of a programme plan is linked to a number of other activities. The general elements of an actual environmental restoration programme may comprise:

- Preparing the programme plan;
- Estabilish stakeholder involvement;
- Perform a historical site assessment;
- Conducting a radiological site characterization;
- Establishing remediation criteria;
- Selecting the remediation approach;
- Implementing remediation activities;
- Conducting post-remediation activities;
- Considering special aspects;
- Establishing a quality assessment program;
- Reporting and archiving.

Each of these elements requires pre-planning. It is helpful to prepare reports which detail all the supporting activities related to these elements before significant levels of funds and efforts are committed. The preparation of this programme plan will usually require several iterations. A number of preliminary choices or strategic decisions will have to be taken as the plan is developing.

2.2.1.1 Potential human health and ecological impacts

The remediation plan and associated monitoring requirements should be designed and implemented so as to identify possible adverse health and environmental effects of the contaminants and to optimize protection. These considerations apply to the workers performing the remediation, to the public and to the environment.

To achieve the objectives of an environmental remediation, decisions should be taken concerning the following:

- The schedule and sequence of the remediation activities;

- Operational quantities (e. g., instrument readings corresponding to the reference levels);
- The criteria for the termination of remedial actions;
- Post-remediation conditions with regard to access to or use of the site.

Dependent on the scale of contamination, remediation of sites may be prioritized following a hazard assessment and reduction process. Political considerations, funding considerations, logistical considerations and public input may play another important role, however.

Considering public health and ecological factors, the decision making relating to priorities with respect to remediation of sites may be influenced by the factors as indicated in the following sections [44].

2.2.1.2 Public perception and response to the problem

Differences may exist between the way communities and engineers think about risk, resulting in communications between the two groups sometimes being rather difficult. Experiences have shown hat 'top-down' risk communication is unlikely to resolve environmental risk controversies. As a result, risk communication and policy practice have moved towards a two-way dialogue between the 'community' and 'experts'.

Despite for example the tendency to consider widely-reported events to be more likely than they really are, or other biases that have impact on the perception of risk, the ability of the general public to rank frequency of death from hazards is often not unrealistic. However, the perception of the general public diverges from 'scientific' risk assessment in that they factor in 'quality' of hazard, e.g., thread, familiarity and catastrophic potential. Different forms of death and disease are not feared equally.

Further, the general public's understanding of a risk should not be confused with the general public's acceptance of the risk. The level of acceptable risk is a matter of values and opinions. Any evaluation of options should therefore explicitly incorporate underlying values and social factors such as fairness and the balance of benefit and risk. Steps that result in a fair and more voluntary distribution of risk will be helpful.

2.2.1.3 Likely permanence of adverse effect of contamination

The nature of the response to environmental problems at the national level, and eventually at the programme or project level, will depend on the nature, the extent and the likely permanence of adverse effects of contamination. This includes the information on radionuclides involved, their distribution affected media, actual or potential exposures of individuals and the general public, and the potential negative effects on the environment.

2.2.1.4 The potential for spread of contamination

An important step should be to assess the potential for spread of exposure from the contamination to humans and the environment. After the seriousness of the problem has been evaluated, the urgency for action can be determined. Situations requiring immediate or urgent action are high priority, as the actual or perceived threat to human health and safety may require a quick response. If the environmental contamination resulted from a past or present practice about which historical information is mostly available, the decision making authority, has more time and flexibility to consider all relevant factors and assess their relative importance

2.2.1.5 Established radiological and other criteria

The criteria for deciding whether to terminate environmental remedial actions should be clearly stated in the plan. This way an unnecessarily continuation of environmental remediation can be avoided beyond the point at which it is justified and optimized. As an integral part of any successful environmental remediation there should be a clear understanding by the interested parties of the environmental remediation end criteria.

Clean-up or restoration criteria can help in the allocation of resources for clean-up in a cost effective manner. Such criteria are generally derived from radiation protection criteria. International and national organizations and regulatory bodies have established a great variety of limits to restrict or constrain doses that might be received by man. They may, where appropriate, be adopted directly for use in evaluating the need for the restoration of a site.

Restoration criteria can be site specific or generic. Site specific criteria for restoration are typically based on calculated risks to humans or to the environment. This approach allows for the adaptation of clean-up levels to local site conditions. For example, the health risk at a particular site may depend on the combined effect of many factors, such as the radioactive species, its distribution and concentrations, possible pathways, climatic conditions, soil conditions, hydrology, meteorology, and demographics.

Since each site presumably has different conditions, the use of site specific criteria allows the tailoring of restoration criteria to each specific site. In other words, it is possible to assign different clean-up levels while keeping the risk at a uniform level for all sites. However, site specific criteria, typically leading to different restoration levels at different sites (the very reason for its use) may lead to social/political questions of perceived injustice and inequity.

Generic criteria will usually also be based on risk consideration but are not necessarily directly related to the conditions at the site under investigation. Generic criteria are uniform for all sites in a region or country. The major advantage of generic criteria may be their greater political acceptability. As generic criteria do not give rise to different restoration levels, they avoid the appearance of providing different treatment of different population groups. Because of their clarity, generic criteria are also easier to regulate and enforce. The disadvantage of generic criteria is that they may not be universally applicable. By adhering to them, the opportunity of tailoring the expensive clean-up activity to minimum locally required levels can be lost. In some instances, this could dramatically increase the cost over what would be necessary under site specific standards.

In general, the interaction between specific (or local) and generic (or national) regulations, if not harmonized, can significantly increase the cost of and time for the restoration. It is of value to resolve conflicts between these regulations prior to the start of restoration otherwise programme/project focus is lost. Negotiations should be initiated to determine the primacy of regulations for each expected situation at the start of the decision making process. It is suggested that communications between local, regional, and national regulators and with the project managers are established and maintained throughout the life of the project. It is also important to consider the full range of regulatory regimes that could impact work at the site. For example, unless allowances are made for local building permits and restrictions (if applicable) there could be significant project delays if facility construction was not carried out in conformance with the local requirements.

2.2.1.6 Potential for trans-boundary effects

The movement of environmental contaminants across national boundaries can have serious consequences for the affected countries.

International agreements exist on the trans-boundary movement of wastes and the disposal of said wastes in international waters. In addition, international standards and conventions exist on waste management practices and radiation protection. An additional area where international factors can be of considerable interest is in the areas of technical or financial assistance. The ability to access technical knowledge from other countries can significantly reduce the challenges to a country with limited experience. Also, the availability of international funding can assist with environmental contamination that threatens other countries.

2.2.1.7 Availability of technological solutions and resources

A wide range of in-situ and ex-situ instruments is available for the detection of radioactivity and hazardous materials to characterise radioactively contaminated sites. In general different radiation detectors will be required to detect different types of radioactivity (e.g. alpha, beta and gamma). EURSSEM gives guidance and a detailed description of instruments available and this is presented in 0 (not claiming to be 100% complete).

Most environmental remediation technologies currently available are expensive to implement and may take long periods of time to complete. Continued research is ongoing worldwide to develop new techniques for in-situ and ex-situ remediation. A general list and description of these technologies can be found in Section 4.5 of this document. Care should be taken to evaluate the success or failure of the technologies which have been developed and to compare the site specific characteristics against the test site to determine the viability at a particular site.

Provisions for the different actions in the plan, e.g., establishing stakeholder involvement, historical site assessment, characterisation, remediation, post-remediation etc., should be addressed in the remediation plan. As remediation progresses, the plan should be updated to reflect any changes or provisions relating to the conduct and progress of the remediation.

2.2.1.8 Financial capability

The parties who caused the contamination or allowed it to occur should be held responsible for the remediation programme and its funding, in accordance with the ‘polluter pays’ principle [**Principle 4**]. However, circumstances in many instances may be complex and the total remediation costs may be disproportionately high in comparison with the actions of the organization that caused the contamination. The contamination may, for example, have been caused by changes to exposure pathways that were unforeseen when a discharge authorization was given, or by an accident. In some cases, the economic costs apportioned to an organization would be such that they could lead to its bankruptcy and consequent inability to pay. Adequate funding mechanisms should be foreseen, therefore, and costs may fall wholly or in part on owners, industry, developers, local communities or national governments, as well as on the original polluter [12].

Since the apportionment of liabilities may be contentious, particularly when large sums of money are involved, and formally designating a site as requiring intervention may bring an unwelcome depreciation in the value of the surrounding properties, the responsible party should engage with interested parties to negotiate voluntary and cooperative action in preference to the regulatory body initiating enforcement action. Among interested parties should be included: local authorities, owners, tenants, users, potential developers, liability insurance companies, local communities near the site who may benefit from the intervention, those responsible for the source of the pollution and environmental groups.

Regulatory oversight should be maintained and adequate and proportionate funding should be provided, to enable the regulatory body to ensure that any remediation is carried out properly. The government should fund regulatory oversight, or otherwise the regulatory body may fund its regulatory activities through a system of fees chargeable to the project. When urgent action is needed, responsibilities for the remediation should be assigned to a specific organization with adequate technical and human resources to establish and perform the remediation programme urgently and to recover the costs at a later time.

2.2.1.9 Lessons learned

The process of designing an environmental remediation plan should take advantage of lessons learned from similar environmental remediation projects that have been completed in the past. These lessons learned may provide both positive and cautionary advice. In effect, information on the failure of a particular method of environmental remediation in certain circumstances may help to narrow the choice of feasible environmental remediation strategies when planning new remedial actions.

2.2.2 Initial decision making

2.2.2.1 Overall approach

In principle, an overall remediation process for radioactively contaminated and potentially radioactively contaminated sites and/or groundwater may involve five main activities (Figure 2.2) [12]:

1. Historical site assessment
2. Initial site characterisation and establishing remediation criteria;
3. Identification of remediation options and their optimization, followed by subsequent development and approval of the remediation plan;
4. Implementation of the remediation plan; and
5. Post-remediation management and stewardship

Following completion of each of these main activities, a decision should be taken about whether to release the site or part of the site for either restricted or unrestricted use, or to proceed to the next activity. The differences in implementation for specific sites will be in the degree of detail and complexity of the activities undertaken in each step in the process. An iterative approach based on the potential risks should be used.

Planning for remediation should begin once a radioactively contaminated or potentially radioactively contaminated site and/or groundwater has been identified or following a priority list defined in a larger project. The necessary funds should be made available either from the responsible party or through other mechanisms provided for in the legislation. The responsible party should collect available information about the radioactively contaminated or potentially radioactively contaminated site and/or groundwater and should perform a historical site assessment [**Principle 4**]. Interested parties, including past and present owners, workers, local industry, residents, neighbouring states and/or local governments, should be consulted to obtain information, as appropriate.

General or specific reference levels should be used for an early analysis to determine the type and the extent of contamination that would require remediation. These levels should provide assistance in the early planning and help to establish the end criteria of any possible remediation activities.

A site characterization should then be performed on the basis of the relevant site information to determine whether the remediation end criteria (in terms of individual doses or derived concentration values) have been met. If the criteria have been met and this is confirmed by a survey, the site can be released without restrictions (i.e., no remedial actions are necessary).

If the site does not meet the criteria for unrestricted release, suitable remedial measures should be identified and an options study should be performed to compare the benefits and detriments of these measures. The options should cover a broad range of situations and should be based on a set of credible exposure scenarios.

For all options identified, a study should be performed to determine the option that is best for the site. The study should factor in both justification and optimisation [**Principle 1**]. This study should include estimates of the costs and other resources associated with the treatment, removal, transport and disposal of contaminated material for each option; estimated doses to workers and the public due to exposure before, during and after the remediation; overall safety issues during remediation; available technologies; considerations for monitoring and sampling; amounts of wastes that will be generated; and the institutional controls required after implementation of the option, if applicable.

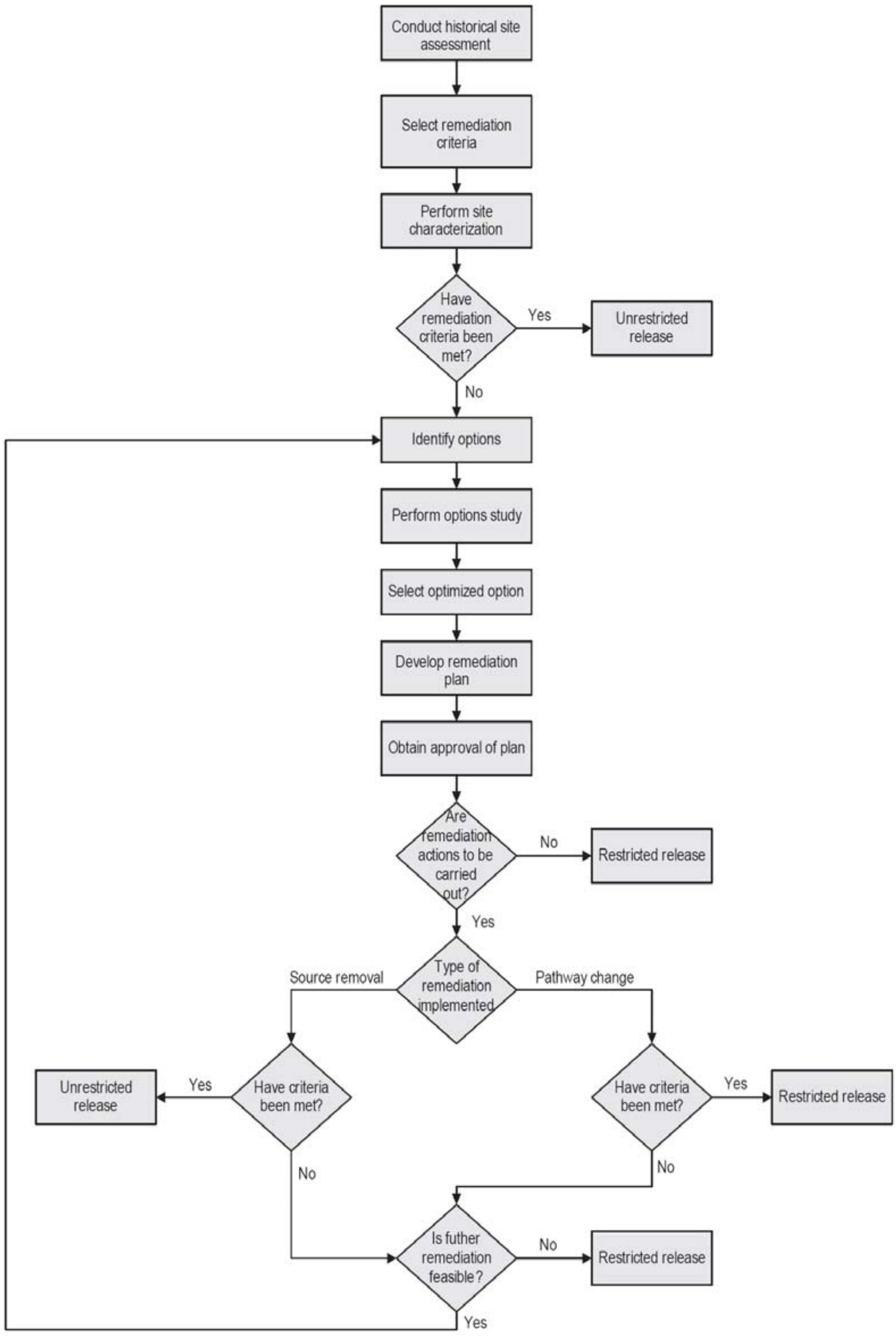

Figure 2.2 Overall remediation process

For the options under consideration, optimisation of protection should be performed for the justified options to determine the option that has the highest net benefit. On the basis of this optimization, a preferred option should be selected that also takes into account non-quantitative considerations such as social and political aspects [**Principle 3**].

The most suitable option may be the one that can be implemented with assurance of success and that provides the most benefits or results in the least damage to the environment as a whole, at acceptable cost, in the long term, as well as in the short term [7]. The process of making judgements on what might be the most suitable management option in environmental remediation projects has been illustrated in Figure 2.3 as an example.

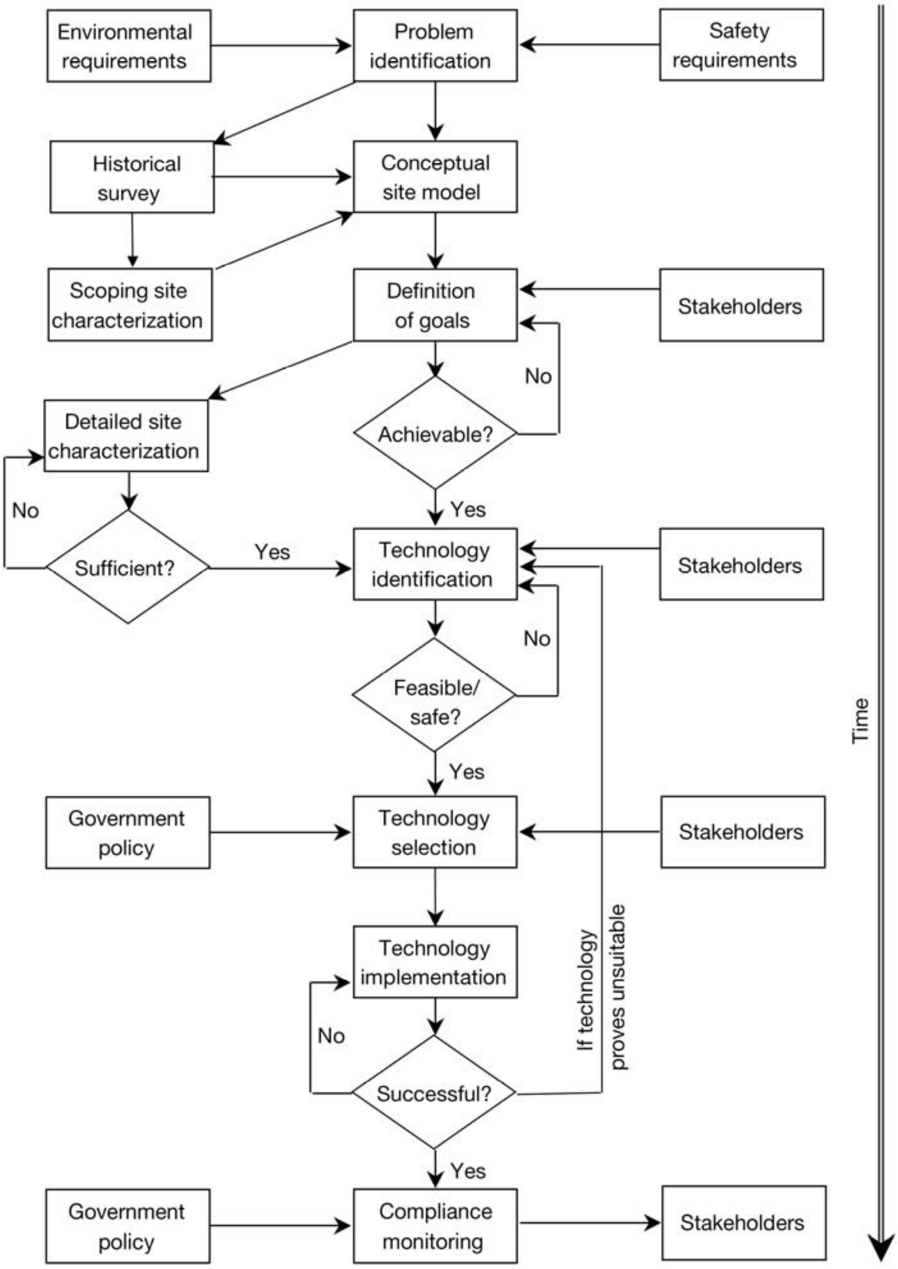

Figure 2.3 Example of phases of decision making in remediation strategies and technologies

For the selected option, a detailed remediation plan showing that remediation can be accomplished safely should be prepared for each radioactively contaminated site and/or groundwater, unless otherwise required by a competent authority and the remediation plan should be subject to the approval of the competent authority prior to its implementation.

Plans should be provided for both the remediation work and the necessary measures for post-remediation, such as maintenance, monitoring and institutional controls to enforce restrictions on land use and buildings, if applicable. Although institutional controls may last for a long period of time, they are part of the post-remediation process and should therefore be covered in the remediation plan.

Once the remediation plan has been approved, it should be implemented as soon as possible. If it is decided not to remediate the site, decisions should be taken on imposing restrictions on its use or access prior to release. If remedial actions are required, they should be implemented as soon as possible.

Two types of remedial action are possible: (1) source removal, or (2) pathway change. After the approved remedial actions have been completed, the effectiveness of the implementation should be evaluated, for example by a competent authority.

If the established remediation criteria have been met after source removal actions, the site should be released without further restrictions. If the criteria have been met after pathway change actions, the site should be released with appropriate restrictions. These restrictions would be in the form of institutional control on the use of the site, for example to ensure that restrictions on grazing are followed.

If, after remedial actions have been carried out, the criteria have not been met, the responsible party should determine whether further remediation is feasible or whether the site should be released with restrictions, and should submit a proposal accordingly to the competent authority for approval. If conditions have changed or additional information has been collected, and further remediation is justified, the process illustrated in Figure 2.2 should again be followed, starting at the stage at which the options are to be identified.

2.2.2.2 Historical site assessment

A historical site assessment may be performed for a site subject to a remediation project to collect the information about the historical radiological conditions and to identify what additional information may be necessary to enable an evaluation of the site to be performed. This assessment could be made on the basis of operational and available information.

The objectives of a historical site assessment could be:

1. To identify possible sources of radiological and non-radiological contamination and other hazards;
2. To identify the characteristics of the contaminants;
3. To identify related past activities or accidents that occurred on the site;
4. To determine the impact of the site on human health or the environment;
5. To provide input into the design of the characterization survey;
6. To provide an assessment of the likelihood of migration of contaminants;
7. To determine possible responsible parties.

Existing information providing a physical description of the site should be collected, including aspects such as location, buildings, buried material, physical barriers, geological and hydro-geological characteristics, type of soil and human activities on or near the site that may help to identify parties that may potentially be affected by the remediation. The information may be collected by means of (1) a review of operational records, past radiological and non-radiological surveys and local government records and files, and (2) interviews with present and former employees or residents.

In the assessment of any environmental contamination, all available information should be used to estimate the scope of the problem and to determine the type, quality and quantity of measurements necessary to make a decision on the extent of the remediation required.

2.2.2.3 Remediation criteria

Reference levels have been defined for use within the system of protection [13]. A reference level (often expressed in terms of annual effective dose[3]) indicates a level below which remediation is normally unlikely to be justified, and it serves as a criterion for the unrestricted release of a site. A generic reference level for aiding decisions on remediation is an existing annual effective dose of 10 mSv from all sources, including natural background radiation. This will normally be assessed as the mean dose for an appropriately defined critical group. Remedial measures may be justified below the generic reference level and national authorities may define a lower reference level for identifying sites that might need remediation [14].

Additionally, a reference level specific to a particular component of the dose (such as that due to the inhalation of radon) may be established to limit the contribution of this component to the annual dose. This specific reference level should be expressed in terms of annual dose as an appropriate fraction of the generic reference level, or in terms of a subsidiary quantity such as dose rate or activity concentration.

In addition to a generic reference level for the total effective dose, a generic reference level for organ doses may also be required. An existing annual equivalent dose of 100 mSv (inclusive of all existing contributions, including doses due to natural background radiation) to any organ shall justify intervention under almost any circumstances [10].

The reference levels for the annual effective dose and equivalent organ doses, together with the specific reference levels for dominant components (as far as established by the competent authority), establish the remediation end criteria. These levels should refer to the actual exposures as well as to potential future exposures. Potential future exposures should correspond to the scenarios considered in the options study, which is referred to in Figure 2.2.

In general, dose criteria cannot be directly measured, and therefore it is necessary to use assessment models to derive operational quantities that can easily be measured. By proper modelling of the exposure pathways, both the generic reference levels and specific reference levels can be converted into operational quantities, such as activity concentrations in Bq/g or Bq/m^2, above which remedial actions should be implemented. This will enable the responsible party to implement remedial actions and demonstrate compliance with dose criteria.

On the basis of a generic reference level for the total effective dose of 10 mSv/year (or lower levels if specified by the competent authority), radionuclide specific generic reference levels for remediation, expressed in terms of bulk activity concentration (for soil and other material) as well as surface activity concentration, should be calculated by acceptable methods and in consideration of the components (e.g., material characteristics).

As an example, a specific approach for the implementation of remediation criteria may be summarised as indicated in the form of the reference levels indicated in Table 2.1 [15].

The reference levels relate to the annual individual doses, to an average member of the critical group, additional to the regional level of background. For Bands 5 and 6 (and possibly 4), however, the additional dose is usually large compared to this background, and so the criteria might reasonably be applied to the total dose including background if this is more convenient.

The reference levels would, in the first instance, be compared to the doses estimated on the basis of the initial level of contamination. This comparison will give an indication of whether remediation is likely to be justified radiologically. The end point for remediation would then,

[3] The annual effective dose is the sum of all significant components of annual dose incurred by a typical individual in an exposed group of people, from all relevant sources and via all pathways of a human habitat subjected to prolonged exposure. The existing annual dose therefore includes: the annual dose from natural sources of radiation; the annual dose caused by the accumulation of long lived radio-nuclides released from practices under control; and the annual dose caused by long lived radioactive residues from previous human activities and from long standing accidental contamination of the environment.

in principle, be determined by optimization, but the reference levels can also be used to give an indication of the likely acceptability of different end points as a new 'background' level, i.e. for a return to normality. With the possible exception of situations initially in the upper end of Band 4 (where a justified and optimized remediation might conceivably leave a situation towards the lower end of Band 4), any remediation would normally need to produce an end point at least one band lower, and no higher than Band 4.

Table 2.1 Examples of reference levels for remediation criteria

Band No.	Range of annual doses (to average member of the critical group)	Is remediation needed?	
		With constraint	Without constraint
Band 6	> 100 mSv/a	Always	Always
Band 5	10 – 100 mSv/a	Always	Almost always
Band 4	1 – 10 mSv/a	Almost always	Usually
Band 3	0.1 – 1 mSv/a	Usually	Sometimes
Band 2	10 – 100 µSv/a	Sometimes	Rarely
Band 1	< 10 µSv/a	Almost never	Almost never

The annual doses dividing the bands are approximations in view of the uncertainties involved. Nevertheless, it is convenient to have single numbers to represent criteria, and considerable presentational problems may be expected if slightly different numbers are quoted in different situations.

In this case, the most significant criterion that cannot readily be linked to existing criteria is probably that dividing Bands 4 and 5. This represents a point above which remediation would normally be expected to be undertaken in unconstrained situations, and therefore also represents the maximum level of residual dose that (apart from exceptional circumstances) might be considered acceptable as a new 'background' level. Therefore, situations with annual individual doses above this level would never be considered as normal whereas situations with annual doses below this level could, depending on the situation, be considered as normal.

The choice of 10 mSv/a for the boundary is necessarily a judgement, but is felt to be robust in the face of a number of considerations, including:

- Worldwide variation in annual natural background dose;
- Action levels recommended by ICRP and the Basic Safety Standards for radon in dwellings;
- Doses implied by interdiction levels of activity in foodstuffs; and
- IAEA recommendations on criteria for resettlement of populations.

The generic criteria in Table 2.1 may not be appropriate in all situations. However, any perceived inconsistency in criteria may have negative effects in terms of public acceptance that could well outweigh the economic or radiological benefits to be gained by using situation specific rather than generic criteria. Therefore, where local factors do support the use of situation specific criteria that differ significantly from the generic ones, these factors, and the effect they have been considered to have on the criteria (including any judgements or assumptions made), should be clearly stated. Such factors would include the distribution of individual doses and risks within the population.

2.2.2.4 Development of site specific criteria for remediation

If the responsible party introduces site specific reference levels in place of the generic reference levels, these should be derived from a process of justification and optimization of protection [**Principle 1**]. Within this justification process (ALARA), it should be demonstrated that the resulting avertable[4] doses and other beneficial effects of the remediation are worthwhile in terms of costs, exposures of workers, any harmful environmental impacts and other disadvantages. From this, a site specific reference level should be derived in terms of an acceptable residual dose. A site specific reference level should not be interpreted as a strict limit but as a level against which the residual doses resulting from a justified and optimized remedial measure are to be compared.

While remediation may contribute to social and economic improvements in the area, remedial measures may also involve considerable cost and social inconvenience, and the line between caution and over-reaction may be difficult to distinguish. In applying the site specific reference levels, therefore, the exposures to be compared with these levels should be assessed on the basis of the average dose to the critical group determined by making realistic assumptions about diet and lifestyle, using realistic socio-economic factors and habitability data, and accounting for all possible pathways. The assumption of extreme or unrealistic characteristics in the dose assessment would be inconsistent with the goal of selecting the most appropriate remedial measure.

The outcome of the assessment of individual doses should be compared with the reference levels for remediation. If these reference levels correspond to doses that are lower than the average individual dose to the critical group, remedial measures are justified and should be implemented. The effects of different remediation options on individual doses should be calculated by using models that are consistent with those that are used to assess the individual doses from the contaminated environment.

As with using a generic reference level, the derivation of operational quantities expressed both as bulk activity concentration (for soil and other material) and as surface activity concentration (for surfaces) should also be performed. These calculations should yield remediation end criteria that are radionuclide specific and site specific. The calculations should be based on the same models, or at least models that are consistent with those that were used for calculating the radionuclide specific generic reference levels for remediation.

"The normal exposure of individuals shall be restricted so that neither the total effective dose nor the total equivalent dose to relevant organs or tissues, caused by the possible combination of exposures from authorized practices, exceeds any relevant dose limit" [6]. The dose limit of 1 mSv in a year for members of the public represents an upper bound on the sum of effective doses from all possible combinations of exposures arising from practices.

Clean-up and release from regulatory control of a site is one of the sources of exposure for which a dose constraint should be applied as for an authorized practice [13]. This dose constraint should take into account multiple pathways of exposure and should not exceed 300 μSv in a year above background [6].

Before commissioning a new facility, therefore, the operator should ensure that a baseline survey of the site, including obtaining information on radiological conditions, is performed to define the levels of background radiation at the facility site. These levels will be further used at the end of the practice as a basis for comparison with the levels used to release the site. For existing facilities for which no such baseline survey was carried out in the past to determine these background levels, data from analogous, undisturbed areas with similar characteristics should be used for this purpose. These analogous areas should be areas that have similar physical, chemical, radiological and biological characteristics to those of the site considered for release, but they should not have been contaminated with radioactive material as a result of activities at the site. Such areas are not limited to natural areas undisturbed by human activities [6].

The applicable dose constraint for the public after the release of a site should be expected to be no higher than that applied for the operational phase of the practice. However, the two

[4] Avertable dose is the dose to be saved by a protective action; that is to say, the difference between the dose to be expected with the protective action and that to be expected without it [9].

phases do not necessarily share a common set of circumstances (in particular, they do not necessarily have the same critical groups) on the basis of which to prescribe equality between the dose constraints applied before the termination of a practice and those applied afterwards [6].

In accordance with the Basic Safety Standards [13] and the recommendations of the International Commission on Radiological Protection (ICRP), dose constraints should be applied prospectively to exposure from radioactive residues expected to remain in human habitats after the termination of a practice [48]. The site dose release criteria should thus be based on an optimization of protection under this constraint, with account taken of the fact that optimization below the order of 10 μSv in a year might not be warranted on radiological protection grounds [6].

For the unrestricted use of a site, it should be ensured by means of the optimization of protection that the effective dose to a member of a critical group is kept below the dose constraint of 300 μSv in a year. For the restricted use of a site it should be ensured that, with restrictions in place, the effective dose should not exceed the dose constraint of 300 μSv in a year and that if the restrictions were to fail in the future the effective dose should not exceed 1 mSv in a year. The application of dose limitation to the unrestricted and restricted use of a site is shown in Figure 2.4 [6].

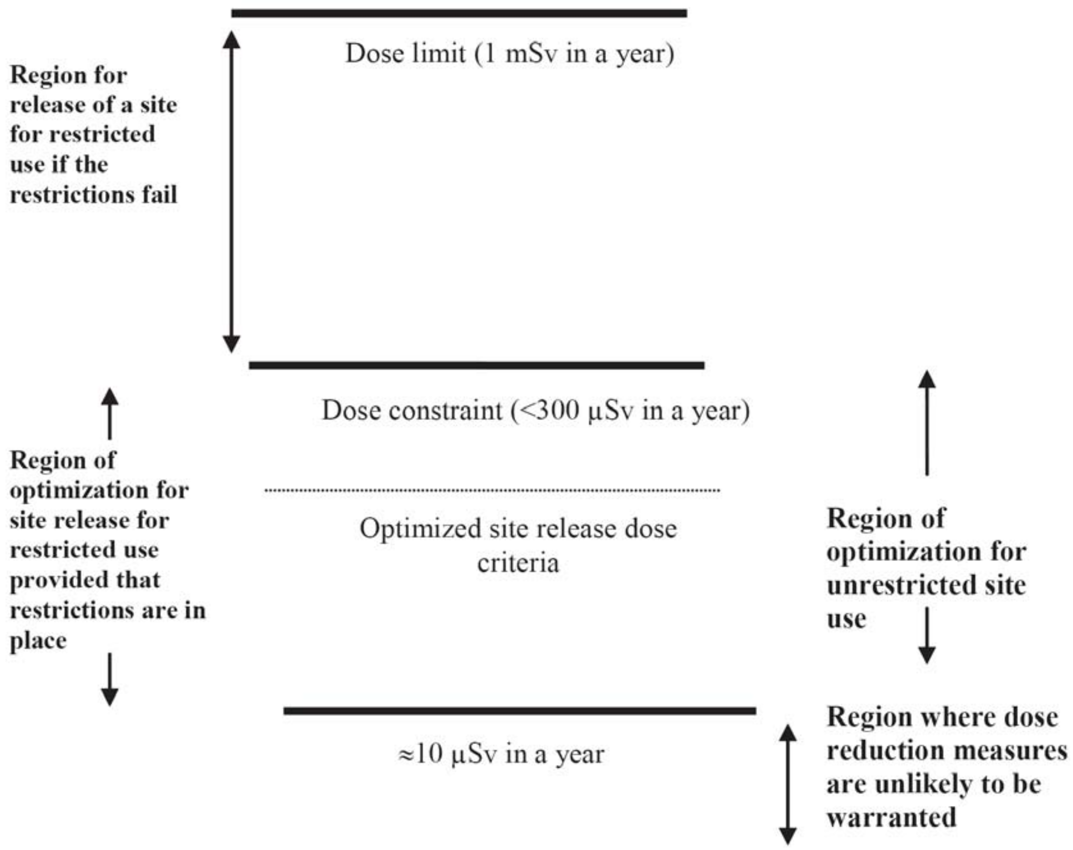

Figure 2.4 Constrained optimization and regions of effective dose for members of the critical group in the release of sites

It is reasonable and appropriate to have different dose constraints for the release of sites than for the clearance of material from regulatory control [6]. Clearance of material may take place frequently over the lifetime of a practice, as well as at the termination stage. The cleared material may enter into trade with a broad range of potential uses and therefore should comply with clearance criteria, which are of the order of 10 μSv in a year. The dose criteria for the release of land from regulatory control should be optimized and can be higher than those for the clearance of material, because land remains in place and hence the degree of certainty about the potential uses of the land is higher than the degree of certainty associated with the uses of material after its release from regulatory control. Thus it is reasonable to allow a larger fraction of the individual dose limit for the release of sites (i.e. the dose constraint (less than 300 μSv in a year)) than for the clearance of material (of the order of 10 μSv or less in a year) [49].

As part of the decision making process for the release for unrestricted use of land and associated buildings or structures, consideration should be given to the potential circulation of material arising from any future modification of the buildings, including demolition after release of the site. Material originating from a released site needs to comply with the national requirements for radiation protection for material outside the scope of regulatory control. The assessment of material originating from the site should be an integral part of the optimization analysis for the clean-up process. Scenarios giving rise to exposure from sites released for unrestricted use should be realistic and should consider the potential uses of the material from the released site [6].

Uncertainties, such as those relating to the level of contamination and hidden buried structures and waste, should be taken into account in determining the impact of the release of the site. These uncertainties, together with the uncertainties associated with the future use of the remaining buildings on the released site, should be considered in the optimization of protection, with account taken of the level of confidence that is required for release of a site from regulatory control [6].

If the site complies with the appropriate release criteria when a reasonable set of potential future uses and their associated uncertainties have been considered, the site should be released by the regulatory body for unrestricted use, which is the preferred option. The decommissioning phase should then be terminated and the regulatory body does not need further involvement beyond keeping records concerning the released site. If after clean-up of the site it is demonstrated that the site meets the release criteria, it may still be released for unrestricted use (see Figure 2.4) [6].

If after clean-up the site does not meet the release criteria, the site can be considered for restricted use [6]. The restrictions should be designed and implemented to provide a reasonable assurance of compliance with the dose constraints. The restrictions should serve to exclude or prevent exposure pathways leading to effective doses higher than the dose constraint; for example, if effective doses via food chain pathways could give rise to doses above the dose constraint, institutional restrictions should be put in place to prevent future use of the land for agricultural purposes. The release of sites for restricted use generally requires ongoing institutional involvement and control to implement the necessary restrictions. Existing regulatory limits on the time frames for institutional control should therefore be taken into consideration in deciding whether it is appropriate and reasonable to release a site for restricted use [48], [49].

2.2.2.5 Site characterisation

In addition to a historical site assessment, a site characterization survey may be performed to collect current information and to validate the information provided in the historical site assessment. The survey may provide information:

1. To determine the nature and extent of radiological contamination;
2. To identify receptors and provide input to pathway analysis and dose assessment or risk assessment models;
3. To identify various options for the remediation;
4. To evaluate environmental, occupational and public health and safety issues during remediation;
5. To evaluate and select remediation technologies;

6. To classify and quantify potential wastes; and

7. To assist in the final survey design.

The characterization survey requires proper selection and calibration of instruments, proper sampling and measurement techniques and recording of data. The survey should utilize all types of techniques for collecting the necessary data properly. The design of the characterization survey should be determined by the conditions on the site, the type and extent of on-site contaminants and the available resources. The data should then be compiled and assessed to allow decisions to be taken. The data from the characterization survey should be used as input to models for assessing the individual doses expected to arise from the contaminated environment.

The results of the characterization of the site and the evaluation of the possible remediation options should be reported to the competent authority and to the stakeholders, and the review of the evaluation should constitute a key step in the decision making process. Interested parties should be involved in this process at an early stage before decisions are finalized.

A characterization report should be prepared and submitted to the competent authority as part of the remediation plan.

2.2.3 Basic considerations about planning for remediation

When a decision has been taken to remediate a radioactively contaminated site and/or groundwater, a remediation plan should be prepared. The first steps in developing this plan should be to determine and evaluate possible remediation options. These options can range from complete remediation and unrestricted release of the site to more limited remediation with some subsequent uses of the site being restricted.

The degree of complexity of a given remediation process may vary depending on site specific situations. However, there are several components of the remediation process that should be considered essential for any site being considered for remediation.

2.2.3.1 Justification and optimisation of remedial measures

Interventions in the form of remedial measures should be intended to decrease existing and potential annual exposures, by removing existing sources, modifying pathways or reducing the number of exposed people. For contamination resulting from past activities and accidents, the required level of remediation should be established on a site specific basis and in accordance with the protection principles that apply to intervention situations. These principles include the justification of remedial measures [**Principle 1**] and the selection of the optimum measures among those justified [**Principle 3**]. In applying these two principles to derive an optimized option for protection, all relevant advantages and disadvantages should be taken into account. These include avertable doses (individual and collective), radiological and non-radiological risks, environmental effects, risks to the workers implementing the remedial measures, but also economic costs, improvement of the economic situation, the generation of secondary waste, as well as increased or reduced anxiety on the part of interested parties and social disruption arising during and after the implementation of the remedial measures.

2.2.3.2 Justification of remedial measures

The remedial measures shall be justified by means of a decision aiding process requiring a positive balance of all relevant attributes relating to the contamination [**Principle 1**]. The justification principle should be implemented by means of an assessment of the overall radiological impacts from the contaminated sites, identification of options for reducing these impacts, evaluation of the reductions achievable in doses and in other harmful impacts and assessment of the harm and costs associated with these remediation options. Decisions taken on this basis should involve balancing benefits from the reductions in impacts and costs and other factors of influence. An informed decision should be taken on the basis of a full integration of all the advantageous and disadvantageous attributes for society resulting from the proposed remediation options.

Situations giving rise to potential exposures as well as actual exposures should be considered during the assessment.

2.2.3.3 Optimisation of remedial measures

The remedial measures should be optimized following the general approach to the optimization of protection in the context of practices [**Principle 1**]. The optimum nature, scale and duration of the remedial measures should be selected from a set of justified options for remediation. The aim should be to obtain not only a positive benefit but also optimized protection. The decision aiding techniques for deciding on the optimum remediation option are independent of the nature of the situation causing the exposure. Normally, there would be a range of justified remediation options for which the net benefit would be positive.

Some remediation options could involve restrictions on the use of the site, even when the remediation end criteria have been met. Such an option would, however, require institutional control as long as the restrictions are deemed necessary. Options that lead to unrestricted release of the site after the remediation criteria have been met have the additional benefit of not requiring institutional control or other regulatory burdens, and so should be favoured. However, site specific features such as topography, size of the site and lack of waste management facilities might limit the feasibility of a remediation option that leads to unrestricted release.

In some circumstances, remediation may be required to protect the present population and may be justified on the basis of attributable health effects among people in future generations. While in most cases the cost of remediation, in terms of aspects such as disruption and inconvenience, will be borne by the present population, remedial measures taken to protect the present generation should be designed in such a way that predicted impacts on the health of future generations will not be greater than the levels of impact that are acceptable today.

When the performance and costs of all remediation options have been assessed, a comparison should be performed to determine the optimum option. If this optimum is not obvious, the comparison should be performed using a quantitative decision aiding technique. The result of the application of quantitative techniques is termed the analytical solution. If, in addition, there are non-quantifiable, non-radiological factors to be taken into account, the analytical solution may not be the optimum solution. These qualitative factors should be combined with the analytical solution to determine a true optimum solution, after consultation with interested parties.

The optimization of remedial measures should result in reference levels expressed in terms of a residual activity concentration or dose criteria for the remediated site.

Remedial measures may remove all of the contamination, or remove only part of it, or may only alter the exposure pathways or the number of people exposed without removing the contamination itself. Depending on the expected residual dose, which can be derived from the expected effectiveness of the proposed remedial measures, associated restrictions should be defined as part of the remediation option, if necessary. The residual dose, as well as the advantages and disadvantages of the associated restrictions, should be integrated into the optimization process. If the option includes on-site disposal of radioactive waste, the resulting exposure from this disposal option should also be taken into account.

Owing to time or resource constraints, general sources of information or default parameters may have to be used for modelling calculations. Sensitivity analyses should be performed within the optimization procedure to assist in determining when and where generic input parameters should be replaced by site specific values.

2.2.3.4 Remediation plan

A remediation plan showing that remediation can be accomplished safely should be prepared for each contaminated site, unless otherwise required by a competent authority. The remediation plan should be subject to the approval of the competent authority prior to its implementation.

The remediation plan and associated monitoring requirements should be designed and implemented so as to identify possible adverse health and environmental effects of the contaminants and to optimize protection [**Principle 1**]. These considerations apply to the workers performing the remediation, to the public and to the environment.

To achieve the objectives of remediation, decisions should be taken concerning the schedule and sequence of the remediation activities; operational quantities (e.g., instrument readings corresponding to the reference levels); the criteria for the termination of remedial actions; and post-remediation conditions with regard to access to or use of the area.

The criteria for deciding whether to terminate remedial actions should be clearly stated so that remediation is not unnecessarily continued beyond the point at which it is justified and optimized [**Principle 1**]. As an integral part of any successful remediation there should be a clear understanding by the interested parties of the remediation end criteria.

Provisions for the post-remediation state should be addressed in the remediation plan. As remediation progresses, the plan should be updated to reflect any changes or provisions relating to the conduct and progress of the remediation.

The process of designing a remediation strategy should take advantage of lessons learned from similar remediation projects that have been completed in the past. These lessons learned provide both positive and cautionary advice. In effect, information on the failure of a particular method of remediation in certain circumstances may help to narrow the choice of feasible remediation strategies when planning new remedial actions.

The waste streams resulting from the remediation should be identified early in the planning process. The quantity and types of waste that will be generated should be considered during the planning to ensure that the waste management system will be capable of accommodating this waste.

2.2.3.5 Radiological surveys

Several types of survey, with different objectives, may be necessary during the remediation process, e.g., detailed site characterization surveys, surveys during remedial operations and surveys to confirm that the objectives of the remediation have been achieved. The types and frequency of each survey should be discussed in the remediation plan. Provision should be made to allow changes in the type and frequency of surveys if situations arise that might lead to a change in radiological conditions.

2.2.3.6 Dose assessment

A key parameter in any decision making process for selecting the appropriate remedial measures is the distribution of individual doses to the population affected by the radioactive residues on the site. The ingestion of contaminated foodstuffs or the inhalation of contaminated dust is often a major exposure pathway, and sometimes the associated doses cannot be measured. In such cases the doses should be estimated on the basis of model calculations, with input from the radiological monitoring programme and with realistic scenarios.

The calculation of projected doses requires modelling of the various exposure pathways from an environmental contaminant to people. In general, the models used should be as realistic as is appropriate for making dose projections. Incorporating excessive conservatism can result in operational quantities being impractical or impossible to measure, or in remediation that is more costly than necessary. The models should readily be able to address all relevant exposure pathways. They should readily be able to use site specific data, and they should be tested or validated. Particular attention should be paid to matching the assumptions of the model to the circumstances under consideration.

2.2.3.7 Safety and environmental assessments

Both the radiological and non-radiological hazards involved in the various proposed remedial actions should be identified in safety and environmental assessments. They should include release criteria for the end point, dose predictions and risk assessments for each proposed activity associated with the remediation. The impact on the public and the environment of possible accidents or emergencies associated with the remediation should also be considered. The safety and environmental assessments should detail the protective measures that will be taken to ensure the safety of workers and the public and protection of the environment.

Specific consideration should be given to activities associated with waste management and their possible effects on neighbouring States.

2.2.4 Practical implementation of the management and selection of remedial actions

A general approach for the management and selection of remedial options for radioactively contaminated sites and/or groundwater should consist of a phased strategy to allow for the most cost effective and environmentally sound remedial approach [**Principle 1**]. It should also allow that the decisions and choices made during the management and selection process may be clearly seen and examined. This is an essential part of the process, and it can be particularly important, for example, when communicating with affected parties (e.g., members of the public) and competent authorities [9].

The initial discovery of radioactive contamination on a site or in the groundwater system and the decision to begin site investigation can result from various factors. For example, a site operator may become aware that the groundwater is contaminated and then must decide what action should be taken to prevent it from leaving the site boundary. Another possibility is that the problem may be discovered through epidemiological studies identifying health problems arising from the utilization of contaminated groundwater. In the former case, there might be ample time to plan a complex strategy, whereas in the second case immediate action would obviously be required. In situations where immediate action is indicated, e.g., to prevent health risks, it should be stressed that hasty decisions regarding remediation may not always be most appropriate. A more satisfactory approach might be to alleviate the health risk by institutional control, e.g., providing alternative water supplies; this would then allow time for a more structured approach to making decisions regarding the remedial action.

A phased approach can be particularly useful to allow for the most cost effective and environmentally sound disposition of a contaminated site. The phased approach would generally consist of the following elements:

- Assessment of the existing information and data (scoping analysis);
- Initial planning and decision making to consider what further action is required;
- Selection of the site characterization or monitoring requirements;
- Assessment of remediation technologies for appropriate application to the problems at hand; and
- Selection of the remediation strategy to be employed.

2.2.4.1 Preliminary or scoping analysis on existing data

The logical approach to assessing a contaminated site is to identify the source, the hydro-geologic setting, and the potential receptors, i.e., the affected population, by:

- Compiling, reviewing and analysing existing data and information;
- Identifying the contamination and its source;
- Describing the hydro-geological system, developing a useful conceptual model; and
- Identifying the potential affected population and their points of contact with the contaminated site and/or groundwater.

This should be based on site history, background information, previous investigations, known and suspected sources of contamination, processes used which generated the waste, routes of migration, and potential human and environmental receptors.

The history and background of the site should be evaluated to determine if any previous activities took place that could potentially impact decisions to be taken concerning characterization or remediation of the site. Such considerations could include previous industrial, commercial, agricultural or military uses.

A literature search or interviews with persons with historical knowledge should be performed to acquire a knowledge base on how the site became contaminated, the period of time which the contamination was released to the environment, release mechanisms, the types and quantities of contamination, and so on.

The existing geologic and hydrologic data for the site should be evaluated to help determine the fate and transport of the contaminants. Information regarding geologic formations and hydrologic parameters may be obtained through the description of sediment samples collected during drilling of production wells, irrigation wells or any other soil borings that may have taken place at the site. The quality assurance of data collected in this manner may be suspect and therefore conclusions based on the data should be treated with caution.

At this stage, some modelling may take place. The complexity of the modelling should reflect the quality and the quantity of site data available. This modelling may include groundwater. As a first pass, relatively simple calculations of radiation dose and risk to individuals and populations may be made using assumptions that are conservative, resulting in estimates for dose and risk that are maximums.

2.2.4.2 Early decisions regarding further action

After all or most of the existing data and information on the contaminated site have been collected and analysed, further action should be defined. The alternatives to be considered may include: (1) no further action required; (2) no further action required other than to further monitor the contaminant plume; (3) more data are needed to make a decision; or (4) a remedial action should be undertaken.

- *No further action needed*: A decision of no further action can be made if it is determined that there is no contamination or that the extent of the contamination is below an acceptable risk level and below the regulatory requirements of concentration or radiological dose.
- *Further monitoring of contaminant plume is required*: Although no further action (e.g., remedial action) may be required, it might still be necessary or advisable to continue to monitor the site to ensure that the initial assessment of the situation is correct, for example, when it appears that natural processes such as dispersion and radioactive decay would result in the contamination having no significant impact on the receptors, i.e., the affected population. Continued monitoring would allow the assumptions regarding movement of the groundwater contaminant to be routinely

checked. In addition, continued monitoring could provide comforting reassurance to affected parties such as the local population.

- *Insufficient data exist to make a decision*: Following the assessment of existing data and information, it could be decided that there are insufficient data to make an informed decision regarding the possibility or advisability of remedial action. Under such circumstances, it is common that a site characterization programme be implemented to fill the identified gaps in information and data. If there is a decision to collect additional data, the data collection objectives should be clearly identified and used in designing the site characterization programme.
- *Remedial action is required*: In some cases, there will be sufficient data and information regarding a site and the groundwater contamination problem to conclude that remedial action is required. In such a case, the strategy will advance to the technologies evaluation and remedial design phases.

2.2.4.3 Public involvement

A factor to be considered when evaluating technologies or screening for remedial alternatives is involvement by affected parties and the general public [**Principle 2**]. The public's perception of risk due to radiation exposure may be substantial enough to warrant a more stringent remedial goal for a contaminant in groundwater. It is important to involve the public and all affected parties in the decision making process as indicated in Section 2.3, Stakeholder involvement, of this document.

2.2.4.4 Establishment of remediation goals

Preliminary remediation goals are normally site specific. The initial remediation objectives should be established on the basis of the nature and the extent of the contamination, the water resources that are currently or potentially threatened, and the potential for human and environmental exposure. These quantitative goals should define the extent of clean-up that is required to satisfy the established objectives. They include the required clean-up levels and the restoration time frame. Clean-up levels of contaminants are typically based on either drinking water standards or on excess lifetime cancer risk levels.

Past practices have used extremely conservative scenarios for determining the risks of ionizing radiation to human health. As a result, remedial activities have been extremely costly. Recently, using more realistic risk scenarios appears to becoming acceptable. In some cases, remediation has been avoided, with only the cost of monitoring remaining. This strategy has reduced the cost while continuing to adequately protect human health [**Principle 1**]. It is recommended that when selecting and analysing the risk scenarios, the expected land use, the impacts on affected parties and the environment, and the future groundwater needs should all be evaluated. A realistic scenario can then be developed which would allow for a more cost effective remediation while still ensuring the safety of the public. Obviously, the effectiveness and reliability of institutional controls may affect these decisions.

Risk assessment methods may be used, coupled with regulatory requirements, to determine achievable goals. The beneficial use of an aquifer must also be considered. Water which does not meet the required standards for domestic use may still be useful for agricultural or industrial purposes.

The potential effects on environmental receptors such as plant and animal species at or near the site may also affect the remediation goals.

2.2.4.5 Site characterisation

Site characterisation activities should take place if more data are needed to evaluate risks associated with the contaminated site or to understand the parameters necessary for selecting an appropriate remedial technology. Data collection objectives should be selected with an understanding of the associated uncertainties.

If necessary, a site specific data collection strategy should be organized to provide sufficient data to formulate a conceptual model of the contaminated site. The data collection activities should focus on understanding of:

- The source term;
- The geology (i.e. formations, grain size, plasticity, moisture content, density, mineralogy);
- The hydrogeology, aquifer properties;
- The geochemistry;
- The nature and the extent of the contaminant plume; and
- The exposure pathways.

In characterising contaminated sites, inherent uncertainties may be encountered. Many of these uncertainties arise from the necessity of characterising the heterogeneity of the aquifer with a limited number of sample points. Aquifer heterogeneity should be considered when developing a strategy for site characterisation.

Aquifer system uncertainties may be identified and addressed using the preliminary site conceptual model to identify the remedial strategy with the highest probability of success. At this stage of the decision making process, the probability of success is based on the “most probable site conditions.” Acknowledging that site conditions have inherent uncertainties, reasonable variations from the “most probable conditions” are identified early, and contingency remedial action strategy alternatives are not ruled out.

To better plan the site characterisation activities, a sensitivity analysis is often used for defining the importance of the parameter input to predicted costs and remedial action performance. Data worthiness (e.g., adequacy or worth) evaluations are also becoming more popular for decision makers in their understanding of the relationship between uncertainty and sensitively of site conditions, and remedial costs and performance. The observational method is an effective and economical means to manage uncertainties associated with remediating contaminated groundwater.

Using the Data Quality Objectives Process will help to ensure that when data collection has been completed it will have accomplished two goals:

- Provided sufficient data to make the required decisions within a reasonable uncertainty;
- Collected only the minimum amount of necessary data.

The Data Quality Objectives Process embodies both of these two main goals and it is difficult to separate which is the more important or which drives the other. For example, the Data Quality Objectives Process will strive to provide the least expensive data collection scheme, but not at the price of providing answers that have too much uncertainty.

Data Quality Objectives are intended to ensure that the data generated during site characterisation activities are adequate to support management decisions. A clear definition of the objectives and the method by which decisions will be taken must be established early in the scoping process. Data Quality Objectives are determined based on the end uses of the data to be collected. The level of detail and data quality needed will vary based on the intended use of the data. Data Quality Objectives should be reviewed throughout the characterisation activity and adjusted based on new available information as appropriate.

All of the data collected during the scoping and characterisation phases of the project should be analysed with the results formally documented. This activity should be co-ordinated with the risk assessment and modelling personnel to provide for a more efficient use of the data.

All decisions should be documented with an explanation of the logic used to arrive at the given conclusion. This includes decisions made as a result of scoping, establishment of preliminary remediation goals, data collection objectives, data quality objectives and screening, and the selection of remediation technologies.

2.2.4.6 Development and screening alternatives

Guiding principles for developing alternatives include, among others, technical practicability, cost/benefit analysis, and schedule for implementing and completing the remedial action.

The nature of the source, the size of the plume, and the transmissivity of the aquifer also will directly affect the effectiveness of the remediation whether it be an in-situ or ex-situ treatment. Most groundwater technologies currently available are expensive to implement and take long periods of time to complete. Continued research is ongoing world wide to develop new techniques for in situ and ex situ remediation. A general list and description of these technologies can be found in Section 4, Environmental remediation of radioactively contaminated sites, of this document. Care should be taken to evaluate the success or failure of the technologies which have been developed and to compare the site specific characteristics against the test site to determine the viability at a particular site. Critical parameters of the technology being evaluated should be identified for comparing the viability of success at the site. For example, a technology may work quite well at a site with alluvial sands, but not at all at a site with fractured rock.

Based on the analysis performed on the site characterisation data, a list of alternatives and technologies may be compiled. A screening process should determine if an active remediation is required or if a passive alternative (institutional controls, no action, monitoring, etc.) is desired. If an active remediation option is chosen, a detailed analysis of the technologies should be performed.

2.2.4.7 Institutional controls

Institutional controls may be implemented to reduce or eliminate potential impact of exposure to human health. The following kinds of institutional controls have been established and may be considered to prevent exposure to contaminated sites and/or groundwater:

- Regulatory restrictions on construction and use of private water wells, such as well construction permits and water quality certifications;
- Acquisition of property by the government from private entities;
- Exercise of regulatory and police powers by governments, such as zoning and issuance of administrative orders;
- Restrictions on property transactions, including negative covenants and easements;
- Non-enforceable controls, such as well use advisories and deed notices;
- Relocation of affected populations (in extreme cases).

The effectiveness and reliability of these controls should be evaluated when determining whether rapid remediation is warranted. If there is adequate certainty that institutional controls will be effective and reliable, there is more flexibility to select a response action that has a longer restoration time frame or a determination that no remedial action is required.

2.2.4.8 Analysis and design of preferred alternatives

During the detailed analysis, remedial alternatives that have been retained from the alternative development phase should be analysed against a number of evaluation criteria. The purpose of the detailed analysis should be to compare alternatives so that the remedy that offers the most favourable balance among a set of criteria can be selected [**Principle 1**]. The analysis of a remedial action for contaminated sites and/or groundwater may be made on the basis of the following evaluation criteria:

- Overall protection of human health and the environment;
- Compliance with applicable regulations;
- Long-term effectiveness and permanence;
- Reduction of toxicity, mobility, or volume;
- Short term effectiveness;
- Implement ability;
- Cost;
- Community or government acceptance;
- Final disposal of residues.

Other criteria may also be established based on site specific conditions. A discussion and summary table should be prepared for each part of the detailed analysis to provide a historical paper documenting the decision process.

2.2.4.9 Implementation action and performance assessment

Based on monitoring data, performance evaluations of the remedial action should be conducted periodically to compare actual performance to expected performance. The performance monitoring should be designed to provide information such as:

- Horizontal and vertical extent of the plume and contaminant concentration gradients, including a mass balance calculation;
- Rate and direction of contaminant migration;
- Changes in contaminant concentrations or distribution over time;
- Rates of contaminant mass removal and transition from advective removal to diffusion rate limited removal;
- Effects of hydrological events, such as above average rainfall, on contaminant mass removal and changes to groundwater flow;
- Calibration of model based on actual results and effects of changes of operational parameters to model predictions;
- Effects on regional groundwater levels and the resulting impacts;
- Effects of reducing or limiting surface recharge (if applicable);
- Effects of re-injection (if applicable);
- Effects of any modifications to the original remedial action; and
- Other environmental effects of remedial action, such as saltwater intrusion, land subsidence, and effects on wetlands or other sensitive habitats.

The frequency and duration of the performance evaluations should be determined by site specific conditions. Conducting performance evaluations and modifying remedial actions is part of a flexible approach to attaining the remedial action goals. Decisions should be verified or modified during remediation to improve a remedy's performance and ensure protection of human health and the environment.

The performance assessment may provide information that can be used to determine whether the remediation goals are being met, have been achieved or, in some cases, are technically impracticable to achieve in a reasonable time.

2.3 Stakeholder involvement

2.3.1 The purpose of stakeholder involvement

The aim of stakeholder involvement in the management of radioactively contaminated sites and/or groundwater is to ensure effective external participation, whether required by the regulatory framework or included in the organisational policy, in order to improve the decision-making process, to develop approaches that can be implemented with community support, to improve transparency, to build trust and to take better decisions [**Principle 2**] [1]. Stakeholder involvement is also important to risk management and it can prevent, resolve or help to manage problems caused by external opposition to projects. Where something has gone wrong, systematic involvement can re-establish effective communication and help to resolve difficulties. Not all conflicts may be prevented or resolved and disagreement may remain on some principles, but it should enable co-operation and mitigating the sources of particular dispute.

It is considered that not all stakeholders have to be involved in all decision-making steps for each radioactively contaminated land and/or groundwater issue on every site. In case of doubt, stakeholder involvement should be included, but the level of consultation and involvement should be proportionate to the technical and societal significance of the decision. The aim should be to strive for consensus support within the community, and therefore account should be taken of the local community's perception of the need for involvement. This means, there is a need for building trust.

2.3.2 The importance of trust

Contributions of external participation should be objectively considered and there should be a genuine willingness to take a different course of action if new information or insights are provided. Involvement coming after the options have effectively been narrowed down to one, will be seen as a closed process, as a means of legitimising a prior decision, and at best, there will be no ownership.

Community involvement programmes are unlikely to be effective unless first a degree of trust can be established. Relationships with stakeholders and the public have to be built up over time. It can not be expected that the trust and the credibility required for a successful consultation can be established quickly, especially where a project is contentious and the debate polarised from the start.

Acceptable motives, realistic strategies and effective regulation are prerequisites for building trust, but the most important factor may be openness, in the context of a community involvement programme including: admitting mistakes, acknowledging uncertainty, and giving people the full picture.

Reliability is another important contributor to trust, meaning that the legal entity should also be efficient and competent so that its promises mean something. Poor reliability can easily grow into a more general lack of trust.

2.3.3 Communication with stakeholders about risk

2.3.3.1 The perception of risk

Differences may exist between the way communities and engineers think about risk, resulting in communications between the two groups sometimes being rather difficult. Experiences have shown hat 'top-down' risk communication is unlikely to resolve environmental risk controversies. As a result, risk communication and policy practice have moved towards a two-way dialogue between the 'community' and 'experts'.

Despite for example the tendency to consider widely-reported events to be more likely than they really are, or other biases that have impact on the perception of risk, the ability of the general public to rank frequency of death from hazards is often not unrealistic. However, the perception of the general public diverges from 'scientific' risk assessment in that they factor in 'quality' of hazard, e.g., thread, familiarity and catastrophic potential. Different forms of death and disease are not feared equally.

Further, the general public's understanding of a risk should not be confused with the general public's acceptance of the risk. The level of acceptable risk is a matter of values and opinions. Any evaluation of options should therefore explicitly incorporate underlying values and social factors such as fairness and the balance of benefit and risk. Steps that result in a fair and more voluntary distribution of risk will be helpful.

The feeling that the measures have been implemented that can sensibly be taken to reduce the risk, and that effective monitoring and emergency response arrangements have been installed, is important to acceptability. Communities also tend to look for independent monitoring and open reporting of results, in addition to other indications that adverse findings will not be concealed, so that action will be taken if things do not turn out as predicted. Moreover, communities look for a design that allows for a change of plan if the unexpected happens, and the potential for effective countermeasures on the occurrence of a failure.

Motivation is very important, and the corporate values of the organisation(s) involved will make a difference. It is important to identify who will benefit from a project and whether this benefit is 'deserved'.

Any stakeholder programme has to deal with these risk perception and acceptability factors in an open and straightforward way if participants are expected to see it as addressing their concerns, which must never be considered as 'unscientific'.

2.3.3.2 Credibility

The credibility of a person talking about risk not only depends on the person's technical competence. It is also strongly influenced by the commitment shown to stakeholder involvement, whether the concerns being expressed are understood and considered with sympathy, and whether the person acts in an open, honest and direct manner.

Independence and objectivity are important considerations as well. Information from 'biased' sources will tend to be distrusted, particularly where the motives of the organisation(s) involved are primarily commercial or political. Highest appreciation will be given to information that is clearly neutral and addresses all sides of the arguments. An independent peer review of the important subjective judgements supporting the analysis may be necessary to underpin a comparison of the options for a controversial project.

2.3.3.3 Linking issues

The public rarely sees decisions as independent of a wider context. Decisions that are part of a wider programme, such as site restoration, are perceived as being linked, and if the wider picture can not be seen, the public will likely feel mistrust and/or frustration. An involvement process will be successful only if the participants fully understand the context, for example, how a decision on one element of a wider plan fits together with decisions on other elements and on the overall framework. Participants need to be informed if proposals may be overturned or modified at a later stage or if other bodies might initiate a separate consultation (e.g., regulators). Communities link issues and decisions that seem separate to industry and regulators. Communities also see little distinction between a policy and its implementation.

Members of the public usually wish to express their views on the overall merits of a project and of alternatives. They are rarely in a position to make much contribution on the technical development of the proposal. However, a programme that aims to involve members of the public by allowing them to comment only on technical details will create frustration.

Frequently, members of the public want to be heard on matters of their concern that may be outside the formal scope of the consultation process and even outside the scope of the project team's decision making. Exclusion and abrupt rejection of comments as 'outside the scope of what is to be discussed' is liable to provoke angry reactions. Therefore, some flexibility is required, and mechanisms are needed for passing on such comments and obtaining a response.

In general, for environmental debates representing conflicts over competing social values as well as disagreements over scientific and economic data, the public and wider stakeholder community may provide a social peer review function. This may be compared to a technical peer review but represents different sorts of processes and require different, perhaps parallel, approaches.

In addition, there is the challenge of integrating the technical, the social and the local democratic inputs. Unless the decision-making process is tailored to accommodate all three types of input and is agreed before the process starts, the hard-won social input from the general public may simply be put to one side.

2.3.4 Planning and implementation of stakeholder involvement programme

In planning and implementing a typical stakeholder involvement programme key stages may be defined as outlined below. However, each programme may be unique and may need to be tailored for its purpose and audience. In general, the larger the scope and the reach, the better defined and more formal the stages will have to be. In smaller consultations they may be implicit or merged together, but even in these cases it will usually not be adequate to rely on written consultation alone.

Organisations involved must be clear and honest with themselves and with the prospective participants about the reasons for being involved, freely offering opportunities for involvement but focussing on getting active and representative participation at key points. They should not push for a 'broad involvement' simply from the principle point of view, or design stakeholder programmes with a very broad scope as it is not clear what type of process is really needed.

Early consultation is often the key to the success of an initiative, and to securing co-operation. Omitting it may cause delays and more expenses in a later phase. Usually, it is the objective to identify and involve the key players early, build trust and improve understanding of potential priorities and needs of the participants, thereby helping to design a more effective consultation programme and encouraging participation. A key aim is to ensure that there are no surprises for either key stakeholders or the organisation(s) involved once the project enters the public domain.

It is important that the agenda for early consultation is not too circumscribed, so that interested participants can have part in developing it. It is helpful to let interested participants know the likely timing, and any later changes to it, of different forms of consultation as early as possible.

Attention should be given to reliance solely for local representation. Part of the trust problem may be that participants can be regarded locally as having been enrolled, through long participation, into views overly sympathetic to the organisation(s) involved.

The key stages in planning and implementing a typical stakeholder involvement programme may be:

1. *Scoping* – what is the scope and the purpose; how does it fit with wider decision-making and other initiatives; which stakeholders should be involved and what are their particular needs and potential contributions.
2. *Programming* – what mix of activities is required; how should the programme be promoted; what documentation needs to be prepared; who should be allocated to the

programme project team; what resources and training do they need; are internal workshops required first; how will the programme be evaluated.

3. *Planning* – inform the community of proposals; review the scope and the design of the programme with some of those likely to be involved; test examples of any promotional and information material; failing to show willing to inform and recruit as widely as possible may compromise all the subsequent steps.
4. *Promoting* – launch the programme; if required, make media announcements; inform internal and external stakeholders; encourage and facilitate involvement by individuals and groups in the community; start a stakeholder registration database; set out details of access to information and any outreach events.
5. *Informing* – disseminate and make available key documents; organise poster displays, site visits, presentations to community groups, as required; if deemed necessary, set up library for participants, web site with supporting information, telephone help lines.
6. *Consultation* – consult interested stakeholders; provide various means to comment; acknowledge and record comments; consider interactive outreach activities such as public meetings and 'surgeries', and use of surveys or questionnaires to canvas opinions.
7. *Participation* – hold meetings with stakeholders; answer questions; provide background information; consider facilitated events such as meetings, workshops and focus groups to explore specific issues in more depth; consider joint problem solving and group decision making methodologies or deliberative methods such as citizens' juries; discuss proposed events with potential participants.
8. *Extended participation* – if necessary, involve community liaison groups; consider possibilities for joint working parties and 'neutral' data gathering or monitoring.
9. *Compiling input to decision* – assess comments and outputs from participative events; seek further clarification or new analysis as necessary; document the process.
10. *Providing feedback* – provide feedback to participants on comments received and how they were taken into account, decision made, next steps etc.; inform stakeholders not directly involved in this specific programme.
11. *Evaluation* – seek the views of participants; incorporate the lessons in internal guidelines; feedback to stakeholders.

2.3.5 The selection of stakeholders

Stakeholders may be constituencies, organised groups or individuals with direct or indirect interest in the decision. This may be, for example, because they are potentially affected, because they have a view on what the outcome ought to be, or perhaps because they are representative in some way of a wider constituency.

The focus will mainly be on the local community, but other types of stakeholders also need to be involved if the external input to decision-making is not to be dominated by one perspective or set of interests. Stakeholders are much less likely to respond constructively in future if they feel unfairly excluded.

Internal or external stakeholders that have a reasonable degree of commonality of interest with the organisation involved are the most obvious category of stakeholder, and are sometimes referred to as 'true stakeholders'. However, there are other classes of stakeholder that are affected by the decisions an organisation takes or that have a strong view on its conduct, even if their interests are very different.

Organisations require a 'licence to operate' from a wider range of stakeholders. This is obvious in the case of regulators, where authority has been delegated by society. The right of shareholders to regulate the direction of a business is also readily appreciated. In practice, organisations find that their ‘licence to operate’ can also be compromised or even withdrawn because they have lost the consent of the local community in which they operate, or they have lost the confidence of politicians and financiers.

Campaign groups often see themselves as having a ‘license to operate’ or watchdog role, but they are also often significant as opinion formers able to influence other stakeholders. Failure to inform a local community of the existence of other groups with experience of similar issues may undermine trust and may result in a waste of time later on. The media are sometimes considered to be stakeholders, but are more often considered separately with other opinion formers, on the basis that there is usually no strong commonality of interest. They may have considerable influence on other stakeholders, however, and may also be seen in turn as an indicator of a broader, unobserved, public mood.

A community cannot be treated as a single entity. Relationships between the site and the community are complex and all the different types of stakeholder described above are contained within it. The people who live around the site and the community groups, and local authorities that speak for them, have a wide range of inter-relationships and perspectives. In reality, there is no such a thing as ‘the community view’ and this has to be born in mind.

In practice, the stakeholders and stakeholder groups who should be considered include those whose support for the project will help it go ahead smoothly and those whose opposition will delay the project, obstruct it, or reduce its viability. The starting point is normally those who may be, or would think they may be, affected by the project, their representatives and local liaison groups. Beyond that, programmes may look to include people and groups influential in the area, those with an interest in a particular outcome and also stakeholders that have been involved in the issue in the past.

The full range of stakeholders does not need to be involved in every part of the project. The scale of involvement generally reflects the nature and the extent of the perceived potential impact, and the project's importance as a precedent. The presumption in case of doubt should be for inclusion, but the level of consultation and involvement should be proportionate to the technical and societal significance of the decision. Strategies need to be capable of commanding consensus support within the community, and therefore should also be proportionate to the local community’s perception of the need for involvement.

Where there is significant potential off-site impact or interest in a contaminated land management decision, the views of a wider range of external stakeholders should always be sought before a preferred option is selected and submitted for regulatory approval. The emphasis for smaller projects may be on information provision and consultation may be limited to the local community. There will also be contamination issues that have little or no significance for stakeholders and where quick action is a priority, for instance clean-up of a small spillage. It may then be appropriate simply to include it in routine reports to local community groups.

In general, the degree to which external stakeholders are brought into the process and the balance between local, regional and national involvement depends on the potential impact and significance of the project.

An important issue in some projects will be the transport of radioactive wastes. This is likely to prove an emotive topic and accordingly needs to be handled with great care. Communities along the proposed transport route may need to be informed and invited to participate. Some would go further, and say that they should always be invited. Certainly, communities at the ‘receiving end’ should be involved if there is any significant change to existing arrangements.

2.3.6 The involvement of the community

People and organisations in the community need to be quite strongly motivated to participate in consultation or decision making. It takes a great deal of time and effort - often unpaid -

and it can be an intimidating experience for non-technical members of the community. Successful involvement programmes are those that are ‘stakeholder friendly’, designed to improve the benefits people get from participation and lower the barriers to involvement. The relevance of the programme to them personally is explained. They feel that they have something useful to contribute, and that their involvement has the potential to affect the course of the decision-making process in a meaningful way.

Consultation on safety, environment and the introduction of new technology has tended to be dominated by institutional stakeholders and pressure groups. Such participants are usually equipped to provide technical comment at a level the organisation(s) involved in the programme will find useful, and they understand the decision-making and regulatory process.

In contrast, members of the public usually wish to express their views on the overall merits of a project or course of action, but only rarely they can make much contribution to the technical debate unless local issues are involved. However, organisation(s) involved are nowadays increasingly carrying out broad-based public consultation and making more effort to reach ‘ordinary people’ and factor their views into the decision. Lay members of the public are also capable of making reasoned and reasonable contributions and their involvement is often particularly important in contaminated land projects. Members of the public also increasingly feel that they have a right to information and to be consulted on a wide variety of issues. One consequence of the growing recognition of the benefits and importance of consulting the general public is the wide variety of approaches and facilitated workshop techniques that have been developed specially for this purpose. Only those with strong prior views tend to respond readily to opportunities for participation, so active measures generally need to be taken to recruit a more representative cross-section.

Where there is less experience of involvement, there may need to be an initial capacity-building stage to strengthen and provide resources to community institutions to allow them to participate fully. If people are being asked to participate in decision-making, time may need to be spent to inform them about the issues, ideally using briefings from a ‘neutral’ source.

Table 2.2 Issues in making involvement programmes stakeholder friendly

Issue	**Comments**
Competing demands	Participating properly takes time and commitment, and there are many competing demands. Participation should be made as easy as possible.
Access	Access to consultation documents and outreach events should be carefully considered.
Time	Sufficient time within the programme should be allowed for participants to prepare for events and to read and comment on documents.
Awareness	People have to be aware of the programme to participate. Informing and encouraging people through a co-ordinated promotion campaign should be considered.
Information	A range of information should be presented, taking account of the format and level of detail required by different participants.
Public speaking	The stress of speaking in a meeting may deter many from participating. Surgeries and exhibitions are more flexible and less intimidatory.
Access to the Internet	Internet gives people access to a wide range of information and opinions from all sides of the argument. As not everybody has access to the Internet, a web site on its own is not enough.

Long-term community liaison groups exist for several nuclear sites and are an obvious channel for communication. They can play a key role in helping to define the scope of the community involvement programme and the documentation package and to drive the information agenda more actively than if there were no community focus. Where there is no such group, it may be necessary to set-up one. This may best be done well in advance, to give time to build up trust between the group and the site management, and between the group and the wider community.

As indicated before, there is always the potential for conflict between the role of local elected representatives and other groups who may be perceived as speaking for the community. Therefore, more than one local stakeholder group may need to be recognised, but these issues need to be dealt with sensitively.

Issues in making involvement programmes stakeholder friendly are given in Table 2.2.

2.3.7 The involvement of campaign and community groups

The participation of campaign groups may be important to an effective and credible programme for both practical and democratic reasons:

- They can help develop the format of a stakeholder involvement programme on the basis of their experience, and provide feedback during it.
- Some pressure groups can provide critical scrutiny of documentation and make a technical contribution to participatory decision making.
- Consultation with pressure groups may give their supporters, who may include part of the people taking active interest in the project, an organised channel for expressing their views.
- It is fair to assume that pressure groups represent their membership directly, but not the general public. However, they are one channel by which evidence of public opinion might be communicated.

Different groups may have different approaches, may make different judgements on the same information, and may have very different long-term agendas. As far as possible, consultations should be co-ordinated to keep the demands on participating stakeholders to a reasonable level.

Where subject matter and/or the documentation is complex, where there is only little authoritative third party analysis in the public domain, and where involvement of the community has a high priority, providing reasonable levels of financial or other support should be considered carefully. Local campaign or community groups in particular may need practical support, a contribution to expenses, and help in securing access to independent sources of information and advice.

Pressure groups have the right to choose whether to participate in a community involvement programme. If they do choose to participate, it will imply acceptance of certain responsibilities, e.g., to behave with integrity and separate protest from participation so far as practicable, and to recognise the difficulties inherent in any programme and help avoid problems rather than exploit them unfairly.

2.3.8 The level of involvement

2.3.8.1 Range of levels

Information: To a minimum, stakeholder involvement may include keeping local people informed about activities on site, including safety and environmental issues and future plans.

Consultation: Consultation is a two-way process, whereby the organisation(s) involved ask individuals and groups for their views and take these into account in decision making.

Participation: Where more involvement is appropriate, members of the community may participate directly in the analysis and decision making. Ultimate responsibility for the decision usually remains with the organisation(s) involved, but the objective of participation is often to reach a degree of consensus between the organisation, the community and other stakeholders on the way forward.

Any one of these levels of involvement – information, consultation or participation – may be on-going, or may be case-by-case activities focused on a specific issue.

The parties often start with different understandings of the level of involvement proposed and with different perceptions of what is fair and appropriate. Therefore, the purpose and the relevance of the programme should be presented openly and honestly to ensure that everybody is absolutely clear from the outset what is proposed.

The stakeholder involvement process should never be an end in itself. Rather, it should be an integral part of decision-making and management processes and it only has meaning if all parties have this intent. The aim should be to secure agreement for a stakeholder involvement programme that meets the aspirations of both the organisation(s) involved and its stakeholders, but also one that takes account of the balance of cost and benefit and can be delivered in a timely and cost-effective manner.

2.3.8.2 Providing information

A public information process is intended solely to provide information to stakeholders. Stakeholders may seek clarification, but are not invited to contribute to the decision-making process. A local information programme may almost always be required for a major project dealing with contaminated land. Typically, an information programme may cover things such as plans, progress, events, public safety and environmental performance. Local programmes should offer people the option to obtain more information or become more closely involved and should include information relating to groups with relevant expertise and experience. Tools available include newsletters, web sites, outreach events etc. Information on individual projects will often be part of a wider programme. Early, accurate and complete communication is a key element in building trust.

As a minimum, education and information provision form part of all participation programmes. The need for a greater level of participation must be determined in each situation. It is not important to achieve the highest possible level of participation, but the level that is most appropriate. Techniques at the lower level of participation may also be used to support techniques at a higher level; for example, the provision of information would support methods of consultation.

Poor information provision is a common cause of complaint in consultations and lack of usable information is often the main barrier to understanding and participation in a stakeholder programme. Access to the right information, at the right level of detail and at the right time is the key to effective stakeholder involvement.

Good communication requires the organisation(s) involved to look at the information needs from the perspective of a range of potential participants - from the least informed, least educated member of the community to the technically competent professional organisation. Common sense suggests that it is not likely to be effective if the organisation(s) involved merely circulate scientific or legal documents drawn up for other purposes and other audiences. Some people may not be able to read technical language. Therefore, the information should be presented in digestible forms but without oversimplifying the facts and issues. No single document is likely to fulfil these requirements, however, and therefore a suite of documents may need to be provided.

In most cases, organisation(s) involved provide only limited additional information on request. Typically, information is released to allow detailed comment on the data and analysis, but there is no obligation to provide information needed to conduct alternative analyses. This can be a major source of contention and stakeholders may complain that documents are being unnecessarily withheld. Therefore, organisation(s) involved should think through in advance which supporting documents they are able to release and discuss the options with stakeholders likely to be involved.

In cases where implementation work extends over a longer period of time, as a minimum, stakeholders should be kept informed of progress with implementation. In addition, site owners/operators should provide the stakeholders with opportunities to review and discuss the progress. They should also be involved in deciding on any changes to strategies or options in the light of progress with implementation.

2.3.8.3 Consultation

The objective of a consultation programme is to get input from stakeholders to support and inform the decision-making process. The organisation(s) involved typically provide information to the local community and other stakeholders and make it possible for these groups to submit comments or ask questions about proposals. Consultation offers large numbers of people the opportunity to comment on a proposal or on options. They allow for community peer review of proposals and may identify new technical issues that need addressing. They may also help organisation(s) involved understand stakeholder views and concerns, which can be taken into account in decision making and risk communication. However, there is usually little scope for contributing to identifying solutions or for taking part in the decision-making process.

2.3.8.4 Participation

Participative decision making allows stakeholders to take an active role in the decision-making process rather than simply providing comment on proposals. Stakeholders are involved in shared analysis and agenda setting, even though the responsibility for the final decision lies with others.

A commitment to participation implies recognition of the benefits of consensus, even if there is no specific prior commitment to it. When considering consensus it is essential to be clear about what is meant. One meaning is ‘unanimity’, i.e., each party must positively support the decision. More frequently, it is used to describe a situation where a sufficient fraction of the participants positively support the decision. Others simply consent to it - although they may not prefer it personally - because they consider it to be tolerable, or to be the best solution or agreement that can be achieved under the circumstances.

The more complex the issue and, in most cases, the more controversial the issue, the more likely a higher level of participation will be expected by stakeholders, required to develop understanding in the community, and necessary to get the quality of input being sought. The more participative the process, the more rewarding it generally is for all parties but there are limits to the contribution stakeholders can be asked to make.

Participative processes cannot easily reach large numbers of people and so usually need complementing with other initiatives to communicate with and gauge the opinion of the wider community.

2.3.9 Key concepts of stakeholder dialogue

When initiating a stakeholder dialogue, participants may immediately want to start talking about content issues. It should be outlined, however, that discussion of certain process elements is necessary in order to maximise participants’ ownership of the process and to begin developing common ground [11].

2.3.9.1 Positions, interests, needs

Situations with high levels of uncertainty often result in a conversation that is largely positional (i.e., defending the own position, attacking the others' position). In more complex situations judgements over right and wrong may be difficult, however. In order to avoid positional conversations it is necessary to clarify the background of these positions. Therefore, it should be discovered what are the interests of the stakeholders or the organisation(s) involved and what are their needs (Figure 2.5).

The more the interests and the needs of the different parties are explored, the more the interests and the needs that are in common should appear which should result in an area of overlap. There will always be issues that participants cannot fully agree on, but participants should understand this and focus on common grounds and agreements. In practice, this starts from gaining common ground on the process.

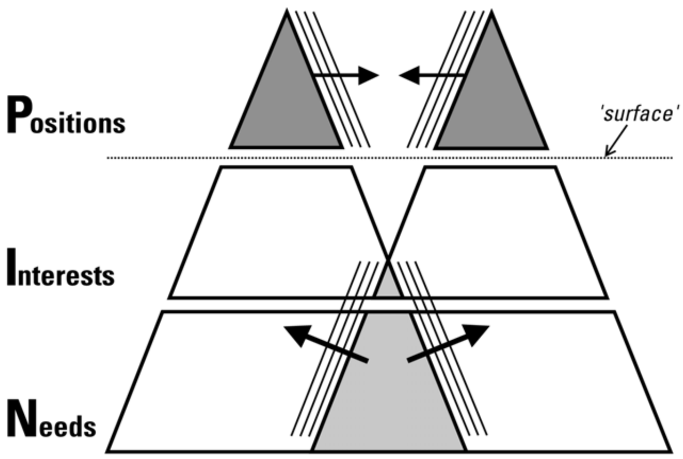

Figure 2.5 Positions, interest and needs of stakeholders and organisation(s) involved

2.3.9.2 Consensus, compromise

If two parties are working towards agreement on an issue, the percentage of the needs of each party that are met will vary depending on the outcome. Outcomes may occur anywhere along the neutral line of compromise (Figure 2.6). Traditional decision-making processes tend to work towards the middle of the line of compromise, giving 50% each. In complex circumstances, these decisions often tend not to stand the test of time. Power and influence may be exercised leading to the potential for increasingly adversarial positions.

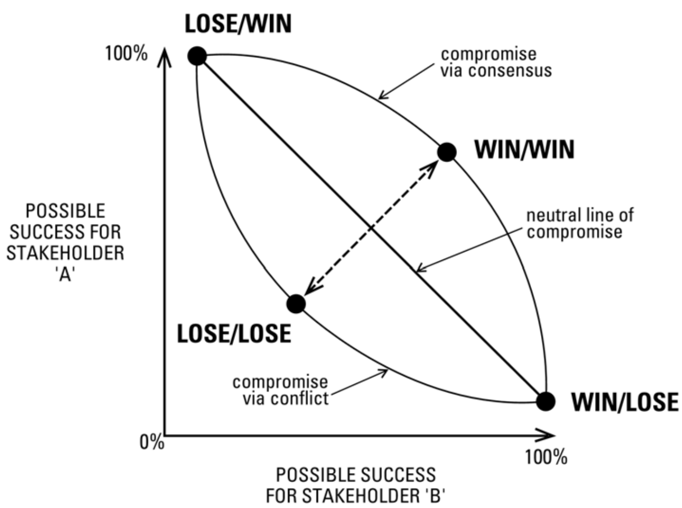

Figure 2.6 Possible outcomes of stakeholder involvement processes

Consensus-building processes should enable parties to reach more of their needs. These kind of processes start to provide invisible benefits (for example an extended network, a greater understanding of the issues and the underlying complexities and problems) as well as the usual visible benefits (for example reports, hard outputs). In order for such a process to be able to work it is essential to give it solid foundations and to get the process right at the start.

During the consensus-building process, the participants should remain in contact with their wider groups and their aims. The participants should keep their wider groups updated and return the views of these groups to the meeting room.

2.3.9.3 Roles and responsibilities

Within any stakeholder dialogue process a number of key roles and responsibilities may be defined:

- The decision-maker(s) - who makes decisions informed by the process.
- The organisation(s) involved - the organisation(s) responsible for initiating the process and providing funding.
- The convenor - an independent third party responsible for designing and managing the process. This will usually include one key individual with overall responsibility for process and running meetings, the facilitator. She/he may be supported by others as co-facilitators, project managers etc.
- The stakeholders – who represent different groups and are brought together by the convenor to discuss the issues with the decision-maker(s).
- The evaluator – who reviews the process and its success.
- Reporter and expert roles may be defined if necessary or valuable.

It is recommended to define these roles as they may be confused. The decision-maker and the organisation(s) involved are often the same and some evaluation is usually carried out by the convenor. Separating the role of convenor from the decision-maker(s) and organisation(s) involved may be crucial for maintaining the integrity of the process.

Decision-maker/Organisation(s) involved: The decision-maker/organisation(s) involved should provide guidance on the framework of its stakeholder engagement, for example, guidance on the aim of stakeholder dialogue, definition of a national stakeholder, legal obligations the decision-maker/organisation(s) involved has to meet and the position on enabling stakeholders to participate in the dialogue through the provision of funds.

Convenor: The role of the convenor may be to ensure that the dialogue process and all its participants operate in accordance with agreed ground-rules and all stakeholders are treated equally from the very moment they enter the process. The convenor will also bring expertise and experience as to the best way to achieve the goals of the dialogue process. Although funded by the sponsor the convenor works on behalf of the dialogue process, i.e., all stakeholders.

Facilitator: The role of the facilitator is vital to achieving an effective outcome. He or she should aim to maintain productive dialogue by:

- Providing working methods which enable contributions from all;
- Offering practical frameworks which bring clarity and structure;
- Managing time to best effect;
- Encouraging clear communication;
- Ensuring that a clear record of proceedings is maintained;
- Making sure that discussions keep within agreed ground-rules and parameters;
- Helping participants acknowledge common ground and build progress around it.

The facilitator should not take a view as to the best solution or on the content of the discussion. His focus should be on managing an effective process in which participants can find the best solution for themselves.

Stakeholders: The role of stakeholders (including the organisation(s) involved) is:

- To participate fully and collaboratively in the discussions, this means being willing to listen to other points of view and without resorting to the re-iteration of well known negotiating positions;
- To provide input to both the content and the process of discussions;
- To abide by any ground-rules agreed by the group;
- To represent their group fully by both inputting their group's views to the discussions and provide feedback to their group in a timely manner.

Evaluator: The evaluator will regularly look for feedback from the stakeholders and the organisation(s) involved on how they could improve any aspect of the workshops and overall programme to make them more effective.

Other Roles: The stakeholder group may agree on the need and role of others such as reporters and experts under the guidance of the convenor. A *reporter* could be a person who would focus on producing a record of the meeting which could be used by stakeholders to refer to after the meeting and to brief their groups. In addition, not all stakeholders may have the same level of knowledge on all issues. So sometimes it may be necessary to provide an *expert* who can be utilised by stakeholders to supplement their own knowledge. This could be a technical expert or an expert on a particular decision making process.

2.3.9.4 Stakeholder dialogue process ground rules

When initiating a stakeholder dialogue, the need to establish an open and interactive relationship with the stakeholders is recognised. All experience of consultation and dialogue projects suggests that overall ground-rules are needed in order to ensure that the stakeholder dialogue process will be as effective and clear as possible, to the benefit of everyone.

Ground-rules are to serve everyone involved. If a set is to be adopted, all participants should agree on it and all should be clear on why they are needed and what they should achieve.

As with all ground-rules, the intention is to enable participants to openly express their views and share information; it encourages free discussion - participants usually feel more relaxed if they do not have to worry about their reputation or implications if they are publicly quoted.

Ground-rules may cover anything which may disrupt the process of discussion, prevent other stakeholders from taking a full part, undermine the agreed process or create unnecessary conflicts. A typical coverage of a set of ground-rules may comprise:

- The aim of the process;
- Access to the process;
- Responsibilities of participants;
- Responsibilities of those in key roles;
- Establishment, responsibilities of any sub-groups;
- Information sharing and use;
- How the process will be managed and the pre-dominant style(s) of working;
- How decisions will be reached;
- Internal and external communication;
- Resources;

- Meeting records and reports;
- Evaluation and monitoring;
- Anything else that stakeholders consider will help maintain a productive process.

In an ideal situation a stakeholder dialogue process should be started drafting ground-rules together for maximum buy-in and understanding. Once adopted, ground-rules should be kept as an open, working document for the duration of the process. Anyone in the process should be able to suggest changes to existing ground-rules, or propose new ones at anytime.

Ground-rules should be morally binding. They have no legal standing and are only as valuable as participants' willingness to respect them and abide by them. Working within ground-rules is a matter of trust and respect and it is crucial that they are understood and 'owned' by all those who participate in the process that they support.

Operating within the structure of an agreed set of ground-rules is considered to be a continuing act of commitment to the process, by every stakeholder, and an act of respect to other participants. Seriously breaching a ground-rule is usually considered to be a withdrawal of commitment and an act of disrespect. In these circumstances the convenor may require the party concerned to formally withdraw from the process. The convenor should look for the views of a range of stakeholders in making judgements about whether or not a stakeholder should be asked to formally withdraw, but the decision rests with the convenor, whose independence is vital at such times.

2.3.9.5 Confidentiality

Total confidentiality will not be appropriate in a stakeholder dialogue process, but might be in small group discussions on complex issues. Ground-rules should aid the process in this respect.

2.3.9.6 Decision-making

It is important to provide clarity over how decisions will be made, including who will be responsible for decisions, what the dominant style of working will be, and how stakeholder views will get incorporated in the conclusions.

2.3.9.7 Reporting

The need to choose how to make meeting outputs open and transparent in the most digestible manner to the widest possible audience should be identified. In general, it will be important to make primary source documentation requested by issue groups publicly available.

A distinction could be made between supplying information when asked and providing information by a separate primary publishing route. Within a policy of openness and transparency, it should be the intention to make any reports produced public as soon as possible. This may not include, unless a valid reason for not doing so is provided, documents which some stakeholders may be used to remaining confidential to the stakeholder process, such as 'photo reports' and 'working documents' (documents not in the public domain and only released to dialogue participants within the dialogue's ground-rules).

In addition, the participants in the stakeholder dialogue process should decide how they want their meetings to be recorded. If the participants feels that having their meeting reports made public will not be conducive to them discussing the issues freely enough, then other arrangements will have to be agreed for a record of the meeting to be made public.

In any case, the convenor should hold a library of the documents distributed to the participants in the stakeholder dialogue process.

2.3.9.8 Presence of the press

The stakeholders should discuss if/how they wish to communicate with the press and the public and whether they should be allowed as observers at meetings within the stakeholder dialogue process.

In the spirit of transparency and openness, there should be no reason why the press should be prevented from attending meetings within the stakeholder dialogue process to be able to report. However, there may be participants present not used to dealing with the press and public. With the press present these participants would refrain from saying things they do not want to be reported and in the context of a stakeholder dialogue process, it is considered to be important to remove any barriers to productive conversations. In addition, it could be discussed not to have press or public in meetings within the stakeholder dialogue process in order to avoid discussions becoming inhibited. Separate press briefings in conjunction with main meetings may be an alternative option that the stakeholder group could consider.

2.3.10 Tools and techniques

In addition to inviting written or telephone comments, a range of techniques are available that can be used as part of a stakeholder involvement programme [1]. Some examples are described below with a brief indication of advantages and disadvantages in various contexts.

The mix of information, consultation and participation techniques has to be designed according to the context. A simple clean-up of a pipeline spill may only merit a mention in a newsletter and community liaison group meeting. Major site remediation projects may require a much more sophisticated programme including participative techniques such as workshop-based formats or more in-depth deliberative approaches.

Where opinions on matters connected with the proposal are polarised and where reliance is placed on pressure groups, the techniques listed here may have much more serious resource implications.

2.3.10.1 Newsletters

Written material used to convey information might involve a series of publications. Newsletters provide ongoing contact and information can be updated. They are a flexible form of publicity that can be designed to address the changing needs of the audience. They are useful to support liaison groups and have potential for feedback. Care should be taken in establishing the boundaries of distribution. The disadvantage is that not everyone will actually read a newsletter.

2.3.10.2 Project information centres

‘Project information centres’ have been valuable on many projects where consultations have strong links to a particular community. Documents, reports, data, and information - including those from third parties - are made available for interested participants to use. An information centre may be housed on site, in a local library, or it may be an on-line ‘virtual’ library.

2.3.10.3 Opinion surveys

Sending out a document to selected organisations and individuals for comment may help collect representative views, but favours those with more time to respond, may miss key groups, and can fail to get people really thinking through the issues and practicalities of proposals. Also, the balance of opinions expressed by those who self-select to respond to consultation initiatives or self-selecting surveys may bear no relation to the balance of opinions in society more widely. It is unwise to assume that opinions from a self-selected audience are representative of society at large. Interviews and questionnaires may therefore be required.

2.3.10.4 Focus groups

Focus groups or forums are meetings of invited participants designed to gauge the response to proposed actions and gain a detailed understanding of the participants' perspectives, values and concerns. They provide a quick means of gauging what public reaction to a proposal might be. Disadvantages are that selection of group members may exclude some sectors of the community, groups require facilitation and support to them is time consuming.

2.3.10.5 Public meetings

Public meetings may bring together interested and affected parties to present and exchange information and views on a proposal. They can provide a useful way of meeting other stakeholders and allowing people to hear a range of views. They may demonstrate that the proponent is willing to meet with other interested parties. Though appearing simple, they may be one of the most complex and unpredictable methods, and result effectively in no consultation. Unless care is taken to represent all views, the public may be dissatisfied and mistrustful. In addition, the format may be too superficial to allow wide differences of opinion to be resolved.

Large public meetings can be intimidating and tend to discourage meaningful dialogue between the public and the organisation(s) involved. Smaller informal meetings and separate meetings with specific groups of stakeholders are recommended to be included in programmes.

2.3.10.6 Surgeries/'Open house'

In the open house model, interested parties are encouraged to visit the site or some other convenient venue on an informal basis to find out about a proposal and provide feedback. This can be an effective way of informing the public and other interested parties. People can visit at a convenient time, view materials and ask questions at their leisure.

2.3.10.7 Participative workshops

Workshops with a limited number of participants can be used to provide background information, discuss issues in detail and solve problems where there is a demand. They may provide a more open exchange of ideas and facilitate mutual understanding. They may be useful for dealing with complex, technical issues and allowing more in-depth consideration, and may be targeted at particular groups – typically the more technically focussed stakeholders and local authorities.

2.3.10.8 Strategic stakeholder dialogue

Many activities could be described as dialogue. In this context, strategic stakeholder dialogue means an inclusive process that brings stakeholders together to address broader or strategically important decisions. Typically, corporate strategic stakeholder programmes run over 12 months or more to explore shared and different interests, and to build on common ground to reach an understanding or consensus. They are appropriate where a range of stakeholder groups need to be involved to address otherwise intractable issues and promote culture change.

2.3.10.9 Community liaison groups

Long-term community liaison groups exist for many large industrial sites and are an obvious channel for communication. They are a public demonstration of commitment to openness and respect for neighbours. They can give early warning of difficulties and can be used to test reaction to possible changes. They are likely to have a key role in helping to scope project stakeholder involvement programmes, particularly the more complex or potentially controversial ones.

2.3.10.10 Project liaison groups

Where there is no standing local liaison group a project liaison group may be set up as a channel of communication and focus for consultation. They are common in some industry sectors, including the construction industry and may be relevant also to contaminated land projects.

2.3.11 Examples of possible stakeholder involvement programmes

Some examples of possible stakeholder involvement programmes may be defined as outlined below, illustrating a typical mix of scope, stakeholders, tools and techniques. It has to be stipulated, however, that every situation is different and the history, local situation and wider context will affect the appropriate scale and scope of involvement. In addition, the programmes mentioned do not list all activities required.

In all cases:

- Check for factors that might indicate that additional measures are appropriate.
- Anticipate, support and comply with regulatory requirements for notification, provision of information and consultation.

A ‘routine’ operational local contamination or clean-up issue with no impact on the community and unlikely to cause concern:

- In many cases, it will be sufficient to notify the local community liaison group at the next routine meeting.

A contamination or clean-up issue with the potential to generate significant local interest and debate:

- Contact the local liaison group as soon as practicable and look for their advice on the appropriate level and scope of stakeholder input.
- Invite the key local stakeholders (including local authorities) to provide input on issues to be taken into account and potential options.
- Keep the local community and the local stakeholders informed.
- Consider external input into option selection.
- Consider event or other means of providing the public with information.
- Invite the local stakeholders to provide input on implementation issues.
- Make arrangements for on-going feedback of monitoring results.

A contamination or clean-up issue with strategic significance, likely to involve stakeholders at the national level:

- Contact the local liaison group as soon as practicable and look for advice on the appropriate level and scope of stakeholder input.
- Plan and make resources available for a significant stakeholder programme, co-ordinated with other consultations as necessary.
- Develop stakeholder, communication and (if required) training programmes. Make backgrounds and project specific information available (typically through web site and links).

- Initiate a ‘front end’ stakeholder programme to explore issues, perspectives, strategic implications and options with local and national level stakeholders. Pass on to third parties as appropriate.
- Integrate external stakeholder input explicitly into option selection.
- Initiate a stakeholder programme to review option selection and implementation issues.
- Make arrangements for on-going feedback of monitoring results.

2.4 Historical site assessment

2.4.1 Introduction

The historical site assessment is an investigation to collect existing information describing a site’s complete history from the start of site activities to the present time. The necessity for detailed information and amount of effort to conduct a historical site assessment depend on the type of site, associated historical events, regulatory framework, and availability of documented information. For example, some facilities - such as licensees following under nuclear regulations that routinely maintain records throughout their operations - already have historical site assessment information in place.

Other facilities may initiate a comprehensive search to gather historical site assessment information. In the former case, the historical site assessment is essentially complete and a review of the following sections ensures that all information sources are incorporated into the overall investigation. In still other cases, where sealed sources or small amounts of radio-nuclides are described by the historical site assessment, the site may qualify for a simplified decommissioning procedure.

The objectives of a historical site assessment could be:

- To identify possible sources of radiological and non-radiological contamination and other hazards;
- To identify the characteristics of the contaminants;
- To identify related past activities or accidents that occurred on the site;
- To determine the impact of the site on human health or the environment;
- To provide input into the design of the characterization survey;
- To provide an assessment of the likelihood of migration of contaminants;
- To determine possible responsible parties.

The historical site assessment may provide information needed to calculate derived concentration guideline levels (DCGLs as described in Section 3.3.6) and furthermore provide information that reveals the magnitude of a site’s derived concentration guideline levels. This information is used for comparing historical data to potential derived concentration guideline levels and determining the suitability of the existing data as part of the assessment of the site. The historical site assessment also supports emergency response, removal activities, fulfils public information needs, and furnishes appropriate information about the site early in the site investigation process. For a large number of sites (*e.g.* currently licensed facilities), site identification and reconnaissance may not be needed. For certain response activities, such as reports concerning the possible presence of radioactivity, preliminary investigations may consist more of a reconnaissance and a scoping survey in conjunction with efforts to gather historical information.

The historical site assessment is typically described in three sections:

- Identification of a candidate site;

- Preliminary investigation of the facility or site;
- Site reconnaissance.

The reconnaissance, however, is not a scoping survey. The historical site assessment is followed by an evaluation of the site based on information collected during the historical site assessment.

2.4.2 Historical site assessment data quality objectives

The data quality objectives (DQO) process assists in directing the planning of data collection activities performed during the historical site assessment. Information gathered during the historical site assessment supports other data quality objectives when this process is applied to subsequent surveys.

Three historical site assessment data quality objectives are expected:

- Identifying an individual or a list of planning team members - including the decision maker;
- Concisely describing the problem;
- Initially classifying site and survey unit as impacted or non-impacted.

Other results may accompany these three, and this added information may be useful in supporting subsequent applications of the data quality objective process.

The planning team clarifies and defines the data quality objectives for a site-specific survey. This multidisciplinary team of technical experts offers the greatest potential for solving problems when identifying every important aspect of a survey. Including a stakeholder group representative is an important consideration when assembling this team. Once formed, the team can also consider the role of public participation for this assessment and the possible surveys to follow. The number of team members is directly related to the scope and complexity of the problem. For a small site or simplified situations, planning may be performed by the site owner. For other specific sites a regulatory agency representative may be included.

The representative's role facilitates survey planning - without direct participation in survey plan development - by offering comments and information based on past precedent, current guidance, and potential pitfalls. For a large, complex facility, the team may include technical project managers, site managers, scientists, engineers, community and local government representatives, health physicists, statisticians, and regulatory agency representatives. A reasonable effort should be made to include other individuals - that is, specific decision makers or data users - who may use the study findings sometime in the future.

It is advised that the leader of the planning team is a member of the team who is referred to as the decision maker. This individual is often the person with the most authority over the study and may be responsible for assigning the roles and responsibilities to planning team members. Overall, the decision-making process arrives at final decisions based on the planning team's recommendations.

The following steps may be helpful during the development of data quality objectives:

- Describe the conditions or circumstances regarding the problem or situation and the reason for undertaking the survey;
- Describe the problem or situation as it is currently understood by briefly summarizing existing information;
- Conduct literature searches and interviews, and examine past or ongoing studies to ensure that the problem is correctly defined;
- If the problem is complex, consider breaking it into more manageable pieces.

The initial classification of the site involves developing a conceptual model based on the existing information, collected during a preliminary investigation. Conceptual models describe a site or facility and its environs and present hypotheses regarding the radionuclides for known and potential residual contamination. The classification of the site is discussed in Section 2.4.8, Evaluation of historical site assessment data.

Several results of the data quality objective process may be addressed initially during the historical site assessment. This information or decision may be based on limited or incomplete data. As the site assessment progresses and as decisions become more difficult, the iterative nature of the data quality objective process allows for re-evaluation of preliminary decisions. This is especially important for classification of sites and survey units where the final classification is not made until the final status survey is planned.

2.4.3 Site identification

A site may already be known for its prior use and presence of radioactive materials. Elsewhere, potential radiation sites may be identified through the following:

- Records of authorization to possess or handle radioactive materials;
- Notification to national regulator of possible releases of radioactive substances;
- Ground and aerial radiological surveys;
- Contacts with knowledge of the site.

Once identified, the name, location, and current legal owner or custodian (where available) of the site should be recorded.

2.4.4 Preliminary historical site assessment investigation

The limited scope of this preliminary historical site assessment investigation serves to collect readily available information concerning the facility or site and its surroundings. The investigation should be designed to obtain sufficient information to provide initial classification of the site or survey unit as impacted or non-impacted. Information on the potential distribution of radioactive contamination may be used for classifying each site or survey unit and is useful for planning scoping and characterization surveys.

Table 2.3 provides a set of questions that can be used to assist in the preliminary historical site assessment investigation. Apart from obvious cases *(e.g., licensees following under nuclear regulations),* this table focuses on characteristics that identify a previously unrecognized or known but undeclared source of potential contamination. Furthermore, these questions may identify confounding factors for selecting reference sites.

Table 2.3 Questions useful for a preliminary historical site assessment investigation

1	Was the site ever licensed for the manufacture, use, or distribution of radioactive materials under Agreement State Regulations?	Indicates a higher probability that the area is impacted.
2	Did the site ever have permits to dispose of, or incinerate, radioactive material onsite? Is there evidence of such activities?	Evidence of radioactive material disposal indicates a higher probability that the area is impacted.
3	Has the site ever had deep wells for injection or permits for such?	Indicates a higher probability that the area is impacted.
4	Did the site ever have permits to perform research with radiation generating devices or radioactive materials except medical or dental x-ray machines?	Research that may have resulted in the release of radioactive materials indicates a higher probability that the area is impacted.
5	As a part of the site's radioactive materials license were there ever any Soil Moisture Density Gauges (Americium-Beryllium or Plutonium-Beryllium sources), or Radioactive Thickness Monitoring Gauges stored or	Leak test records of sealed sources may indicate whether or not a storage area is impacted. Evidence of radioactive material disposal indicates a higher probability that the area is

	disposed of onsite?	impacted.
6	Was the site used to create radioactive material(s) by activation?	Indicates a higher probability that the area is impacted.
7	Were radioactive sources stored at the site?	Leak test records of sealed sources may indicate whether or not a storage area is impacted.
8	Is there evidence that the site was involved in the Manhattan Project or any Manhattan Engineering District (MED) activities (1942-1946)?	Indicates a higher probability that the area is impacted.
9	Was the site ever involved in the support of nuclear weapons testing (1945-1962)?	Indicates a higher probability that the area is impacted.
10	Were any facilities on the site used as a weapons storage area? Was weapons maintenance ever performed at the site?	Indicates a higher probability that the area is impacted.
11	Was there ever any decontamination, maintenance, or storage of radioactively contaminated ships, vehicles, or planes performed onsite?	Indicates a higher probability that the area is impacted.
12	Is there a record of any aircraft accident at or near the site (*e.g.*, depleted uranium counterbalances, thorium alloys, radium dials)?	May include other considerations such as evidence of radioactive materials that were not recovered.
13	Was there ever any radiopharmaceutical manufacturing, storage, transfer, or disposal onsite?	Indicates a higher probability that the area is impacted.
14	Was animal research ever performed at the site?	Evidence that radioactive materials were used for animal research indicates a higher probability that the area is impacted.
15	Were uranium, thorium, or radium compounds (NORM) used in manufacturing, research, or testing at the site, or were these compounds stored at the site?	Indicates a higher probability that the area is impacted or results in a potential increase in background variability.
16	Has the site ever been involved in the processing or production of Naturally Occurring Radioactive Material (*e.g.*, radium, fertilizers, phosphorus compounds, vanadium compounds, refractory materials, or precious metals) or mining, milling, processing, or production of uranium?	Indicates a higher probability that the area is impacted or results in a potential increase in background variability.
17	Were coal or coal products used onsite? If yes, did combustion of these substances leave ash or ash residues onsite? If yes, are runoff or production ponds onsite?	May indicate other considerations such as a potential increase in background variability.
18	Was there ever any onsite disposal of material known to be high in naturally occurring radioactive materials (*e.g.*, monazite sands used in sandblasting)?	May indicate other considerations such as a potential increase in background variability.
19	Did the site process pipes from the oil and gas industries?	Indicates a higher probability that the area is impacted or results in a potential increase in background variability.
20	Is there any reason to expect that the site may be contaminated with radioactive material (other than previously listed)?	See Section 3.6.3.

2.4.5 Existing radiation data

Site files, monitoring data, former site evaluation data, national, or local investigations, or emergency actions may be sources of useful site information. Existing site data may provide specific details about the identity, concentration, and areal distribution of contaminations. However, these data should be examined carefully because:

- Previous survey and sampling efforts may not be compatible with the established historical site assessment objectives or may not be extensive enough to characterize the facility or site fully.

- Measurement protocols and standards may not be known or compatible with the established historical site assessment objectives (*e.g.*, quality assurance/quality control (QA/QC) procedures, limited analysis rather than full-spectrum analysis) or may not be extensive enough to characterize the facility or site fully.
- Conditions may have changed since the site was last sampled (*i.e.*, substances may have been released, migration may have spread the contamination, additional waste disposal may have occurred, or decontamination may have been performed).

The following existing data can be evaluated:

- *Licenses, Site Permits, and Authorizations.* The facility or site radioactive materials license and supporting or associated documents are potential sources of information for licensed facilities. If a license does not exist, there may be a permit or other document that authorized site operations involving radioactivity. These documents may specify the quantities of radioactive material authorized for use at the site, the chemical and physical form of the materials, operations for which the materials are (or were) used, locations of these operations at the facility or site, and total quantities of material used at the site during its operating lifetime. Governmental agencies maintain generally files on a variety of environmental programs. These files may contain permit applications and monitoring results with information on specific waste types and quantities, sources, type of site operations, and operating status of the facility or site.
- *Operating Records*. Records and other information sources useful for site evaluations include those describing on-site activities; current and past contamination control procedures; and past operations involving demolition, effluent releases, discharge to sewers or on-site septic systems, production of residues, land filling, waste and material storage, pipe and tank leaks, spills and accidental releases, release of facilities or equipment from radiological controls, and on-site or off-site radioactive and hazardous waste disposal. Some records may be or may have been classified for national security purposes and means should be established to review all pertinent records. Past operations should be summarized in chronological order along with information indicating the type of permits and approvals that authorized these operations. Estimates of the total activity disposed of or released at the site and the physical and chemical form of the radioactive material should also be included. Records on waste disposal, environmental monitoring, site inspection reports, license applications, operational permits, waste disposal material balance and inventory sheets, and purchase orders for radioactive materials are useful - for estimating total activity. Information on accidents, such as fires, flooding, spills, unintentional releases, or leakage, should be collected as potential sources of contamination. Possible areas of localized contamination should be identified.

  Site plats or plots, blueprints, drawings, and sketches of structures are especially useful to illustrate the location and layout of buildings on the site. Site photographs, aerial surveys, and maps can help verify the accuracy of these drawings or indicate changes following the time when the drawings were prepared. Processing locations - plus waste streams to and from the site as well as the presence of stockpiles of raw materials and finished products - should be noted on these photographs and maps. Buildings or outdoor processing areas may have been modified or reconfigured such that former processing areas were converted to other uses or configurations. The locations of sewers, pipelines, electric lines, water lines, *etc.*, should also be identified. This information facilitates planning the site reconnaissance and subsequent surveys, developing a site conceptual model, and increasing the efficiency of the survey program.

  Corporate contract files may also provide useful information during subsequent stages of the radiation survey and site investigation process. Older facilities may not have complete operational records, especially for obsolete or discontinued processes.

Financial records may also provide information on purchasing and shipping that in turn help to reconstruct a site's operational history.

While operating records can be useful tools during the historical site assessment, the investigator should be careful not to place too much emphasis on this type of data. *These records are often incomplete and lack information on substances previously not considered hazardous. Out-of-date blueprints and drawings may not show modifications made during the lifetime of a facility.*

2.4.6 Contacts and interviews

Interviews with current or previous employees are performed to collect first-hand information about the site or facility and to verify or clarify information gathered from existing records. Interviews to collect first-hand information concerning the site or facility are generally conducted early in the data-gathering process. Interviews cover general topics, such as radioactive waste handling procedures. Results of early interviews are used to guide subsequent data collection activities.

Interviews scheduled late in the data gathering process may be especially useful. This activity allows questions to be directed to specific areas of the investigation that need additional information or clarification. Photographs and sketches can be used to assist the interviewer and allow the interviewees to recall information of interest. Conducting interviews on-site where the employees performed their tasks often stimulates memories and facilitates information gathering. In addition to interviewing managers, engineers, and facility workers, interviews may be conducted with labourers and truck drivers to obtain information from their perspective. The investigator should be cautious in the use of interview information. Whenever possible, anecdotal evidence should be assessed for accuracy and results of interviews should be backed up with supporting data. Steps that ensure specific information is properly recorded may include hiring trained investigators and taking affidavits.

2.4.7 Site reconnaissance

The objective of the site reconnaissance or site visit is to gather sufficient information to support a decision regarding further action. Reconnaissance activity is not a risk assessment, or a scoping survey, or a study of the full extent of contamination at a facility or site. The reconnaissance offers an opportunity to record information concerning hazardous site conditions as they apply to conducting future survey work. In this regard, information describing physical hazards, structural integrity of buildings, or other conditions, defines potential problems that may impede future work. This section is most applicable to sites with less available information and may not be necessary at other sites having greater amounts of data, such as licensed facilities.

To prepare for the site reconnaissance, begin by reviewing what is known about the facility or site and identify data gaps. Given the site-specific conditions, consider whether or not a site reconnaissance is necessary and practical. This type of effort may be deemed necessary if a site is abandoned, not easily observed from areas of public access, or discloses little information during file searches. These same circumstances may also make a site reconnaissance risky for health and safety reasons - in view of the many unknowns - and may make entry difficult. This investigative step may be practical, but less critical, for active facilities whose operators grant access and provide requested information. Remember to arrange for proper site access and prepare an appropriate health and safety plan, if required, before initiating the site reconnaissance.

Investigators should acquire signed consent forms from the site or equipment owner to gain access to the property to conduct the reconnaissance. Investigators are to determine if Governmental or local officials, and local individuals, should be notified of the reconnaissance schedule (stakeholder involvement). If needed, local officials should arrange for public notification.

It is advised to prepare a study plan before the site reconnaissance to anticipate every reconnaissance activity and identify specific information to be gathered. This plan should incorporate a survey of the site's surroundings and provide details for activities that verify or identify the location of: nearby residents, worker populations, drinking water or irrigation wells, foods, and other site environs information.

Preparing for the site reconnaissance includes initially gathering necessary materials and equipment. This may include a camera to document site conditions, health and safety monitoring instruments including a radiation detection meter for use during the site visit, and extra copies of topographic maps to mark target locations, water distribution areas, and other important site features. A logbook is critical to keeping a record of field activities and observations as they occur. For documentation purposes EURSSEM recommends that the logbook should be completed in waterproof ink, preferably by one individual. Furthermore, each page of the logbook should be signed and dated, including the time of day, after the last entry on the page. Corrections should be documented and approved.

2.4.8 Evaluation of historical site assessment data

The main purpose of the historical site assessment is to determine the current status of the site or facility, but the data collected may also be used to differentiate sites or parts of a site that need further action from those that pose little or no threat to human health and the environment. This screening process can serve to provide a site disposition recommendation or to recommend additional surveys. Because much of the data collected during historical site assessment activities is qualitative or is analytical data of unknown quality, many decisions regarding a site are the result of professional judgment.

There are three possible recommendations that follow the historical site assessment:

- An emergency action to reduce the risk to human health and the environment.
- The site or area is impacted and further investigation is needed before a decision regarding final disposition can be made. The site may be classified as class 1, class 2, or class 3, and a scoping survey or a characterization survey should be performed. Information collected during the historical site assessment can be very useful in planning these subsequent survey activities.
- The site or area is non-impacted. There is no possibility or an extremely low probability of residual radioactive materials being present at the site. The site can be released.

Historical analytical data indicating the presence of contamination in environmental media (surface soil, sub-surface soil, surface water, groundwater, air, or buildings) should be used to support the hypothesis that radioactive material was released at the facility or site. A decision that the site is contaminated can be made regardless of the quality of the data, its attribution to site operations, or its relationship to background levels. In such cases, analytical indications are sufficient to support the hypothesis - it is not necessary to definitively demonstrate that a problem exists. Conversely, historical analytical data can also be used to support the hypothesis that no release has occurred. However, these data should not be the sole basis for this hypothesis. Using historical analytical data as the principal reason for ruling out the occurrence of contamination forces the data to demonstrate that a problem does not exist.

In most cases it is assumed there will be some level of process knowledge available in addition to historical analytical data. If process knowledge suggests that no residual contamination should be present and the historical analytical data also suggests that no residual contamination is present, the process knowledge provides an additional level of confidence and supports classifying the area as non-impacted. However, if process knowledge suggests no residual contamination should be present but the historical analytical data indicate the presence of residual contamination, the area will probably be considered impacted.

The following sections describe the information recommended for assessing the status of a site. This information is needed to accurately and completely support a site disposition recommendation. If some of the information is not available, it should be identified as a data need for future surveys.

2.4.8.1 Identify potential contaminants

An efficient historical site assessment gathers information sufficient to identify the radio-nuclides used at the site - including their chemical and physical form. The first step in evaluating historical site assessment data is to estimate the potential for residual contamination by these radio-nuclides.

Site operations greatly influence the potential for residual contamination. An operation that only handled encapsulated sources is expected to have a low potential for contamination - assuming that the integrity of the sources was not compromised. A review of leak-test records for such sources may be adequate to demonstrate the low probability of residual contamination. A chemical manufacturing process facility would likely have contaminated piping, ductwork, and process areas, with a potential for soil contamination where spills, discharges, or leaks occurred. Sites using large quantities of radioactive ores - especially those with outside waste collection and treatment systems - are likely to have contaminated grounds. If loose dispersible materials were stored outside or process ventilation systems were poorly controlled, then windblown surface contamination may be possible.

Consider how long the site was operational. If enough time elapsed since the site discontinued operations, radio-nuclides with short half-lives may no longer be present in significant quantities. In this case, calculations demonstrating that residual activity could not exceed the derived concentration guideline level (DCGL) may be sufficient to evaluate the potential residual contaminants at the site. A similar consideration can be made based on knowledge of a contaminant’s chemical and physical form. Such a determination relies on records of radio-nuclide inventories, chemical and physical forms, total amounts of activity in waste shipments, and purchasing records to document and support this decision. However, a number of radio-nuclides experience significant decay product in-growth, which should be included when evaluating existing site information.

2.4.8.2 Identify potentially contaminated areas

Information gathered during the historical site assessment should be used to provide an initial classification of the site areas as impacted or non-impacted.

Impacted areas have a reasonable potential for radioactive contamination (based on historical data) or contain known radioactive contamination (based on past or preliminary radiological surveillance). This includes areas where:

- Radioactive materials were used and stored;
- Records indicate spills, discharges, or other unusual occurrences that could result in the spread of contamination;
- Radioactive materials were buried or disposed. Areas immediately surrounding or adjacent to these locations are included in this classification because of the potential for inadvertent spread of contamination.

Non-impacted areas - identified through knowledge of site history or previous survey information - are those areas where there is no reasonable possibility for residual radioactive contamination. The criteria used for this segregation need not be as strict as those used to demonstrate final compliance with the regulations. However, the reasoning for classifying an area as non-impacted should be maintained as a written record. Note that - based on accumulated survey data - an impacted area's classification may change as the radiation site survey investigation process progresses.

All potential sources of radioactivity in impacted areas should be identified and their dimensions recorded (in 2 or 3 dimensions - to the extent they can be measured or estimated). Sources can be delineated and characterized through visual inspection during the site reconnaissance, interviews with knowledgeable personnel, and historical information concerning disposal records, waste manifests, and waste sampling data. The historical site assessment should address potential contamination from the site whether it is physically within or outside of site boundaries.

2.4.8.3 Identify potentially contaminated media

The next step in evaluating the data gathered during the historical site assessment is to identify potentially contaminated media at the site. To identify media that may and media that do not contain residual contamination supports both preliminary area classification (Section 2.4.9 and Section 3.3.2.1) and planning subsequent survey activities.

The following sections provide guidance on evaluating the likelihood for release of radioactivity into the following environmental media: surface soil, subsurface soil, sediment, surface water, ground water, air, and buildings. The evaluation will result in either a finding of "Suspected contamination" or "No suspected contamination," which may be based on analytical data, professional judgment, or a combination of the two.

Subsequent sections describe the environmental media and pose questions pertinent to each type. Each question is accompanied by a commentary. Carefully consider the questions within the context of the site and the available data. Avoid spending excessive amounts of time answering each question because answers to every question are unlikely to be available at each site. Questions that cannot be answered based on existing data can be used to direct future surveys of the site. Also, keep in mind the numerous differences in site-specific circumstances and that the questions do not identify every characteristic that might apply to a specific site. Additional questions or characteristics identified during a specific site assessment should be included in the historical site assessment report.

2.4.8.4 Surface soil

Surface soil is the top layer of soil on a site that is available for direct exposure, growing plants, re-suspension of particles for inhalation, and mixing from human disturbances. Surface soil may also be defined as the thickness of soil that can be measured using direct measurement or scanning techniques. Typically, this layer is represented as the top 15 cm (6 in.) of soil. Surface sources may include gravel fill, waste piles, concrete, or asphalt paving. For many sites where radioactive materials were used, one first assumes that surface contamination exists and the evaluation is used to identify areas of high and low probability of contamination (e.g., Class 1, Class 2 or Class 3 areas).

- Were all radiation sources used at the site encapsulated sources?
  A site where only (proven) encapsulated sources were used would be expected to have a low potential for contamination. A review of the leak-test records and documentation of encapsulated source location may be adequate for a finding of "No suspected contamination."
- Were radiation sources used only in specific areas of the site?
  Evidence that radioactive materials were confined to certain areas of the site may be helpful in determining which areas are impacted and which are non-impacted. This should be supported by other gathered information, e.g., interviews, documents dealing with the transport of radioactive materials and storage at the site.
- Was surface soil re-graded or moved elsewhere for fill or construction purposes?

This helps to identify additional potential radiation sites.

2.4.8.5 Subsurface soil and media

Subsurface soil and media are defined as any solid materials not considered to be surface soil. The purpose of these investigations is to locate and define the vertical extent of the potential contamination. Subsurface measurements can be expensive, especially for beta- or alpha-emitting radionuclides. Removing areas from consideration for subsurface measurements or defining areas as non-impacted for subsurface sampling conserves limited resources and focuses the site assessment on areas of concern.

- Are there areas of known or suspected surface soil contamination?
  Surface soil contamination can migrate deeper into the soil. Surface soil sources should be evaluated based on radionuclide mobility, soil permeability, and infiltration rate to determine the potential for subsurface contamination. Computer modelling may be helpful for evaluating these types of situations. See also Sections 3.3.3 and 3.3.4).

- Is there a groundwater plume without an identifiable source?
  Contaminated groundwater indicates that a source of contamination is present. If no source is identified during the historical site assessment, subsurface contamination is a probable source.

- Is there potential for enhanced mobility of radionuclides in soils?
  Radionuclide mobility can be enhanced by the presence of solvents or other volatile chemicals that affect the ion-exchange capacity of soil (see Section 3.3.4).

- Is there evidence that the surface has been disturbed?
  Recent or previous excavation activities are obvious sources of surface disturbance. Areas with developed plant life (forested or old growth areas) may indicate that the area remained undisturbed during the operating life of the facility. Areas where vegetation is removed during previous excavation activity may be distinct from mature plant growth in adjacent areas. If a site is not purposely replanted, vegetation may appear in a sequence starting with grasses that are later replaced by shrubs and trees. Typically, grasslands recover within a few years, sagebrush or low ground cover appears over decades, while mature forests may take centuries to develop.

- Is there evidence of subsurface disturbance?
  Non-intrusive, non-radiological measurement techniques may provide evidence of subsurface disturbance. Magnetometer surveys can identify buried metallic objects, and ground-penetrating radar can identify subsurface anomalies such as trenches or dump sites. Techniques involving special equipment are discussed in Section 3.3.8 and Section 3.6.6.

- Are surface structures present?
  Structures constructed at a site - during the operational history of that site - may cover below-ground contamination. Some consideration for contaminants that may exist beneath parking lots, buildings, or other onsite structures may be warranted as part of the investigation. There may be underground piping, drains, sewers, or tanks that caused contamination (see Section 3.6.4).

2.4.8.6 Surface water

Surface waters include streams and rivers, lakes, coastal tidal waters, and oceans. Note that certain ditches and intermittently flowing streams qualify as surface water. The evaluation determines whether radio-nuclides are likely to migrate to surface waters or their sediments. Where a previous release is not suspected, the potential for future release depends on the distance to surface water and the flood potential at the site. With regard to the two preceding sections, one can also consider an interaction between soil and water in relation to seasonal factors including soil cracking due to freezing, thawing, and dessication that influence the dispersal or infiltration of radio-nuclides.

- Is surface water nearby?
  The proximity of a contaminant to local surface water is essentially determined by run-off and radionuclide migration through the soil. The definition for *nearby* depends on site-specific conditions. If the terrain is flat, precipitation is low, and soils are sandy, nearby may be within several meters. If annual precipitation is high or occasional rainfall events are high, within 1,200 meters (3/4 mile) might be considered nearby. In general, sites need not include the surface water pathway where the overland flow distance to the nearest surface water is more than 3,200 meters (2 miles).

- Is the waste quantity particularly large?
  Depending on the physical and chemical form of the waste and its location, *large* is a relative term. A *small* quantity of liquid waste may be of more importance - *i.e.*, a greater risk or hazard - than a *large* quantity of solid waste stored in water tight containers.

- Is the drainage area large?
  The drainage area includes the area of the site itself plus the up-gradient area that produces run-off flowing over the site. Larger drainage areas generally produce more run-off and increase the potential for surface water contamination.

- Is rainfall heavy?
  If the site and surrounding area are flat, a combination of heavy precipitation and low infiltration rate may cause rainwater to pool on the site. Otherwise, these characteristics may contribute to high run-off rates that carry radio-nuclides overland to surface water. Total annual rainfall exceeding one meter (40 inches), or a once in two-year-24-hour precipitation exceeding five cm (two inches) might be considered "heavy".
  Rainfall varies for locations across Europe as also the precipitation rates during the year at each location due to seasonal and geographic factors. These value rates should be known for making a correct judgement about the migration of radio-nuclides.

- Is the infiltration rate low?
  Infiltration rates range from very high in gravelly and sandy soils to very low in fine silt and clay soils. Paved sites prevent infiltration and generate run-off.

- Are sources of contamination poorly contained or prone to run-off?
  Proper containment which prevents radioactive material from migrating to surface water generally uses engineered structures such as dikes, berms, run-on and run-off control systems, and spill collection and removal systems. Sources prone to releases via run-off include leaks, spills, exposed storage piles, or intentional disposal on the ground surface. Sources not prone to run-off include underground tanks, above-ground tanks, and containers stored in a building.

- Is a run-off route well defined?
  A well defined run-off route - along a gully, trench, berm, wall, *etc.* - will more likely contribute to migration to surface water than a poorly defined route. However, a poorly defined route may contribute to dispersion of contamination to a larger area of surface soil.

- Has deposition of waste into surface water been observed?
  Indications of this type of activity will appear in records from past practice at a site or from information gathered during personal interviews.

- Is ground water discharge to surface water probable?
  The hydrogeology and geographical information of the area around and inside the site may be sufficiently documented to indicate discharge locations.

- Does analytical or circumstantial evidence suggest surface water contamination? Any condition considered suspicious - and that indicates a potential contamination problem - can be considered circumstantial evidence.

- Is the site prone to flooding? In national or local archives information may be available about the flood rate and occurred floods in the past. Generally, a site on a 500-year floodplain is not considered prone to flooding.

2.4.8.7 Groundwater

Proper evaluation of groundwater includes a general understanding of the local geology and subsurface conditions. Of particular interest is descriptive information relating to subsurface stratigraphy, aquifers, and groundwater use.

- Are sources poorly contained? Proper containment which prevents radioactive material from migrating to groundwater generally uses engineered structures such as liners, layers of low permeability soil (*e.g.*, clay), and leachate collection systems.

- Is the source likely to contaminate groundwater? Underground tanks, landfills[5], surface impoundments and lagoons are examples of sources that are likely to release contaminants that migrate to groundwater. Above ground tanks, drummed solid wastes, or sources inside buildings are less likely to contribute to groundwater contamination.

- Is waste quantity particularly large? Depending on the physical and chemical form of the waste and its location, *large* is a relative term. A *small* quantity of liquid waste may be of more importance - *i.e.*, greater risk or hazard - than a *large* quantity of solid waste stored in water tight containers.

- Is precipitation heavy? If the site and surrounding area are flat, a combination of heavy precipitation and low infiltration rate may cause rainwater to pool on the site. Otherwise, these characteristics may contribute to high run-off rates that carry radio-nuclides overland to surface water. Total annual rainfall exceeding one meter (40 in.), or a once in two-year-24-hour precipitation exceeding five cm (two in.) might be considered "heavy".

- Is the infiltration rate high? Infiltration rates range from very high in gravelly and sandy soils to very low in fine silt and clay soils. Unobstructed surface areas are potential candidates for further examination to determine infiltration rates.

- Is the site located in an area of karst terrain? In karst terrain, groundwater moves rapidly through channels caused by dissolution of the rock material (usually limestone) that facilitates migration of contaminants.

- Is the subsurface highly permeable? Highly permeable soils favour downward movement of water that may transport radioactive materials. Well logs, local geologic literature, or interviews with knowledgeable individuals may help answer this question.

- What is the distance from the surface to an aquifer? The shallower the source of groundwater, the higher the threat of contamination. It is difficult to determine whether an aquifer may be a potential source of drinking water in the future (*e.g.*, next 1,000 years). This generally applies to the shallowest aquifer below the site.

[5] Landfills can affect the geology and hydrogeology of a site and produce heterogeneous conditions. It may be necessary to consult an expert on landfills and the conditions they generate.

- Are suspected contaminants highly mobile in ground water?
  Mobility in ground water can be estimated based on the distribution coefficient (K_d) of the radionuclide. Elements with a high K_d, like thorium (*e.g.*, K_d = 3,200 cm³/g), are not mobile while elements with a low K_d, like hydrogen (*e.g.*, K_d = 0 cm³/g), are very mobile. The Unted States Nuclear regulatory Commission (NRC) [50] and the Department of Energy (DOE) [51] provide a compilation of K_d values. These values can be influenced by site-specific considerations such that site-specific K_d values need to be evaluated or determined. Also, the mobility of a radionuclide can be enhanced by the presence of a solvent or volatile chemical.
- Does analytical or circumstantial evidence suggest groundwater contamination?
  Evidence for contamination may appear in current site data; historical, hydro-geological, and geographical information systems records; or as a result of personal interviews.

2.4.8.8 Air

Evaluation of air is different than evaluation of other potentially contaminated media. Air is rarely the source of contamination. Air is evaluated as a pathway for re-suspending and dispersing radioactive contamination as well as a contaminated media.

- Were there any observations of contaminant releases into the air caused by any activity performed on the site?
  Direct observation of a release to the air might occur where radioactive materials are suspected to be present in particulate form (*e.g.*, mine tailings, waste pile) or adsorbed to particulates (*e.g.*, contaminated soil) or released by a chimney, and where site conditions favour air transport (*e.g.*, dry, dusty, windy).
- Does analytical or circumstantial evidence suggest a release to the air?
  Other evidence for releases to the air might include areas of surface soil contamination that do not appear to be caused by direct deposition or overland migration of radioactive material.
- For radon exposure only, are there elevated amounts of radium (^{226}Ra or one of its daughters, e.g., ^{210}Pb) in the soil or water that could act as a source of radon in the air?
  The source, ^{226}Ra, decays to ^{222}Rn, which is radon gas. Once radon is produced, the gas needs a pathway to escape from its point of origin into the air. Radon is not particularly soluble in water, so this gas is readily released from water sources which are open to air. Soil, however, can retain radon gas until it has decayed. The rate that radon is emitted by a solid, *i.e.* radon flux, can be measured directly to evaluate potential sources of radon.
- Is there a prevailing wind and a propensity for windblown transport of contamination?
  Information pertaining to geography, ground cover (e.g., amount and types of local vegetation), meteorology (e.g., wind speed at 7 meters above ground level) for and around the site, plus site-specific parameters related to surface soil characteristics enter into calculations used to describe particulate transport. Mean annual wind speed can be obtained from the national weather service surface station nearest to the site.

2.4.8.9 Structures

Structures used for storage, maintenance, or processing of radioactive materials are potentially contaminated by these materials. The questions presented in Table 2.3 help to determine if a building might be potentially contaminated. The questions listed in this section are for identifying potentially contaminated structures, or portions of structures, that might not be identified using Table 2.3.

- Were adjacent structures used for storage, maintenance, or processing of radioactive materials?
  Adjacent is a relative term for this question. A processing facility with a potential for venting radioactive material to the air could contaminate buildings downwind. A facility with little potential for release outside of the structures handling the material would be less likely to contaminate nearby structures.

- Is a building or its addition or a new structure located on a former radioactive waste burial site or contaminated land?
  Comparing past and present photographs or site maps and retrieving building permits or other structural drawings and records in relation to historical operations information will reveal site locations where structures may have been built over buried waste or contaminated land.

- Was the building constructed using contaminated material?
  Building materials such as concrete, brick, or cinder block may have been formed using contaminated material.

- Does the potentially non-impacted portion of the building share a drainage system or ventilation system with a potentially contaminated area?
  Technical and architectural drawings for site structures along with visual inspections are required to determine if this is a concern in terms of current or past operations.

- Is there evidence that previously identified areas of contamination were re-mediated by painting or similar methods of immobilizing contaminants?
  Removable sources of contamination immobilized by painting may be more difficult to locate, and may need special consideration when planning subsequent surveys.

2.4.9 Develop a conceptual model of the site

Starting with project planning activities, one gathers and analyzes available information to develop a conceptual site model. The model is essentially a site diagram showing locations of known contamination, areas of suspected contamination, types and concentrations of radio-nuclides in impacted areas, potentially contaminated media, and locations of potential reference (background) areas. The diagram should include the general layout of the site including buildings and property boundaries. When possible, produce three dimensional diagrams. The conceptual site model will be upgraded and modified as information becomes available throughout the radiation survey and site investigation process.

The model should be used to assess the nature and the extent of contamination, to identify potential contaminant sources, release mechanisms, exposure pathways, human and/or environmental receptors, and to develop exposure scenarios. Further, this model helps to identify data gaps, determine media to be sampled, and assists staff in developing strategies for data collection. Site history and preliminary survey data generally are extremely useful sources of information for developing this model. The conceptual site model should include known and suspected sources of contamination and the types of contaminants and affected media. Such a model can also illustrate known and potential routes of migration and known or potential human and environmental receptors.

The site should be classified or initially divided into similar areas. Classification may be based on the operational history of the site or observations made during the site reconnaissance. After the site is classified using current and past site characteristics, further divide the site or facility based on anticipated future use. This classification can help:

- To assign limited resources to areas that are anticipated to be released without restrictions;

- To identify areas with little or no possibility of unrestricted release.

Figure 2.7 shows an example of how a site might be classified in this manner. Further classification of a site may be possible based on site disposition recommendations (unrestricted vs. release with passive controls).

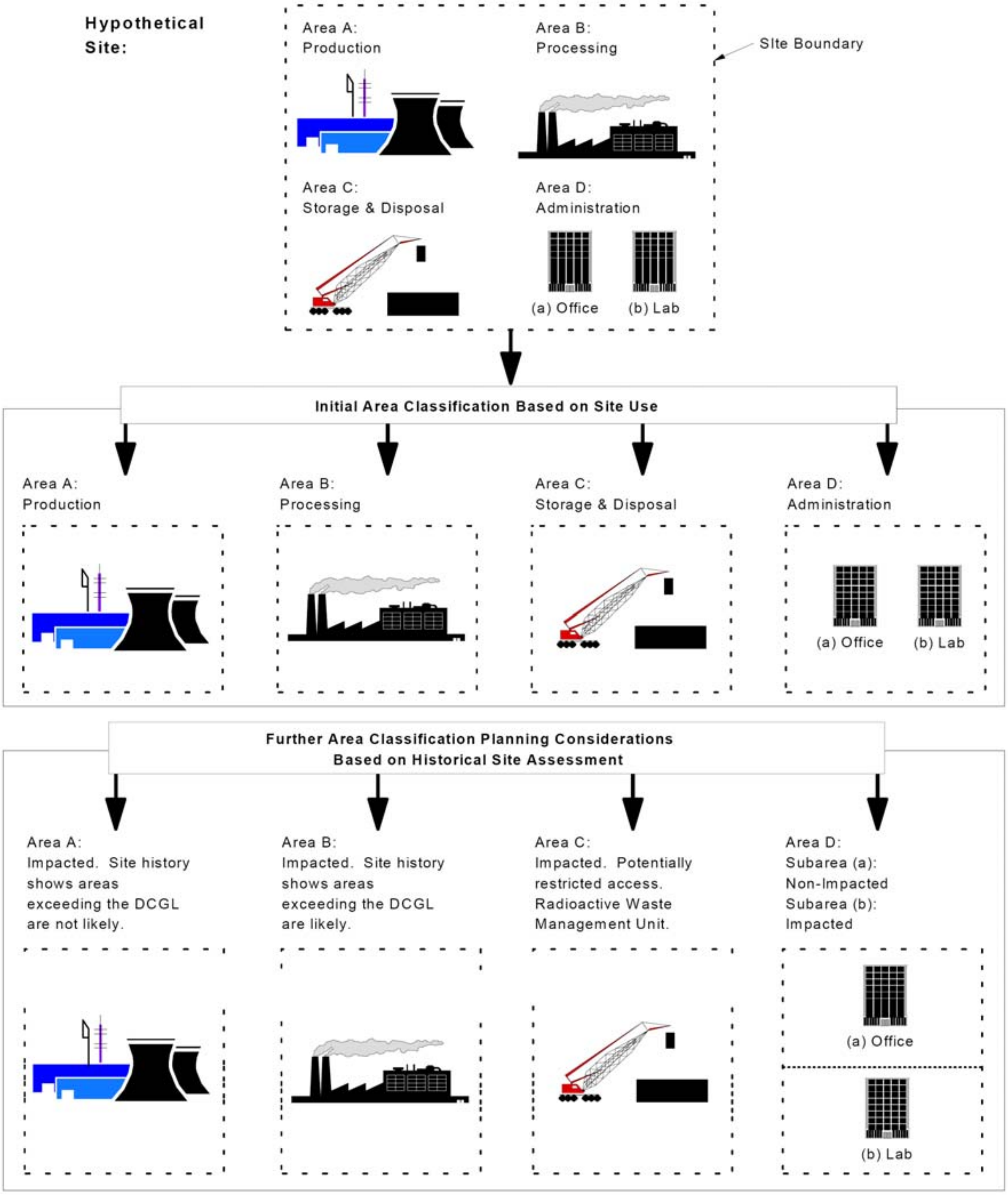

Figure 2.7 Example showing how a site might be classified prior to clean-up based on preliminary investigations, historical site assessment and supplementary investigations

2.4.10 Professional judgment

In some cases, traditional sources of information, data, models, or scientific principles are unavailable, unreliable, conflicting, or too costly or time consuming to obtain. In these instances professional judgment may be the only practical tool available to the investigator. Professional judgment is the expression of opinion that is documented in written form and based on technical knowledge and professional experience, assumptions, algorithms, and definitions, as stated by an expert in response to technical problems. For general applications, this type of judgment is a routine part of scientific investigation where knowledge is incomplete. Professional judgment can be used as an independent review of historical data to support decision making during the historical site assessment. Professional judgment should only be used in situations where data are not reasonably obtainable by collection or experimentation.

The process of recruiting professionals should be documented and as unbiased as possible. The credentials of the selected individual or individuals enhance the credibility of the elicitation, and the ability to communicate their reasoning is a primary determinant of the quality of the results. Qualified professionals can be identified by different sources, including the planning team, professional organizations, government agencies, universities, consulting firms, and public interest groups. The selection criteria for the professionals should include potential conflict of interest (economic or personal), evidence of expertise in a required topic, objectiveness, and availability.

2.4.11 Historical site assessment report

A narrative report is generally a useful product for an historical site assessment. Use this report to summarize what is known about the site, what is assumed or inferred, activities conducted during the historical site assessment, and all researched information. Cite a supporting reference for each factual statement given in the report. Attach copies of references (*i.e.*, those not generally available to the public) to the report. The narrative portion of the report should be written in the plain national language and avoid the use of technical terminology as much as possible.

To encourage consistency in the content of historical site assessment narratives, it is advised for both the structure and content that each report follows the same format. In 0 an example of a format of a historical site assessment report is shown. Additional information not identified in the outline may be requested by the regulatory agency at its discretion. The level of effort to produce the report should reflect the amount of information gathered during the historical site assessment.

In the historical site assessment report attention may be given to subjects that thought or be expected to be present, but could not be proven, a special point in the report can be that information is reported about actions that have never been performed at the site and that certain nuclides have never been present.

2.4.12 Review of the historical site assessment

The planning team should ensure that someone (a first reviewer) conducts a detailed review of the historical site assessment report for internal consistency and as a quality-control mechanism. A second reviewer with considerable site assessment experience should then examine the entire information package to assure consistency and to provide an independent evaluation of the historical site assessment conclusions. The second reviewer also evaluates the package to determine if special circumstances exist where radioactivity may be present but not identified in the historical site assessment. Both the first reviewer and a second independent reviewer should examine the historical site assessment written products to ensure internal consistency in the report's information, summarized data, and conclusions. The site review ensures that the historical site assessment recommendations are appropriate.

An important quality assurance objective is to find and correct errors. A significant inconsistency indicating either an error or a flawed conclusion, if undetected, could contribute to an inappropriate recommendation. Identifying such a discrepancy directs the historical site assessment investigator and site reviewers to re-examine and resolve the apparent conflict.

Under some circumstances, experienced investigators may have differing interpretations of site conditions and draw differing conclusions or hypotheses regarding the likelihood of contamination. Any such differences should be resolved during the review. If a reviewer's interpretations contradict those of the historical site assessment investigator, the two should discuss the situation and reach a consensus. This aspect of the review identifies significant points about the site evaluation that may need detailed explanation in the historical site assessment narrative report to fully support the conclusions. Throughout the review, the investigator from the authorities and site reviewers should keep in mind the need for conservative judgments in the absence of definitive proof to avoid underestimating the presence of contamination, which could lead to an inappropriate historical site assessment recommendation.

2.5 Risk assessment

2.5.1 Introduction

Site remediation activities have to deal with risk assessment, risk management and risk communication [16]. Risk assessment is used to determine the risk to human health and the environment, risk management efforts are directed towards control and mitigation of the potential long term risks of residual contamination, and risk communication actions are used to convey information to affected current and future stakeholders.

- Environmental risk assessment

  Environmental risk assessment is based on the source-pathway-receptor relationship and allows a prediction of the effects on the environment and human health over time to be made. Environmental risk assessment usually takes place prior to any remedial action in order to determine the levels and types of remediation required. The process needs to be rerun following the remediation phase so that the longer term risks of any remaining contamination can be assessed and appropriately managed during stewardship years.

- Risk management

  Three major traditions in sociological analysis of risk have been identified:

  (1) A positivist/realist theory of knowledge, with a bureaucratic rationalistic policy orientation, whereby risk can be measured and mapped, and thus controlled (within limits), and where failures in risk management are understood as being due to inadequate knowledge or competence, or to a failure of political will;

  (2) A social constructivist theory of knowledge, with a liberal pluralistic approach to integrating knowledge and action, whereby the understanding of risks is shaped by history, politics and culture, and risk management requires negotiation and dialogue to enable the inclusion of different perspectives;

  (3) A constructivist theory of knowledge, focusing on the mediation of knowledge and power (among others), which makes risk analysis a particular discourse, and which empowers some groups and excludes others.

  Current (radiological) risk management strategies as promoted by the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA) fall under model (1) listed above.

  The acceptability of residual risks in general is a function of a wide variety of sociological, economic and political factors. It may vary over time for individuals or certain groups of individuals. This acceptability typically evolves as a balance between perceived risk and actual inconvenience imposed by institutional control measures. Inconvenience here is understood to encompass the restrictions on, for example, site use imposed. The higher the perceived risk, the more acceptable become institutional controls.

The definition of what constitutes a *residual risk* is subject to scientific developments and subsequent changes in the regulatory systems. A stewardship programme may have to include provisions for accommodating such changes in the regulatory system. While the legal framework usually ensures that the envisaged objectives do not change, the regulator may deem it necessary to reassess risks. Such reassessment may result in changes to the institutional control measures that in turn require changes in the stewardship arrangements. Therefore, a mechanism should be available for providing (additional) resources.

The need for remediation and the judgement about acceptable residual contamination levels are usually driven by society's perception of the balance between the costs of measures and the benefits obtained. There is a certain 'window' for decision making, bound by minimum required benefits and maximum allowable expenditure. Expenditures for lowering residual risks typically increase in an exponential or similar way. This is captured in the requirement to optimise radiation protection measures.

As an example, the conceptual framework for long term stewardship can be represented on a scale (Figure 2.8). On the left hand side of the scale, a series of weights represent the hazard associated with residual contamination. On the right hand side of the scale, a series of weights represent technical, institutional and societal factors.

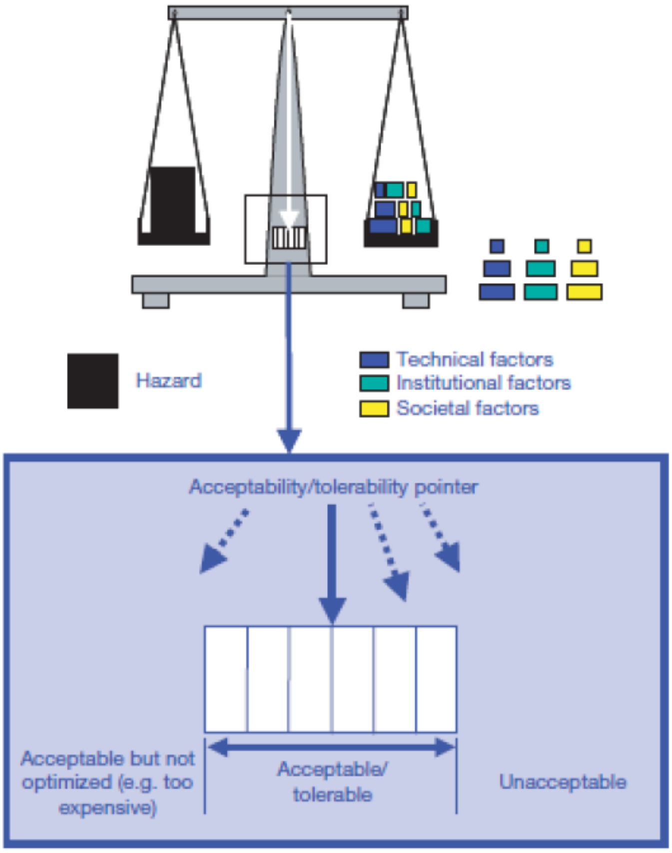

Figure 2.8 Conceptual framework for site remediation activities

Technical factors may include, among others:

- Monitoring and surveillance;
- Verification and validation of predictive models for the fate and transport of contamination;
- Development of durable engineered protective measures.

Institutional factors may include, among others:

- Safety assessments;
- Development of an action plan with contingencies;
- Development of durable institutional controls;
- Reliable funding mechanisms;
- Records and information management.

Societal issues may include, among others:

- Risk perceptions;
- Public values;
- Stakeholder involvement.

When the scale is in balance then human health and the environment are considered to be protected to a level agreed by the stakeholders - for the present and in the future. The aim of long term stewardship for example is to ensure that the scale is kept in balance. Thus with time, if the level of hazard falls due to radioactive decay or natural attenuation, then less weight may need to be added to the right hand side of the scale in Figure 2.8. This may allow the site to reach an interim end state such that less restrictive land uses may be allowed while still maintaining protection of human health and the environment.

Conversely, if the hazard remains the same but there is a partial failure of, for example, a containment system, then further 'weights' need to be added to the right hand side in order to maintain protection of human health and the environment. These additional weights are likely to involve a technical or institutional solution - for the former this could be an engineering intervention to restore the required level of containment, whilst for the latter this might involve further restrictions on land use.

Each of the weights on the right hand side inevitably has an associated cost. Optimisation of a long term stewardship programme for example involves balancing these costs against the benefits of the actions required to contain the hazard and to retain an appropriate level of protection of human health and the environment.

- Risk communication

  Environmental risk assessment is sometimes viewed by the non-scientific community with suspicion, and terms such as 'black box syndrome' are quite often used. It is important, therefore, for scientists to be able to communicate the rationale and benefits behind undertaking environmental risk assessments as well as the results themselves.

2.5.2 Assessments of reuse options for radioactively contaminated land

Considering the assessment of options for the remediation of radioactively contaminated sites and/or groundwater, a set of potentially relevant assessment endpoints may include: radionuclide contamination levels, risks to the health of biota, radionuclide intakes of people and the individual risks, collective doses and a number of health effects associated with those intakes, all as a function of time and space during and after the implementation of the management option [17]. It may be sufficient to assess a subset of these assessment endpoints, depending on the nature of the contamination, the land concerned and the options under consideration and on how the results of the assessment are to be used in characterising options on their attributes.

The time frame for the assessment will depend on the management option and on the radionuclides involved. It is unlikely to be shorter than a hundred years, because of the radioactive half-lives of most of the radionuclides of concern on nuclear and defence sites. It is also unlikely to be as long as thousands of years, because in most cases none of the management options being compared will leave land in a contaminated state for thousands of years or more.

2.5.3 Risk assessment approaches

Two methods for calculating adverse health effects associated with radiation exposure may be distinguished [18]:

- *Dose assessment* - where a dose is calculated by multiplying a dose conversion factor (expressed in terms of unit dose/unit intake) for a given radionuclide by the total intake/exposure to that radionuclide (i.e., ingestion, inhalation, or external exposure). The calculated dose can also be multiplied by a probability coefficient to arrive at a risk value.

  This dose approach originated with the need to protect workers and the public from ongoing nuclear operations. Since dose can be directly measured in the workplace, while cancer risk cannot, it was natural to adopt the dose approach. ICRP methods are based on a "safe dose" below which the exposure to radioactivity is protective of workers and the exposed public. When criteria for license termination have been developed, the dose approach was extended to cover clean-up. Clean-up levels were derived using dose conversion factors to back-calculate radionuclide concentrations (activity per mass) corresponding to a target dose. While ongoing doses can be directly measured, future doses to the public must be modelled.

- *Risk assessment* (cancer slope factor approach) - where risk is calculated directly by assigning a unit of risk for every unit of exposure (i.e., probability of adverse effect/µSv), and multiplying by the total exposure.

  The clean-up of radioactively contaminated sites was approached from the perspective of having studied many cancer-causing chemicals. Future risks were expressed in terms of excess cancer probabilities. This method was extended to radionuclides, and an external radiation pathway was added. Low-level exposure to radionuclides can result in non-carcinogenic risk and well as carcinogenic risk. However, in evaluating exposure to radioactive materials at contaminated sites, only carcinogenic risk is considered for most radionuclides. The non-carcinogenic health effects associated with exposure to ionizing radiation include mutagenic, teratogenic, and acute toxicity effects. These effects are generally less significant for doses associated with environmental exposures. Therefore, carcinogenic risk is considered to be a sufficient basis for assessing radiation related to human health risk at sites.

The two methods both require exposures to be modelled. Using site conceptual models and exposure scenarios, the pathways by which radiation can affect the body are determined. These are external exposure, inhalation, direct ingestion of soil, ingestion of contaminated food (plant, meat, milk, or aquatic), and ingestion of drinking water. Using appropriate transfer equations, the quantity of external gamma exposure or intake of internal radionuclides is calculated over a period of time.

2.5.3.1 Dose assessment approach

The dose approach is based on an annual exposure to radiation. "Dose" generally refers to the Effective Dose Equivalent (EDE), a unit of measure to normalize radiation doses by considering the adverse effects on a total body basis for the purpose of regulation of occupational exposure. The Effective Dose Equivalent is derived by multiplying a Dose Conversion Factor (DCF) for a given radionuclide by the unit intake of exposure to that radionuclide (i.e., ingestion, inhalation, or external exposure). For instance, the standard equation for an inhalation pathway is:

Annual Dose (inhalation pathway) = (DCF) x (radionuclide concentration in air) x (breathing rate) x (exposure duration)

Dose Conversion Factors are defined by the International Commission on Radiological Protection (ICRP) and expressed as dose per unit exposure. Most workplace standards are based on DCFs in *ICRP Publication 30* [19]. The newer DCFs in *ICRP Publication 72* are based on additional scientific data [20]. They are more applicable to the general public, correspond to current cancer slope factors and put more emphasis on the ingestion pathway at the expense of the inhalation pathway.

Each radionuclide has a unique DCF and therefore produces different doses. A total dose is the sum of doses from all applicable pathways (ingestion of contaminated soil, water, and plants; inhalation; and external exposure).

Most health physicists are concerned with radiological doses and do not calculate the risk associated with a given dose. They compare the dose to an appropriate dose-based standard, e.g., 1 mSv/year for public exposure or 50 mSv/year for occupational exposure.

The risk associated with a given dose can be calculated using a probability coefficient. According to the *1990 Recommendations of the ICRP*, the probability coefficient from fatal cancers, non-fatal cancers, and severe hereditary effects is 7.3 x 10^{-2}/Sv [21]. This risk coefficient is based on low, linear energy transfer (LET) (gamma) radiation (clearly not appropriate for some radionuclides) and considers all cancers. As a result, the risk from a given dose may be calculated as:

Risk = (total dose) x (probability coefficient in risk/unit dose)

2.5.3.2 Cancer slope factor approach

The evaluation of risks to human health and the environment from exposure to radioactive substances at sites has been documented in Risk Assessment Guidance for Superfund (RAGS): Part A (EPA, 1989) [22]. The RAGS methodology provides the framework for assessing baseline risks, developing and refining preliminary remediation goals, and evaluating risks associated with various remedial action alternatives. Only cancer risks are considered for most radionuclides; for uranium, non-cancer toxicity hazards are also considered. These methods are confirmed and extended in the document Soil Screening Guidance for Radionuclides (EPA, 2000) [23]. The soil screening levels are not clean-up goals but are risk-based concentrations associated with 10^{-6} risk level, below which the sites do not require further attention.

The risks to potentially exposed human receptors is computed as the product of the estimated lifetime intake or external exposure for a contaminant of concern times a measure of the likelihood of incremental cancer induction per unit exposure for that contaminant, termed the "slope factor." A slope factor is similar to a dose conversion factor, but instead of assigning a unit dose for every unit of exposure (i.e., μSv/Bq), a unit of risk is assigned for every unit of exposure (i.e., probability of adverse effect/Bq). The slope factor is an estimate of the probability of a response, i.e., the probability of an individual developing cancer per unit intake of, or external exposure to, a carcinogen over a lifetime. The slope factor multiplied by an estimate of the total lifetime exposure is used to estimate the probability of an individual developing cancer as a result of that exposure. For instance, the standard equation for an inhalation pathway is

Risk (inhalation pathway) = (inhalation slope factor) x (radionuclide concentration in air)
x (breathing rate) x (exposure duration).

Calculating risk directly in this way yields a lower result than calculating risk using the dose conversion method.

Slope factors have been calculated for most radionuclides, and - just as different radionuclides have different DCFs - different radionuclides generally have different slope factors. The slope factors also vary depending on the exposure route. Therefore, risk associated with inhaling 37 Bq of uranium is different from that of inhaling 37 Bq of cesium.

Also, the risk associated with inhaling 37 Bq of radium is different from that of ingesting 37 Bq of radium via drinking water.

Federal Guidance Report No. 13 (EPA, 1999) provides updated and improved radiation risk coefficients for cancer incidence and mortality [24]. These updated risk coefficients are the basis for new slope factors in the Health Effects Assessment Summary Tables (HEAST) (EPA, 2001) [25].

2.5.3.3 Comparison of radiation risk assessment approaches

Traditionally, impacts from exposure to radioactive materials have been expressed in terms of dose. Most radiation protection standards and requirements are specified in terms of a radiation dose limit (e.g., mSv/year).

Table 2.4 Comparison of radiation risk estimation methodologies

Parameter	Risk Assessment	Dose Assessment
Competing risks	Persons dying from competing causes of death (e.g., disease, accident) are not considered susceptible to radiation-induced cancer. Probability of dying at a particular age from competing risks is considered based on the mortality rate from all causes at that age in the 1979-81 U.S. population.	Competing risks are not considered explicitly.
Risk models	Age-dependent and sex-dependent risk models for 14 cancer sites are considered individually and integrated into the slope factor estimate.	Separate dose conversion factors for infants, children, and adults. Annual dose requires that infants and children be considered separately.
Genetic risk	Genetic risk is not considered in the slope factor estimate.	Effective dose equivalent value includes genetic risk component.
Dose estimate	Low-LET and high-LET dose estimates considered separately for each target organ.	Dose equivalent includes both low-LET and high-LET radiation multiplied by appropriate relative biological effectiveness (RBE) factors (see below).
Relative biological effectiveness (RBE) for alpha radiation	20 for most sites (8 prior to 1994) 10 for breast (8 prior to 1994) 1 for leukemia (1.117 prior to 1994).	20 (all sites).
Organs considered	Estimates of absorbed dose to 16 target organs/tissues considered for 13 specific cancer sites plus residual cancers.	Effective dose equivalent ICRP 1979 considers dose estimates to 6 specified target organs plus remainder (weighted average of 5 other organs). Effective dose ICRP 1991 considers dose estimates to 12 specified target organs plus remainder (average of 10 other organs).
Lung dose definition	Absorbed dose used to estimate lung cancer risk computed as weighted sum of dose to tracheobronchial region (80%) and pulmonary lung (20%).	Average dose to total lung (mass-weighted sum of nasopharyngeal, tracheobronchial, and pulmonary regions).
Integration period	Variable length (depending on organ-specific risk models and considerations of competing risks) not to exceed 110 years.	Fixed integration period of 50 years typically considered.
Domestic/metabolic models	Metabolic model parameters for dose estimates generally follow ICRP 1979 recommendations; exceptions include transuranic radionuclides.	Typically employ ICRP 1979 and ICRP 1991 models and parameters for radionuclide uptake, distribution, and retention.
Standards	Expressed as a target risk of lifetime excess cancer incidence.	Generally expressed as an annual dose limit.

Prior to the development of radionuclide slope factors, cancer risk from radiation exposure was traditionally estimated by multiplying the radiation dose, computed using the DCFs, by an estimate of the cancer risk per unit dose, which is averaged over all organs and tissues. The magnitude of discrepancy in the two methods depends on the particular radionuclide and exposure pathways for the site-specific conditions. These differences may be attributed to factors such as the consideration of competing mortality risks and age-dependent radiation risk models in the development of slope factors, different distribution of relative weights assigned to individual organ risks in the two methods, and differences in dosimetric and toxicological assumptions. A comparison between the bases of the two methods is summarized in Table 2.4 [26], [27].

Considering the foregoing evaluations, it should be recognised that there are uncertainties in the dose to risk relationship [17]. Therefore, risks should be calculated on the basis of best current information, using central values, with no bias towards conservatism or pessimism.

In assessing potential risks from implementing alternative options, differing views of the best current information may be taken into account when forming a preliminary view on the significance of the source term and should be examined in sensitivity analyses. Alternative views may in some cases lead to results that differ by orders of magnitude. However, a complete assessment of options would include, for example, assessment of the impacts of disposing of soil removed from a site as an element to balance against the reduction of risk on-site. Since the same views on radiation risks would apply to the assessment of all risks on- and off-site, the range of final decisions might not be so large.

2.5.4 The risk assessment process; preliminary investigation

A practical way forward in the assessment may be implemented based on a source, pathway, receptor approach [17]. This approach takes note that any harm arising from remaining contamination (the source), arises due to transfer (via various pathways) to those media including humans in which the harm may be expressed (receptors). It is consistent with the process of identification of hazards, the subsequent assessment of these hazards to estimate the risks and finally the evaluation of those risks. It also reflects a tiered approach to evaluation of the problem, so that the level of resources applied can be proportionate to the scale of the problem. If it reveals an unacceptable risk, the risk assessment process will feed into the options appraisal stage which then results in the implementation of a remediation strategy.

2.5.4.1 Establishing a preliminary view of the significance of the source term

This phase should begin with identification of the relevant contamination source term in terms of the activity levels of the main radionuclides, their physico-chemical forms, the size and activity of any particles present, and their spatial distribution over and under the land concerned, and an early view of the immediate near surface litho-stratigraphy of the site. This information will be available from site characterisation. The levels are then compared with those published for other purposes, in order to gain a preliminary view of the order of magnitude of potential committed effective doses to individual people. If doses seem likely to be of the order of microsievert then a simple assessment may be sufficient. If doses are of the order of hundreds of microsieverts or more, then much more detail will be needed.

It is also necessary in this phase to consider scientific uncertainties and stakeholder views. It would be unwise to conclude that levels of a particular radionuclide are of little significance, and to pay little attention to them in assessments, if recent evidence has called into question the scientific basis for the judgement of significance. Similarly, it is sensible to take into account stakeholder concerns about particular radionuclides, and particular physico-chemical forms of radionuclides, when judging source term significance and establishing an assessment methodology.

In addition, it should be noted that remediation work may result in a requirement to transport waste and to dispose of it elsewhere. This results in a need to consider the significance of a potentially wide range of issues marginal to the site being considered.

2.5.4.2 System description

In this phase, the features of the site and its environment should be defined. Relevant features should include soil type and land cover, surface and subsurface groundwater bodies, and the current land use. The amount of detail required will be influenced by the significance of the source term.

The system description needs to be understood sufficiently broadly to address all the environmental and human health risk endpoints of potential interest. Apart from radiation risks to exposed people, adequate emphasis should be given to protection of media.

2.5.4.3 Selection of exposure scenarios

In this phase scenarios should be developed, i.e. simple descriptions, for the evolution of the source term within the described system according to the assumed future land use associated with each option under evaluation. These descriptions should include:

- Controls over land use;
- Assumptions for land use;
- Processes likely to results in migration and accumulation of radionuclides;
- Processes likely to give rise to radiation exposure of people and non-human biota as a result of the presence, or migration and accumulation of radionuclides.

The concept of pollutant linkage from a source, via a pathway, to a receptor, applicable in the context of non radioactive contaminated land, has an equivalent approach in dealing with radioactively contaminated land. There can be a radiological impact from the contamination only if there is a source, pathway and receptor. The receptor will usually be a representative member of an exposed population receiving the highest dose, often termed the critical group. In reality pathways can be very complicated and may need to consider the impact of radioactive decay and in-growth of daughter radionuclides.

Modes of radiation exposure considered could include:

- Ingestion of radioactively contaminated materials, including dust, aerosols, soil, foodstuffs and drinking water;
- Inhalation of radioactively contaminated materials, including dust, aerosols and soil;
- External irradiation from contaminated soils and other materials; and
- Contact with contaminated materials.

As local people may be aware of local conditions, such possibilities should take into account local advice.

The key issue is to identify the more significant mechanisms by which people and other biota could come into contact with the more significant levels of radionuclides. Scenarios should include likely as well as unlikely events and processes.

In any remediation project, selecting appropriate current and future land use scenarios is a critical step in calculating clean-up levels [18]. Scenarios are descriptions of various lifestyles and activity patterns that approximate an individual's exposure to contaminants in environmental media. Conceptual site models display the exposure pathways inherent in a scenario and are useful tools to convey which pathways are reasonable and complete, i.e., capable of transferring harmful effects from radionuclides in surface soil to exposed individuals. By developing conceptual site models, it is possible to estimate representative modes of exposure for target populations, allowing those exposures to be quantified.

Depending on the regulatory framework, a reasonable maximum exposure of the average member of the critical group should be defined based on current land use as a starting point for establishing exposure scenarios. Alternative future land uses may be considered if they seem possible or likely based on available information and professional judgment. It should not be necessary to assume catastrophic events, but rather reasonable land uses and human activities and that the current physical characteristics (i.e., important surface features, soils, geology, hydrogeology, meteorology, and ecology) will exist at the site for the next 1,000 years

Generally, clean-up based on a residential scenario (suburban resident, rural resident, resident farmer, or rancher) will allow unrestricted use of a site. Choosing a less conservative scenario may invoke institutional controls and inherent long-term stewardship issues. The considerable difference in half-lives among various radionuclides is an important consideration in deciding whether long-term controls are feasible and therefore may affect exposure scenario selection.

2.5.4.4 Developing/selecting and applying assessment models and data

Mathematical models are used to approximate human and ecological exposure at a site [18]. The basic equations used to assess health effects due to radiological exposure are relatively straightforward and can be computed with a hand calculator or a spreadsheet. These equations generally sum the exposure from the ingestion, inhalation, and external irradiation pathways, each of which has an intake or source term, an exposure period, and either a dose conversion factor or a cancer slope factor. Modifying factors can be added, which adjust exposure periods and account for fate and transport of radionuclides in the environment. These factors may add considerably to the number of interacting terms and therefore to the complexity of the calculations.

The models are normally developed in stages, including a conceptual description, a mathematical representation of that description and the selection of data for the mathematical models [17]. In general, new models will not be required; rather, based on the output of previous phases and the choice of endpoints, models can be chosen from the literature. Furthermore, many models can be implemented on spreadsheets and do not require sophisticated techniques or software.

The assessment process typically involves some iteration. For example, suitable data may not be available for the initial choice of model, or some variant exposure pathway which is locally relevant may have been identified, and so a variation in the model may be appropriate. Any such developments should be transparently documented and justified. Preliminary results may be used to identify the more significant impacts and hence guide assessment iterations.

In the case of more significant contamination it may be appropriate to apply more sophisticated models, e.g. for the long-term migration of contamination through the ground. Several multimedia/multiple-pathway computer models have been developed to handle these more complex calculations [18]:

- RESRAD family of codes (DOE-Argonne National Laboratory);
- MEPAS (Multimedia Environmental Pollutant Assessment Systems)/-GENII/FRAMES/SUM3 set of codes (Pacific Northwest Laboratories);
- MMSOILS (EPA);
- DandD (NRC);
- Presto-EPA-CPG (EPA);
- PATHRAE-EPA (EPA).

Computer codes can be evaluated or compared through processes known as “benchmarking,” “verification,” and “validation.” Benchmarking compares the results from several different computer codes using the same set of problems. Verification is the procedure that tests for internal mathematical consistency and accuracy. Validation is the process that tests a mathematical model against actual field measurements.

Several criteria can be considered during the computer code selection process:

- Does the code incorporate key processes from the conceptual site model?
- Does the code satisfy study objectives?
- Has the code been verified using published analytical equations in scientific and technical journals?
- Has the code been validated against known site conditions?
- Does the code have the capability of inputting probabilistic analyses?
- Is the code well documented?
- Is the model available in the public domain?

While models are extensively used in risk assessment, the selection and interpretation of results need close examination. Relying excessively on models in the context of waste disposal and site contamination issues should be considered with care, taking into account that:

- Existing major differences between models may be due to differing objectives - where the capabilities of the models overlap, such differences may be due to the formulation of transport components.
- Spreadsheets (or pen-and-pencil calculations) are much more flexible than computer models. The effect of using a computer programme rather than a spreadsheet to implement the risk assessment may be that the assumptions that most need review are hidden where they are not accessible.
- Deterministic models are unable to account for uncertainties in input data and therefore yield outputs (such as contaminant concentrations, exposure doses and risks) of unknown reliability.
- The principle of parsimony should be used to differentiate between alternative operational models. This principle states that among all operational models that can be used to explain a given set of experimental data, this model should be selected that is conceptually least complex and involves the smallest number of unknown (fitting) parameters.
- Models are appropriate, often essential, tools for risk assessment and decision-making concerning clean-up and management of contaminated or potentially contaminated sites. However, it is inappropriate to use models as “black boxes” without tailoring them to site conditions and basing them firmly on-site data. Neither disregard of models nor overreliance on them is desirable.
- The environment constitutes a complex system that can be described neither with perfect accuracy nor with complete certainty. It is imperative that uncertainties in system conceptualisation and model parameters and inputs be properly assessed and translated into corresponding uncertainties in risk and decisions concerning risk management. The quantification of uncertainties requires a statistically meaningful amount of quality site data. Where sufficient site data are not obtainable, uncertainty must be assessed through a rigorous critical review and sensitivity analyses.
- Models and their applications must be transparent to avoid hidden assumptions. Model results must not be accepted at face value, because hidden assumptions are easily manipulated to achieve desired outcomes.
- Decisions concerning site disposition and risk management should account explicitly and realistically for lack of information and uncertainty.

- The monitoring of site conditions and contamination is an imperfect art. It is important that uncertainty associated with monitoring results be assessed a priori and factored explicitly into site remedial design and post-closure management.

2.5.4.5 Selecting input parameters

Many of the key parameters used in calculating clean-up levels are bounded within certain ranges once an exposure scenario is established. For example, typical exposure periods and breathing and ingestion rates for various scenarios have been determined for use in risk or dose calculations. In some cases, especially for sensitive parameters, distributions may be available and used in place of discrete values. Using distributions enables the entire range of possible values to be considered for a parameter and helps to account for the uncertainty and variability inherent in parameter selection. Relatively few input parameters used in computer codes or risk equations have significant influence on the resultant clean-up level. These include inhalation rate, dose conversion factors, soil ingestion rate, mass loading for inhalation, and others.

When assessing human exposure, input parameters should be selected so that the combination of all intake variables results in an estimate of the "reasonable maximum exposure" expected to occur at a site for a given scenario. Exposure is mainly addressed in terms of the "average member of the critical group," which means "the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances."

Behavioural parameters are generally determined, or at least bounded, by the selected exposure scenario. Physical parameters are determined by measurements at or near a particular site, if available. Site-specific values should always be used whenever possible. Differences in physical settings from site to site, or between site-specific and default values, account for some of the variations in calculated risk levels.

2.5.4.6 Selecting clean-up goals

In a risk assessment process, dose-based and/or risk-based values are calculated. In a subsequent risk management process, clean-up goals are established using calculated soil concentrations as a basis.

Various terms are used, sometimes interchangeably, to describe numbers that guide remedial actions at radioactively contaminated sites, such as "action levels," "ALARA goal levels," "allowable residual soil concentrations," "clean-up levels," "clean-up standards," "derived concentration guideline levels," "guideline concentrations," "remedial goal options," "remedial goals," "remediation levels," "risk-based concentrations," "soil clean-up concentrations," and "soil clean-up criteria." Clean-up levels from site to site, or even at a single site, cannot be compared without knowing their purpose, how they were derived, and how they will be applied.

An "*action level*" may refer to the existence of a contaminant concentration in the environment high enough to warrant action or trigger a response such as removal, treatment, containment, stabilization, or institutionally controlling exposure.

"*Derived concentration guideline levels*" may be examples of specific investigation levels derived by converting dose or risk from a release criterion into concentration or activity levels that are directly measurable.

"*Preliminary remediation goals*" may be the initial remedial guidelines usually developed early in the remediation phase to provide risk-reduction targets. Numerical "preliminary remediation goals" for radionuclides are typically based on the upper-bound carcinogenic risk of one in a million (10^{-6}). Until the final remedy is selected and documented, "preliminary remediation goals" constitute initial guidelines, not final cleanup goals.

"*Remediation goals*" may be media-specific clean-up goals for a selected remedial action. Numerical "remediation goals", which are part of the remedial action objectives, can be based on existing standards or on risk calculations. These two criteria are the "threshold criteria" for evaluating both remedial alternatives and remedial action objectives.

As risk-based "preliminary remediation goals" do not necessarily represent realistic exposure and risk, those numbers may not be appropriate clean-up levels. "Preliminary remediation goals" can be proportionally adjusted upward to become "remediation goals" using a level higher in the acceptable carcinogenic risk range to account for the conservatism inherent in the "preliminary remediation goals". Other factors related to technical limitations (e.g., detection or quantification limits) can also be applied. In addition, the "balancing criteria" and the "modifying criteria" for analysing remedial alternatives, such as cost and state and community acceptance, should also be considered. In some cases, "remediation goals" may be adjusted downward to account for multiple radionuclides or co-occurring non-radionuclide chemicals. Final "remediation goals" should be documented as radionuclide-specific "remediation levels" or as qualitative definition of the risk-reduction clean-up objective to be achieved for the non-numerical "remediation goals".

A specific approach for the implementation of remediation criteria has been discussed in Section 2.2.2.3, Definition of a remediation process, initial decision making, based on the form of the reference levels indicated in Table 2.1.

2.5.4.7 Application of clean-up goals

Once a clean-up level has been established, differences may still remain in how the value is applied. The application of a clean-up level, whether risk- or dose-based, should be tied in some way to characterisation data points. The location and density of these data points may be determined by a variety of characterisation sampling schemes:

- *Biased sampling* - locations where process knowledge, limited analytical data, visible staining, topography, vegetation, etc. suggest the possibility of contamination.
- *Standard statistical sampling* - a regular, systematic plot of locations on sites of little or no data; triangular grids and protocols for determining appropriate grid spacing may have to be recommended.
- *Geostatistical sampling* - an iterative process based on the remediation of a contaminated site to a required clean-up level at a specified level of confidence; sampling results are used to determine the optimal number and locations of samples to be collected in the next iteration, if necessary.

If multiple radionuclides are present in the environment, the sum-of-ratios (or sum-of-fractions) method should be used to account for the contribution of each single isotope towards the dose- or risk-based limit. Measured values of all radionuclides present should be compared to clean-up levels by dividing the measured value of each radionuclide by its respective clean-up level, then adding the ratios. If the sum of the individual ratios is greater than 1, then the limit is considered to be exceeded:

$$Sum-of-Ratios = \sum_j \frac{C_j \ (pCi/g)}{CG_j \ (pCi/g)} \leq 1$$

where:

C_j = soil concentration of radionuclide j,

CG_j = clean-up goal for radionuclide j.

Exceedances of clean-up levels may be determined by comparing those levels to aggregations of sampling data over specified areas of concern or exposure units. Clean-up criteria at most sites may also include hot-spot methodologies, which will require evaluation of small areas of elevated sample results within larger areas, which have been determined to require no further remedial action. These hot spot methodologies usually incorporate an area-weighted factor, which - when applied to clean-up levels - provides an upper limit on the amount of activity that can be left in these small isolated spots.

Setting more restrictive clean-up levels will necessarily lead to more clean-up at a higher cost, but for specific projects at some sites, those increased costs may be incrementally small or may reduce long-term stewardship costs.

2.5.4.8 Sensitivity analysis and risk management

In most cases a sensitivity analysis should be carried out to address variations in assumptions and parameter values, and perhaps models [17]. The analysis could be quantitative or semi-quantitative, and need not involve complex calculations. The aim should be to produce a range of results so that it can be seen whether the comparison of options has a different outcome if very different assumptions and parameter values are used in estimating risks.

2.5.5 Recommendations for practical application of modelling in a remediation process

As indicated before, the overall objective of modelling is to provide the basis for making well-founded decisions on possible contaminated sites and/or groundwater remedial actions. It is generally used to complement other decision making processes. Modelling can be used to develop and support [9]:

- Understanding of the role and behaviour of the hydrologic system;
- Understanding of the pathway(s);
- Assessment of contaminant transport and geochemical processes;
- Evaluation of health risks, with and without corrective actions;
- Evaluation of remediation techniques, including their effectiveness and cost benefits; and
- Evaluation and prediction of post remediation or long term results.

Figure 2.9 shows the general principles of model application to remedial analyses and design.

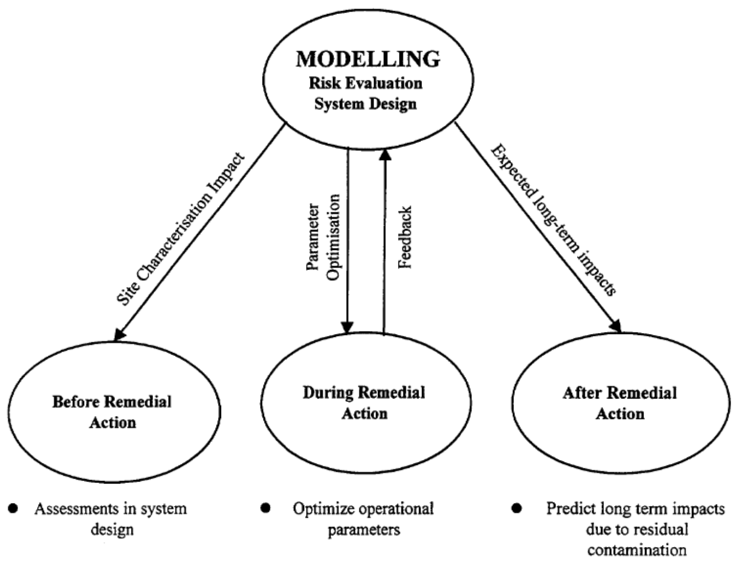

Figure 2.9 General principles of model application to remedial analysis and design

Modelling can also be used as a management tool to organise and prioritise data collection; to analyse results and make predictions; and to assist analysts in the improvement of their understanding of the factors controlling groundwater flow and contamination migration and transport.

An important application of modelling is to assess long-term transport and fate of contaminants in hydro-geological environment, and to predict concentrations of contaminants at exposure points, in order to evaluate health-risk bases for remedial actions. Once contaminant concentrations at receptors (i.e., in contact with the affected population) are assessed, the next step is to calculate doses/risks from exposure to contaminated water. This may be accomplished using relevant risk assessment methodologies, ranging in complexity from simple concentration-dose conversion factors to more sophisticated approaches.

Other applications include: evaluating the expected performance of remedial actions; elucidating the control of specific processes on groundwater systems and contaminant behaviour (sensitivity analysis); and the indirect estimation of hydro-geological and geochemical parameters using historical observation data.

2.5.5.1 Stepwise implementation of the modelling process

Modelling should be seen as an evolving, iterative process which reflects the development and understanding of the site, and is flexible enough to continuously incorporate new data. Modelling of a pathway may typically involve following steps:

- Clear definition of modelling objectives;
- Development of conceptual model(s) of the hydro-geological system;
- Compiling/assembling of hydro-geological and geochemical data (which may involve a simplified level of modelling, e.g. determination of hydraulic conductivity from aquifer pumping tests would typically involve ‘type curve’ matching);
- Formulation of mathematical model(s) of groundwater flow and contaminant transport processes;
- Selection or development of appropriate analytical/numerical model(s);
- Calibrating model(s) using field observations and data;
- Applying the model(s) in a predictive manner; and
- Comparing predictions against observations.

The above list implicitly assumes feedback loops, i.e., many of the steps have to be repeated as new information and data are collected.

The objectives of the modelling process should be clearly defined. They should reflect the ultimate goal of remediation, but may reflect intermediate goals as well.

A conceptual model is a hypothesis or representation as to how a system or process is estimated to operate. Before a meaningful model may be developed, a sufficient understanding of the site is required. The physical processes controlling groundwater flow and transport should be identified which will largely rely on professional judgment. Therefore, it is important that the analyst has a good understanding of the basic hydro-geologic, physical, and geochemical processes. The mathematical model should describe relationships between parameters and the governing processes. The selection of a numerical model should encompass both the conceptual model and the corresponding mathematical description of the system. The types of software used to embody the mathematical description generally reflect the objectives of the modelling, the available data, the experience of the modeller, and the available computational facilities. Relatively simple models may be used in the early or planning phase of remedial design. As more data become available through site characterisation, and a better understanding of the hydro-geological system is developed, more sophisticated, data intensive models may be utilized.

Parameters used in numerical models may be derived from a combination of site specific data, relevant published literature, historical information, and expert judgment. The predictive capacity of a model will depend on adequate input parameters. The general practice should be to refine estimates of uncertain parameters for the purpose of model calibration to match observed, actual data as they are obtained. Confidence should be built in the parameter estimates, to the degree possible, using data from laboratory and field studies. This empirical information is crucial for calibrating and refining the model and making it a useful tool for application in remediation system design and performance optimisation.

Advances in modelling techniques and computing power have resulted in sophisticated models and complex approaches to the evaluation of the pathway. Model assumptions, input parameters and modelling results should be systematically documented, both for quality assurance purposes and for clear presentation to decision makers and other interested parties.

2.5.5.2 Modelling techniques and approaches

The selection of the modelling approach to a given contamination problem should reflect both the objectives and the particular phase of the assessment and remediation process. Two general modelling approaches may be adopted:

- Analytical solutions; or
- Numerical solutions.

Analytical solutions are useful in the preliminary assessment of the hydro-geological system in the absence of significant amounts of data. The advantages of analytical solutions, i.e., solutions described by explicit analytical formulas, are simplicity and computational efficacy. The general shortcoming of analytical models is their simplistic representation of the hydro-geological system, e.g., rather simple assumptions of homogeneity of subsurface environment, steady state flow, one-dimensional transport, etc. may be used. Because of the screening application to which model predictions may be fit, and the fairly simple input data requirements, the analytical approach is often most suitable in the scoping phase of remedial assessment. There are two major types of numerical modelling methods: the finite difference method and the finite element method. Both methods are powerful modelling techniques, used to solve groundwater flow and contaminant transport problems in complex flow geometries. The finite difference method is more conceptually straightforward and physically based; however, the finite element method has proven to have greater flexibility in treatment of a complex geometry.

For modelling to be used with confidence in detailed assessment of remedial analysis requires significant quantities of site specific data. There are a number of methods used to model groundwater flow and contaminant transport. When interpreting the groundwater flow path, particle tracking methods are often used; these can give useful information concerning the travel time to receptors, i.e., the affected population, and the effectiveness of a hydraulic containment scheme. Advanced modelling approaches are based on combining solute transport codes with geochemical thermodynamic models for predicting the speciation of contaminants. However, this is still an area of active research and not really a well established modelling technique. Significant progress has been made in modelling of two and three dimensional saturated and unsaturated flow in porous and fractured geological media. More efficient numerical techniques and significant advances in computing power have opened up opportunities to increase the complexity of modelling; however, this complexity must be justified.

Off-the-shelf groundwater flow and contaminant transport software usually incorporate the processes of advection, diffusion, dispersion, equilibrium sorption, and radioactive decay. These may be steady-state or transient. Pertinent modelling areas of active research include the flow in fractured media; multiphase flow; multi-species flow with chemical interactions; kinetically limited sorption/de-sorption processes; colloidal transport and the facilitated transport of complexes. Assessment of these processes may require development of research-level models and software, and generally requires a high level of scientific expertise of the modeller.

2.5.5.3 Information requirements for modelling

Examples of information requirements for a conceptual model are [10]:

- *Source characteristics:*
  - Timing and duration of contamination;
  - Mechanisms of contamination: e.g., fallout from stack discharge, leaking drain, spillage during transport;
  - Physical, chemical and radiological properties of contaminants;
  - Vertical and lateral extent of source, including discussion of any barriers or preferential pathways;
- *Pathway characteristics (air, soil, and water):*
  - Pathway length (distance to receptor);
  - Pathway characteristics and processes (physical, chemical and biological) that will affect the rate of migration and contamination concentrations;
  - Temporal changes in the pathway;
  - Potential for transfer between environmental compartments, e.g., aqueous to sediment phases or surface soils to airborne dust;
  - Wind direction, velocity and dust loading;
  - Presence of burrowing animals;
  - Surface water flow patterns and distribution of sub-surface drainage systems;
  - Expected groundwater flow patterns and travel times to receptors (including rising groundwater);
  - Influence of artificial structures facilitating contamination migration, e.g., service trenches, drains;
  - Influence of artificial structures constraining contaminant migration, e.g., foundations as barriers;
- *Receptor characteristics:*
  - Humans, e.g., construction workers, site workers, on-site public, off-site public;
  - Specific ecological systems, both on-site and off-site;
  - Property in the form of crops, timber, domestic produce, livestock, other owned or domesticated animals, and wild animals that are subject to shooting or fishing rights both on-site and off-site;
  - Property in the form of buildings both on-site and off-site;
  - Controlled waters, e.g., surface waters, surface water abstractions, wetlands, groundwater abstractions, springs, groundwater within aquifers, estuaries and near shore environments.

2.5.5.4 Parameter uncertainties

Uncertainties are quite inherent in hydro-geological systems. They are present in the definition and nature of geological boundaries of the site, hydro-geological and geochemical parameters, and the spatial distribution of contaminants in the subsurface, etc. Parameter uncertainties may have profound impact on simulation results, and on remedial analysis as a whole. Therefore, uncertainties require a careful treatment in remedial modelling studies.

There are a number of approaches for dealing with uncertainty in hydro-geological analysis:

- Conservative approach;
- Deterministic simulation with sensitivity analysis; and
- Geo-statistic simulation.

A conservative approach attempts to set bounds on input model parameters, to establish bounds on output results, rather than realistically evaluate the behaviour of the simulated system. An example of this is the so called "worst case" scenario, in which the input parameters are assigned extreme values to estimate the maximum possible contaminant concentrations at receptors, i.e., exposure points for the affected population. Conservative analyses may be justified in the scoping phase of a remedial design. More caution is required in the detailed remedial assessment as unrealistically conservative impact assessment may result in unnecessarily high clean-up costs. Remedial assessments should utilise more sophisticated techniques that properly address the issues of uncertainty.

The deterministic approach uses a base-case simulation (model) with a set of “realistic” or “best guess” parametric values. This should be complemented by the application of sensitivity analyses in which the uncertainties in the input parameters can be accounted for in a systematic way. Sensitivity analyses may be used to determine which of the model parameters have the greatest impact on the performance of remedial actions. The results of a sensitivity study may be used to guide the site characterisation activities, including prioritisation of data collection.

Geo-statistical methods may embody the uncertainty in the input parameters in terms of probability distribution functions. These uncertainties can be propagated through the Monte Carlo technique. This approach requires a large number of models to be simulated from sampled input parameters. The results of Monte Carlo simulations provide confidence intervals for the possible outcomes of remediation. This can provide an estimate of the probability that a given remedial action meets the design targets.

2.5.5.5 Cost-benefit analysis and data worthiness

For choosing preferred (“best”) management alternatives for hydro-geological projects with due consideration for the various uncertainties, the decision of remediation alternatives should be based on economic analysis, taking into account the costs and benefits of each alternative, and associated risks [**Principle 1**]. The risk in this case is defined to be the probability of remedial design failure multiplied by the monetary consequences of failure. The probability of remedial design failure arises due to uncertainties in the expected performance of the remediation alternatives. In hydro-geological applications, such uncertainties and risks are often relatively high.

This cost-benefit methodology involves the coupling of three separate models: (1) a decision model based on a risk-cost-benefit objective function, (2) a hydro-geological simulation model, and (3) a parameter uncertainty model. This can be carried out in a Bayesian framework in which additional site characterisation data and remedial system performance data can be incorporated.

A feature of this methodology is the ability to assess the worthiness or adequacy of proposed site characterisation and data collection programmes prior to their actual implementation. The issue is of particular importance in view of the high costs of data collection at contaminated sites, which may not be cost-effective. The value of obtaining additional data (data worthiness or adequacy) may be assessed by comparing the cost of additional data collection versus the expected value of risk reduction that would be provided by the further effort.

The risk-cost-benefit analysis enables decision-makers to have a coherent picture of complex contaminated sites by integrating economical considerations, technical aspects and uncertain site conditions. It documents the reasoning behind remedial decisions, and may be an important tool for communication.

2.5.5.6 Limitations of modelling

Limitations of modelling are due particularly to the complexity of the hydro-geological environment and to a lack of understanding of important physical and chemical processes that may influence contaminant transport in the subsurface, e.g., transport by colloidal geochemical properties of natural rocks and soils which may result in preferential flow and transport processes. It is often impossible to characterise geological heterogeneity on a field scale with a degree of detail needed for adequate modelling.

In addition, long term predictions may be quite uncertain due to possible future changes in stresses on the hydro-geological system as a result of natural or anthropogenic factors, e.g., climate changes; changes induced by industrial activities; etc. Historical changes in the hydro-geological system are often not accurately known, which makes it difficult to obtain a reliable calibration of the model.

Modelling can be most effectively used if it is 'fit for purpose' or 'tailored to need'. In the early phases of site characterisation and remediation design evaluation, the models are generally simple and the expectation of their predictive capacity is low. As the conceptual model and parameters are further developed, confidence in the modelling results will improve. As a consequence, the uncertainties in the modelling can be better addressed and more properly estimated. The model assumptions and predictions need to be continuously checked and refined using observed results, i.e., actual data and measures of remedial system performance. It is desirable that model predictions are always accompanied by some indication of their reliability.

2.6 Health physics, safety, security, and environmental protection plan

This guidance deals with aspects of health physics and safety, security, and environmental protection on all types of radioactively contaminated sites, e.g., nuclear-licensed - nuclear power plants or NORM industry - sites, defense sites, etc.

One of the key aspects of health physics and safety, security, and environmental management on operational nuclear-licensed sites is that the site operator has clearly specified site procedures, which must be followed by all contractors as well as by employees of the licensee. These procedures should cover many issues of relevance to contaminated land investigations, such as excavation and waste management.

It should be noted that site procedures will differ from licensee to licensee, and may differ between sites operated by an individual license and should be depending on the complexity of the site license. It is essential that all parties understand the requirements of the site procedures before any work is undertaken.

For all nuclear-licensed sites, the operator retains ultimate responsibility for all health, safety and environment issues. Thus, it is to be expected that the licensee will manage contractors more closely than would be expected on a conventional contaminated site.

In contrast to nuclear-licensed sites, defense sites and some industrial sites have not always extensive site procedures relevant to the investigation of contaminated land. Defense procedures are more concerned with security and conventional safety. Industrial sites are mainly concerned with conventional safety and site access.

It should be noted that compliance with security procedures is a requirement for contractors and that compliance may have an effect on planned project programmes. Contractors may be permitted to work to their own safety procedures after they have been reviewed and approved by the defense staff.

2.6.1 Health physics and safety

Consistent with the approach for any operation, activities associated with the radiological surveys should be planned and monitored to assure the health and safety of the worker and other personnel, both on-site and off-site, are adequately protected. At the stage of determining the final status of the site, residual radioactivity is expected to be below the derived concentration guideline level (DCGL) values; therefore, the final status survey should in principle not include radiation protection controls. However, radiation protection controls may be necessary when performing scoping or characterization surveys where the potential for significant levels of residual radioactivity is unknown.

2.6.1.1 European Community, national and international legislation relevant to site investigation on radioactively contaminated sites

It is advised to check key safety legislation for health and safety management. In Table 2.5 key terms are given as guidance, as in most countries these topics may be treated under different legalisations.

Table 2.5 Key terms relevant to site investigations on contaminated land

Management: • Management of health and safety at work; • Working time regulations; • Health and safety (first-aid); • Reporting of injuries, diseases and dangerous occurrences.
Working environment: • Workplace (health, safety and welfare); • Provision and use of work equipment; • Fire; • Lifting operations and lifting equipment; • Provision and use of personal protective equipment; • Health and safety (e.g., safety signs and signals);
Construction: • Construction (design and management); • Construction (head protection).
Hazards: • Control of substances hazardous to health; • Ionising radiation; • Electricity at work; • Manual handling operations; • Control of noise at work; • Control of asbestos; • Control of heavy metals, e.g. lead, at work.

2.6.1.2 Health and safety management arrangements

The overall safety principle should be to provide competent and trained employees working under a safe system carried out in a safe place of work with safe plant and materials. These principles are featured in the common law “duty of care” and in occupational health and safety laws. The safety management arrangements provide the basis for the working procedures and for the work activities.

Workers involved with site remediation may be exposed to conventional construction and operations hazards as well as to hazards coming from radioactive materials, toxic metals, organic compounds or bio-hazardous agents, respirable fibres, flammable and combustible materials, corrosive and reactive chemicals, and explosives.

Remediating a contaminated site requires a thorough and disciplined approach to evaluating the potential hazards to site workers, and taking the necessary steps to perform the work in a safe manner. A hazard and operability study (HAZOP) may be required to identify and evaluate the hazards. The results of the safety analyses should be incorporated into a site health and safety plan, along with remediation work plans and procedures and controls. Safety measures resulting from these safety analysis and findings should be made in compliance with the ALARA principle and optimal measures should be put into practice. As new hazards are identified at the site, they should be incorporated into an update of the assessment.

The possible elements of a health and safety plan may involve:

- Establishment of a proper organisation;
- Training;
- Hazard characterisation and exposure assessment;
- Site access and hazard controls;
- Site and worker monitoring and medical surveillance schedules;
- Decontamination (personnel and equipment);
- Arrangements for monitoring of compliance;
- Communications;
- Welfare requirements;
- Emergency action plan, including first-aid facilities;
- Emergency response.

It is advised to update the health, security and safety plan regularly and that a health, security and safety file should be produced and maintained for the duration of the project. This document should include:

- Workplace authorisations (e.g., acknowledgement that workers have read and understood relevant safety procedures and instructions and method statements);
- Training records (to demonstrate that all staff are suitably qualified and experienced personnel and have attended all required site-specific training/induction courses);
- All permits (e.g., permits-to-operate, permits-to-work, excavation permits);
- All personal protective equipment (PPE)/respiratory protective equipment (RPE) service records;
- All radiation and contamination survey records and clearance certificates;
- Site diaries;
- All documentation relating to disposal of wastes (e.g., duty of care notices);
- Records of any permanent changes to land or buildings as a result of the work;
- Adequate monitoring of the system by the management.

2.6.1.3 Establishment of a proper organisation

Establishment of a multidisciplinary team is a first step required to plan, organise, evaluate and conduct a remediation plan. The team should include health and safety specialists with expertise in more than just radiation protection; for example, specialists who can also assess chemical and biological hazards and develop safety procedures accordingly. The organisation typically would also include a health and safety officer who has the responsibility for maintaining the health and safety of the site [7].

The organisation responsible for implementing the remediation activities should have, or should have access to, competent staff to cover the following areas adequately [3], [7]:

- Project management;
- Safety requirements of any permits or authorisations issued;
- Regulatory standards and issues;
- Radiation protection;
- Conventional industrial hazards;
- Data collection and evaluation;
- Environmental monitoring;
- Quality assurance and quality control;
- Radiochemical analysis;
- Geological and hydro-geological expertise;
- Waste management;
- Site security;
- Equipment operators;
- Labour force.

Information should be provided to all interested parties concerning the future implementation of the remediation programme, including: identification of the organisations responsible for implementing the programme; the provision of adequate human resources, equipment and supporting infrastructure; the organisation and allocation of the required funding; the programme for waste management; the safety and health protection protocols for the remediation workers and the public; and the arrangements for pre- and post-remediation monitoring procedures for assessing the efficiency and effectiveness of the remediation programme.

2.6.1.4 Training

Because of its complexity, workers on a remedial action need a wide range of skills and experience. Labourers should be able to critically analyse the situation for both individual safety and the general success of the operation. Equipment operators should be empowered to make decisions about the depth of excavation, etc. Supervising staff should be able to modify the plan according to changing conditions (e.g., weather). Project designers and managers should be able to prepare a holistic approach to the problem, including technical, legal, economic and natural science issues. They also need to determine the education level required from their staff [3].

All persons involved in the remediation should be made familiar with the contaminated area, the hazards and the safety procedures for the safe and effective performance of their duties. Training of personal protective equipment (PPE) proper use must be conducted prior starting of remediation actions of workers. Specialised training may be needed in certain areas of work with the workers certified in both radiological and non-radiological hazardous worker safety. For some activities, the use of mock-ups and models in training can enhance efficiency and safety [7].

The requirements for a basic training programme and for refresher training should be stated in the remediation plan.

The remediation organisation should anticipate possibilities in their plans to revise their health and safety planning in the light of new discoveries. Such ‘contingency’ planning allows a more efficient adaptation to necessary changes in the health and safety approach.

2.6.1.5 Hazard characterisation and exposure assessment

The remediation team typically should conduct a thorough safety analysis to assess potential impacts on site workers (and the public) such as a nuclear safety assessment and a criticality assessment, as well as evaluating the hazards associated with radioactive constituents. In addition, the team should assess exposure scenarios and pathways associated with non-radiological contaminants, such as biological contaminants, chemical contaminants and explosives. The results of the safety analysis should then be incorporated into the site health and safety plan, along with remediation work plans and procedures. As new hazards are identified at the site, they become incorporated into an update of the assessment [7].

2.6.1.6 Site access and hazards controls

An additional component of protecting worker health and safety during the conduct of remediation should be accomplished through the application of a hierarchy of access and hazard control methods. The first option to consider in implementing control of worker access to hazards should be the use of engineering controls to remove or isolate the hazard (e.g., defining a support zone, contamination reduction zone, exclusion zone and control room). The next option should be the use of administrative controls, and finally, protected environments, personal protective equipment and respiratory protective equipment, personal protective equipment may be used as a supplement to the two preferred methods. Different levels of personal protective equipment may be required, beyond dealing with only the radiological component. For example, respiratory protection with specialised filters (e.g., designed to filter out certain toxic organic compounds) may be required [7].

2.6.1.7 Protected environments

When it is decided after a careful consideration to implement an enclosing of the contaminated area to control the exposure of humans and the wider environment, depending on the length of time of the investigation, this may be a semi-permanent building or a tented enclosure.

Consideration of what to do in extreme weather events and at decommissioning of the facility should be taken into account at the planning stage. Further control of the internal environment may be required, by the use of negative pressures. This may extend to creating a negative pressure within the tent to contain contamination, and protecting workers with air-line suits.

2.6.1.8 Protective clothing

Before the start of the project, suitable protective clothing should be selected. Influencing factors on the selection will include the following:

- Full range of hazards and level of protection required;
- Compatibility with other personal protective equipment;
- Availability, storage and maintenance arrangements;
- Cost (e.g., use of disposable items);
- Working environment (dry, wet, muddy, etc);
- Number of workers;
- Project duration.

Typical protective clothing for site characterisation projects (non-radioactively contaminated sites) is shown in Table 2.6. Most of the protective clothing is also suitable for radioactively contaminated sites. It is best practice (and commonly a requirement on nuclear-licensed sites) that separate protective clothing is used for designated and non-designated areas.

Typically, the two sets of protective clothing are distinguished by colour-coding or other marking. Durable personal protective equipment should be carefully looked after and its working life maximised without prejudicing personal safety. Damaged, redundant or discarded personal protective equipment will be treated as waste and this should be factored into the waste management plan.

For areas with known or suspected radioactive contamination, a risk assessment by a suitably qualified and experienced person, such as a radiation protection officer, or a group should be undertaken. This assessment should indicate the actions that are required to ensure protection of the workers through the provision of operational procedures (local instructions) and, potentially, personal protective equipment and respiratory protective equipment (RPE) if appropriate. In general terms it is likely that the requirements necessary for ensuring protection against chemical contamination will also provide protection against radiological contamination. However, it may be that disposable oversuits and boots may be of benefit for contamination control. Personal dosimetry may be required and this could therefore include the requirement to record exposures with an Approved Dosimetry Service. In particular cases health physics support may be appropriate to ensure the radiological protection of workers during specific operations. It is important, where mixed radiological and non-radiological contamination exists, that a holistic approach is taken to ensure the protection of workers.

Table 2.6 Examples of protective clothing and equipment, monitoring equipment and safety procedures that could be applied in characterization projects on contaminated sites

Contamination type	Protective clothing and equipment	Monitoring equipment	Safety procedures
Non-radioactive contamination	Overalls Safety boots Appropriate gloves Tested hard hats Eye protection Face masks and filters Breathing apparatus Safety harness and lanyards Life jackets Safety torches Fire extinguishers First aid equipment Mobile phone (where allowed)	Hand-held gas monitors Automatic gas detectors Personal monitors Environmental monitoring equipment Cable avoidance tool	Training Permit to work systems Notification of emergency services Access to telephone contact Decontamination facilities for plant Decontamination facilities for personnel Safe sampling procedures Safe sample handling procedures Access for emergency vehicles

2.6.1.9 Respiratory protective equipment

Before any respiratory protective equipment is used, an exposure assessment should be carried out. A number of assessments may be needed in projects that are of long duration, or where the nature and/or execution of work changes. All individuals wearing respiratory protective equipment should receive suitable training in its use and they should be aware of its limitations. When not in use, the respiratory protective equipment should be kept in clean, secure and dry storage conditions and it should always be kept fully serviceable (clean, no broken straps, etc). Respiratory protective equipment must be regularly inspected and tested by qualified personnel, and records kept. The selection and use of respiratory protective equipment can be regulated by national legalisation.

2.6.1.10 Site and worker monitoring

The extent of monitoring programmes should be determined on the basis of the activities that will be performed during the remediation and the degree of uncertainty concerning the performance of these activities, and should be consistent with longer term monitoring programmes set up to verify the long term stability of exposure conditions (e.g., by monitoring the covering of mining residues, protection against the infiltration of water and protection against erosion or atmospheric dispersion) [12]. There should also be a medical surveillance programme for site workers in order to minimise adverse health effects on the workforce. The medical surveillance programme would need to be broad enough to anticipate potential exposure to contaminants other than just radiological hazards [7].

2.6.1.11 Worker and equipment decontamination

Worker and equipment decontamination programmes are critical to expedite entry of workers, minimise the generation of costly hazardous wastes and minimise equipment replacement. Before work can begin, contamination control and decontamination programmes for workers and equipment should be documented in the health and safety plan, communicated to site workers and implemented in areas where there is a possibility for exposure to chemical, biological or radiological hazards [7].

2.6.1.12 Emergency preparedness and response

A programme for emergency planning that is applicable for remediation activities should be established and described in the remediation plan. Operating organisations should ensure that procedures for dealing with unforeseen events that may occur during remediation are prepared and put into place. Personnel should be trained in emergency procedures. Provision should be made for the periodic testing and updating of these procedures by conducting periodic exercises. In the event of an unforeseen incident happening during remediation, the responsible parties should without delay notify the regulatory body [12].

The emergency preparedness and response plan should address potential uncontrolled hazardous substance releases causing a potential health, safety or environmental hazard, i.e., one that cannot be mitigated by personnel in the immediate work areas where the release occurs. For example, a fire at the site may come into contact with, and volatilise, certain chemical contaminants that could be released into the air.

Such a plan can include the following items [7]:

- Hazard evaluation;
- Emergency action plan (including evacuation plan);
- Emergency response plan;
- Emergency response organisation;
- Emergency equipment and personal protective equipment;
- Emergency training;
- Medical surveillance;
- Emergency medical treatment, transport and first aid arrangements.

2.6.2 Security

In most countries special security regulations exist that require security plans for certain industries, e.g., biological industry, nuclear industry. In general these plans and arrangements have to be approved by the regulator. This means that for sites of concern these regulations have to be followed and implemented during temporary building works and actions as needed by a remediation program. Compliance with security clearance of all staff, including key sub-contractors, is expected, as a minimum, on these sites.

The level of clearance required will be commensurate with activities, and should be confirmed with the site. In addition, each site will have its own security access arrangements which should be established at the earliest opportunity prior to the planning stage. Special arrangements, for example, may need to be made for courier deliveries and collections. Inevitably the need to comply with security has budget and time implications for the project.

2.6.3 Environmental protection

2.6.3.1 Environmental protection compliance

Participants in a site remediation program will be expected to comply, as a minimum, with the environmental legislation, regulations at all places of work and other guidelines specified in any scope of work. Owners and operators of nuclear-licensed sites and defense sites are large organisations, and can be expected to hold, or have management systems designed to meet, the requirements of ISO 14001 [52].

Such organisations will also be committed to continuous improvement programmes, and it may be expected that these organisations will require their consultants and subcontractors to meet specified requirements of environmental management competency. The adherence of suppliers to these requirements should also ensure:

- Compliance with corporate environmental policies;
- Minimisation of liabilities (i.e., not to exacerbate risk from any existing contamination or create new contamination or impacts);
- Maintenance of integrated compliance with health, safety, security and environmental aspects;
- Management of stakeholder involvement.

2.6.3.2 Operation and control of environmental protection

When producing specifications or evaluating tenders for site remediation works, site owners and occupiers (who are typically also the client) should ensure that the works comply with the requirements of the site’s environmental policy and environmental management system. In demonstrating that this is the case, consultants and subcontractors should ensure that their own assessments are site specific and activity specific. Effective communication and flow of information between the client/liability holder and consultant/contractor is necessary to demonstrate that the environmental protection systems of the two parties are compatible.

Guidance on compliance with an environmental management system is given in the ISO:14000 series [52]. The key principles are listed below:

- Minimise the direct and indirect adverse environmental effects of a site remediation programme. This should be demonstrated by provision of a safety, health and environment plan for performance of the work (not to be confused with a health and safety plan that may be required by the construction - design and management - regulations).
- Every individual should be suitably qualified, trained and experienced to carry out their work and to understand their responsibility for the environmental effects of their activities.
- Managers at all levels should understand their responsibilities for the environmental effects of the activities of the employees, contractors and visitors under their control.
- All staff should know the environmental objectives and targets relevant to their work, and assume personal responsibility for the environmental effects of their actions.
- Equipment and facilities used for site characterisation work should be appropriate for the job, adequately maintained and operated to a suitable system of work. This will minimise, as far as reasonably practicable, direct environmental effects.

- All staff should know the procedures for reporting accidents and emergencies that have environmental implications, and the actions to be taken to minimize the effects of an accident.
- Participation in audits, monitoring and review activities to check compliance with environmental legislation and management systems may be expected.

Identification and evaluation of potentially significant environmental effects will be undertaken in a risk assessment specific to a site remediation activity. Such an assessment is likely to include consideration of the environmental aspects summarised in Table 2.7. An example of an environmental protection checklist is given in 0.

Table 2.7 Some aspects of environmental protection appropriate to remediation activities

Aspect description	Example of activity or process	Mitigation
Waste management	Spoil generation and disposal	Minimisation by choice of technique Control of contaminated drilling returns
Water use	Water flush drilling	Avoid use
Materials storage and handling, including hazardous materials	Fuel storage	Store drums on appropriately sized bunded trays
Air quality	Emission from generators	Fit exhaust filters
Noise and vibration	Use of heavy plant	Refer to code of practice BS5228 - Noise control on construction and other open sites
Effluent including sewerage	Purged borehole water	Collection and disposal via authorised route
Contaminated land	Interconnection of aquifers due to poor borehole design	Borehole design to be approved by regulator
Ecology	Disturbed flora	Careful re-instatement of exaction locations
Odours	Equipment emissions	Site equipment so as to minimise impact, out of hours working
Transport	Vehicle movements and their emissions	Where appropriate ride a bicycle or electrical powered around site

2.6.4 Summary

The preparation of a health physics and safety, security, and environment (HSSE) plan and its approval will be required before any on-site works can commence. The plan will cover but not be limited to:

- Arrangements to ensure the health and safety of all workers (including hazard assessment, hazard evaluation and proposed control measures if required);
- Management and standards;
- Selection of sub-contractors;
- Emergency procedures;
- Accident reporting procedures;
- Arrangements for monitoring of compliance;
- Welfare requirements;
- Communications, co-operation and training arrangements;
- Security procedures;
- Environmental issues;
- Environmental impacts register, which identifies the potential environmental impacts that activities will have. The register should cross-refer to project specific method

statements, in which consideration will have been given to environmental aspects, and to the relevant environmental policies of the client and contractor;

- Environmental mitigation, monitoring and control measures.

2.7 Site characterisation

Site characterisation is needed to provide sufficient data to take early strategic decisions on the likely environmental remediation activities [3]. An environmental baseline and a profile of the contamination should consider the following aspects:

- Characteristics, distribution, and extent of radioactive constituents or contamination sources, as well as the potential for future releases of constituents;
- Risks associated with exposure of humans and the environment to the radioactive constituents, and
- Where appropriate, transport of radioactive constituents in groundwater and hydraulically-connected surface water, as well as any other pathways which may lead to exposure of workers and the population.

The source characterisation should include both waste characterisation and facility or site characterisation, and should provide reliable estimates of the release rates of radioactive constituents as well as constituent distribution. For rural zones, the transport of the constituents from the soil into the vegetation should also be measured or estimated.

2.7.1 Major factors in the radiological characterisation of sites and/or groundwaters

The level of effort associated with planning of the activities for site characterisation should be based on the complexity of the survey. Large, complicated sites generally should receive a significant amount of effort during the planning phase, while smaller sites may not require as much planning effort [2].

Planning radiological surveys using the Data Quality Objectives Process should result in improving the survey effectiveness and efficiency, and thereby the defensibility of decisions. It should also minimise expenditures related to data collection by eliminating unnecessary, duplicative, or overly precise data. The use of the Data Quality Objectives Process should assure that the type, quantity, and quality of environmental data used in the decision making will be appropriate for the intended application. It should provide systematic procedures for defining the criteria that the survey design should satisfy, including when and where to perform measurements, the level of decision errors for the survey, and how many measurements to perform.

2.7.2 Site characterisation data quality objectives

The site characterization Data Quality Objectives Process should provide for early involvement of stakeholders and use a graded approach to data quality requirements. This graded approach should define the data quality requirements according to the type of survey being designed, the risk of making a decision error based on the data collected, and the consequences of making such an error. The approach should also provide a more effective survey design combined with a basis for judging the usability of the data collected.

Data Quality Objectives are qualitative and quantitative statements derived from the outputs of the Data Quality Objectives Process that should enable:

- To clarify the study objective, e.g., define the boundary of the site to investigate;
- To define the most appropriate type of data to collect, e.g., radiological and/or non-radiological data;
- To determine the most appropriate conditions for collecting the data;

- To specify limits on decision errors which will be used as the basis for establishing the quantity and quality of data needed to support the decision.

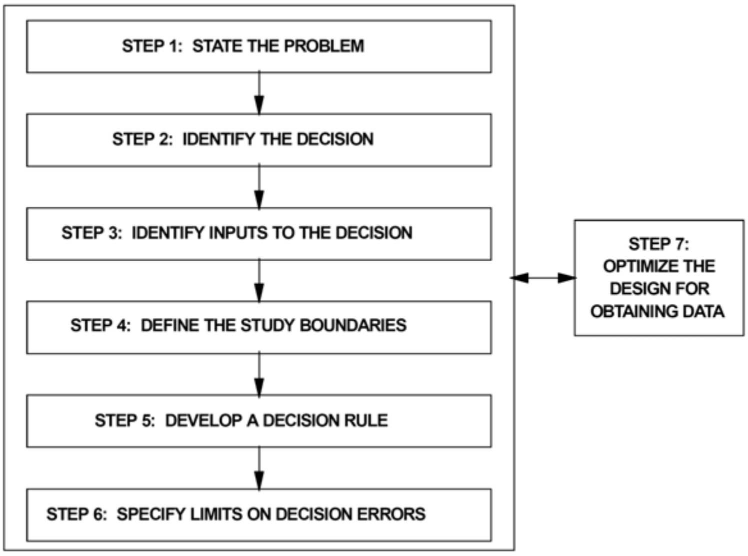

Figure 2.10 The data quality objectives process

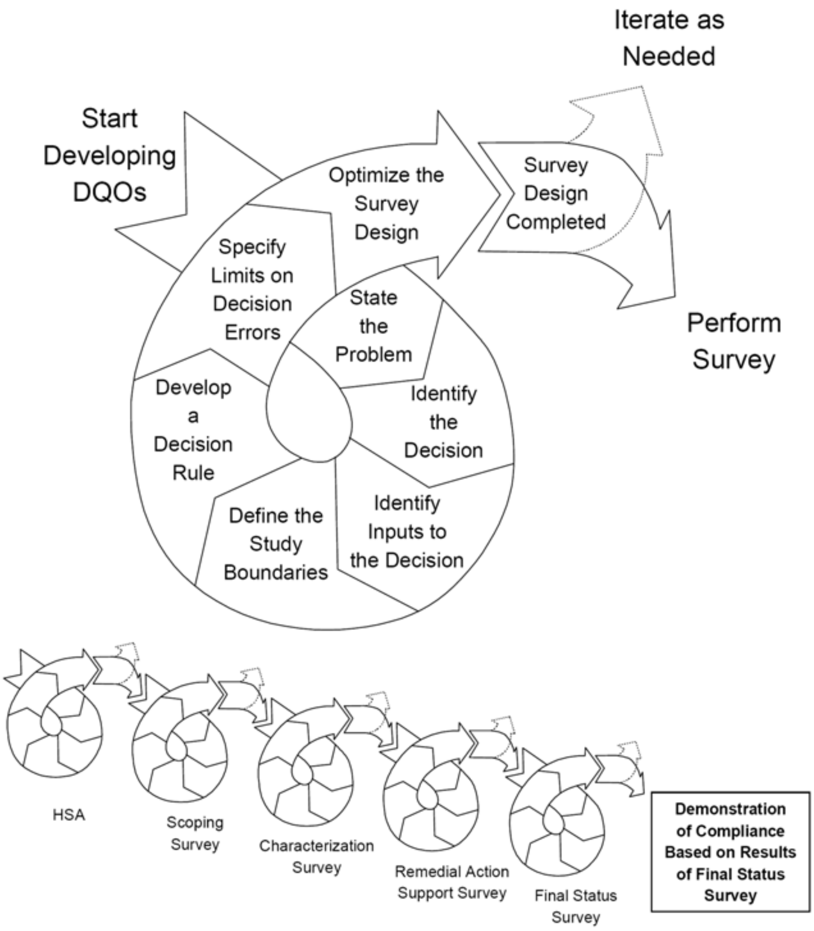

Figure 2.11 Repeated applications of the Data Quality Objectives Process throughout the radiation survey and site investigation process

The Data Quality Objectives Process may consist of seven steps, as shown in Figure 2.10. The output from each step may influence the choices that will be made later in the process. Even though the Data Quality Objectives Process is depicted as a linear sequence of steps, in practice it is iterative; the outputs of one step may lead to reconsideration of prior steps as illustrated in Figure 2.11. For example, defining the survey unit boundaries may lead to classification of the survey unit, with each area or survey unit having a different decision statement. This iteration is encouraged since it ultimately may lead to a more efficient survey design. The first six steps of the Data Quality Objectives Process should produce the decision performance criteria that are will be used to develop the survey design. The final step of the process should develop a survey design based on the Data Quality Objectives. The first six steps should be completed before the final survey design is developed, and every step should be completed before data collection begins.

Data Quality Objectives for data collection activities should describe the overall level of uncertainty that the decision-maker is willing to accept for survey results. This uncertainty should be used to specify the quality of the measurement data required in terms of objectives for precision, accuracy, representativeness, comparability, and completeness.

The Data Quality Objectives Process should remain flexible considering the requirements of each specific situation. For surveys that have multiple decisions, such as characterisation or final status surveys, the Data Quality Objectives Process may be used repeatedly throughout the performance of the survey. Decisions made early in decommissioning are often preliminary in nature. For this reason, a scoping survey may only require a limited planning and evaluation effort. As the site investigation process nears conclusion the necessity of avoiding a decision error becomes more critical.

Depending on the definition of the problem, it should not be absolutely necessary that each step or each activity in a step will be implemented in a consecutive way in each process. This means that, on a case-by-case basis, it may be decided that specific steps or specific activities in a step may not be executed.

The steps within the Data Quality Objectives Process are briefly discussed in the next paragraphs, especially as they relate to final status survey planning, and list the outputs for each step in the process. The outputs from the Data Quality Objectives Process should be included in the documentation for the survey plan.

2.7.2.1 Step 1: State the problem

Any decision making process requires the problem to be defined so that the focus of the survey will be unambiguous. Since many sites or facilities may present a complex interaction of technical, economic, social, and political factors, the success of a project is critically linked to a complete but uncomplicated definition of the problem.

Four activities may be associated with this step:

- Identifying members of the planning team and stakeholders;
- Identifying the primary decision-maker or decision-making method;
- Developing a concise description of the problem;
- Specifying available resources and relevant deadlines for the study.

The expected outputs of this step should be:

- A list of the planning team members and identification of the decision-maker;
- A concise description of the problem, which would typically involve the release of all or some portion of the site to demonstrate compliance with the regulation;
- A summary of available resources and relevant deadlines for the survey which are typically identified on a site-specific basis.

2.7.2.2 Step 2: Identify the decision

The goal of this step should be to define the question that the survey should attempt to resolve and identify alternative actions that may be taken based on the outcome of the survey. The combination of these two elements is called the decision statement. The decision statement would be different for each type of survey in the radiation survey and site investigation process, and would be developed based on the objectives of the survey.

Four activities should be associated with this step in the Data Quality Objectives Process:

- Identifying the principal study question;
- Defining the alternative actions that could result from a resolution of the principal study question;
- Combining the principal study question and the alternative actions into a decision statement;
- Organising multiple decisions.

The expected output from this step should be a decision statement that links the principal study question to possible solutions to the problem.

For a final status survey, the principal study question could be whether the level of residual radioactivity in the survey units in a portion of the site is below the release criterion. Alternative actions may include further remediation, re-evaluation of the modelling assumptions used to develop the derived concentration guideline levels (DCGL), re-assessment of the survey unit to see if it can be released with passive controls, or a decision not to release the survey unit. The decision statement may also determine whether or not all the survey units in a portion of the site satisfy the release criterion.

2.7.2.3 Step 3: Identify the inputs to the decision

Collecting data or information is necessary to resolve most decision statements. In this step, the planning team should focus on the information needed for the decision and identify the different types of information needed to resolve the decision statement.

The key activities for this step should include:

- Identifying the information required to resolve the decision statement; asking general questions such as whether information on the physical properties of the site is required, or whether information on the chemical characteristics of the radionuclide or the matrix is required; determining which environmental variables or other information are needed to resolve the decision statement.
- Determining the sources for each item of information; identifying and listing the sources for the required information.
- Identifying the information needed to establish the action level or the derived concentration guideline level based on the release criterion (the actual numerical value should be determined in Step 5).
- Confirming that appropriate measurement methods exist to provide the necessary data; preparing a list of potentially appropriate measurement techniques based on the information requirements determined previously in this step.

The expected outputs of this step should be:

- A list of informational inputs needed to resolve the decision statement;
- A list of environmental variables or characteristics that will be measured.

For the final status survey, the list of information inputs generally should involve measurements of the radioactive contaminants of concern in each survey unit. These inputs should include identifying survey units, classifying survey units, identifying appropriate measurement techniques including measurement costs and detection limits, and whether or not background measurements from a reference area or areas need to be performed. The list of environmental variables measured during the final status survey should typically be limited to the level of residual radioactivity in the affected media for each survey unit.

2.7.2.4 Step 4: Define the boundaries of the study

During this step, the planning team should develop a conceptual model of the site based on existing information collected in Step 1 of the Data Quality Objectives Process or during previous surveys. Conceptual models describe a site or facility and its environs, and present hypotheses regarding the radio-nuclides present and potential migration pathways. These models may include components from computer models, analytical models, graphic models, and other techniques. Additional data collected during decommissioning should be used to expand the conceptual model.

The purpose of this step should be to define the spatial and temporal boundaries that will be covered by the decision statement so that data can be easily interpreted. These attributes should include:

- Spatial boundaries that define the physical area under consideration for release (site boundaries);
- Spatial boundaries that define the physical area to be studied and locations where measurements could be performed (actual or potential survey unit boundaries);
- Temporal boundaries that describe the time frame the study data represents and when measurements should be performed;
- Spatial and temporal boundaries developed from modelling used to determine the derived concentration guideline levels.

There should be seven activities associated with this step:

- Specifying characteristics that define the true but unknown value of the parameter of interest;
- Defining the geographic area within which all decisions must apply;
- When appropriate, dividing the site into areas or survey units that have relatively homogeneous characteristics;
- Determining the time frame to which the decision applies;
- Determining when to collect data;
- Defining the scale of decision making;
- Identifying any practical constraints on data collection.

The expected outputs of this step should be:

- A detailed description of the spatial and temporal boundaries of the problem (a conceptual model);
- Any practical constraints that may interfere with the full implementation of the survey design.

Specifying the characteristics that define the true but unknown value of the parameter of interest for the final status survey typically should involve identifying the radio-nuclides of concern. If possible, the physical and chemical form of the radio-nuclides should be described. For example, describing the residual radioactivity in terms of total uranium is not as specific or informative as describing a mixture of uraninite (UO_2) and uranium metaphosphate ($U(PO_3)_4$) for natural abundances of ^{234}U, ^{235}U, and ^{238}U.

As an example, the study boundary may be defined as the property boundary of a facility or, if there is only surface contamination expected at the site, the soil within the property boundary to a depth of 15 cm. When appropriate (typically during and always before final status survey design), the site should be subdivided into survey units with relatively homogeneous characteristics based on information collected during previous surveys.

The time frame to which the final status survey decision applies is typically defined by the regulation. Temporal boundaries may also include seasonal conditions such as winter snow cover or summer drought that affect the accessibility of certain media for measurement.

For the final status survey, the smallest, most appropriate subsets of the site for which decisions will be made should be defined as survey units. The size of the survey unit and the measurement frequency within a survey unit should be based on classification, site-specific conditions, and relevant decisions used during modelling to determine the derived concentration guideline levels.

2.7.2.5 Step 5: Develop a decision rule

The purpose of this step should be to define the parameter of interest, specify the action level (or derived concentration guideline level), and integrate previous Data Quality Objectives outputs of the data quality requirements process into a single statement that describes a logical basis for choosing among alternative actions.

Three activities should be associated with this step:

- Specifying the statistical parameter that characterises the parameter of interest;
- Specifying the action level for the study;
- Combining the outputs of the previous Data Quality Objectives Process steps into an “if...then..." decision rule that defines the conditions that would cause the decision-maker to choose among alternative actions.

Certain aspects of the site investigation process, such as historical site assessments, may not be so quantitative that a statistical parameter can be specified. Nevertheless, a decision rule should still be developed that defines the conditions that would cause the decision-maker to choose among alternatives.

The expected outputs of this step should be:

- The parameter of interest that characterises the level of residual radioactivity;
- The action level;
- An “if...then...” statement that defines the conditions that would cause the decision-maker to choose among alternative actions.

The parameter of interest should be a descriptive measure (such as a mean or median) that specifies the characteristic or attribute that the decision-maker would like to know about the residual contamination in the survey unit.

The action level should be a measurement threshold value of the parameter of interest that provides the criterion for choosing among alternative actions.

The mean concentration of residual radioactivity may be the parameter of interest used for making decisions based on the final status survey. The definition of residual radioactivity will depend on whether or not the contaminant appears as part of background radioactivity in the reference area. If the radionuclide is not present in background, residual radioactivity should be defined as the mean concentration in the survey unit. If the radionuclide is present in background, residual radioactivity should be defined as the difference between the mean concentration in the survey unit and the mean concentration in the reference area selected to represent background.

A decision rule may state that, if the mean concentration in the survey unit is less than the investigation level, then the survey unit is in compliance with the release criterion. To implement the decision rule, an estimate of the mean concentration in the survey unit will be required. An estimate of the mean of the survey unit distribution may be obtained by measuring radionuclide concentrations in soil at a set of randomly selected locations in the survey unit. A point estimate for the survey unit mean may be obtained by calculating the simple arithmetic average of the measurements. Due to measurement variability, there might be a distribution of possible values for the point estimate for the survey unit mean, however. In this case, statistical decision rules should be used to assist the decision-maker.

2.7.2.6 Step 6: Specify limits on decision errors

Decisions based on survey results may often be reduced to a choice between “yes” or “no”, such as determining whether or not a survey unit meets the release criterion. When viewed in this way, two types of incorrect decisions, or decision errors, may be identified:

1. Incorrectly deciding that the answer is “yes” when the true answer is “no”; and
2. Incorrectly deciding the answer is “no” when the true answer is “yes”.

The distinctions between these two types of errors are important for two reasons:

1. The consequences of making one type of error versus the other may be very different; and
2. The methods for controlling these errors are different and involve trade-offs.

For these reasons, the decision-maker should specify levels for each type of decision error.

The purpose of this step should be to specify the decision-maker’s limits on decision errors, which should be used to establish performance goals for the data collection design. The goal of the planning team should be to develop a survey design that reduces the chances of making a decision error.

While the possibility of a decision error can never be totally eliminated, it can be controlled. To control the possibility of making decision errors, the planning team should attempt to control uncertainty in the survey results caused by sampling design error and measurement error. Sampling design error may be controlled by collecting a large number of samples. Using more precise measurement techniques or field duplicate analyses may reduce measurement error. Better sampling designs may also be developed to collect data that more accurately and efficiently represent the parameter of interest. Every survey may use a slightly different method of controlling decision errors, depending on the largest source of error and the ease of reducing those error components.

The estimate of the standard deviation for the measurements performed in a survey unit should include the individual measurement uncertainty as well as the spatial and temporal variations captured by the survey design. For this reason, individual measurement uncertainties should not be used during the final status survey data assessment. However, individual measurement uncertainties may be useful for determining an *a priori* estimate of the standard deviation during survey planning. Since a larger value of the standard deviation results in an increased number of measurements needed to demonstrate compliance during the final status survey, the decision maker may seek to reduce measurement uncertainty through various methods (e.g., different instrumentation). There may be trade-offs that should be considered during survey planning. For example, the costs associated with performing additional measurements with an inexpensive measurement system may be less than the costs associated with a measurement system with better sensitivity (i.e., lower measurement uncertainty, lower minimum detectable concentration). However, the more expensive measurement system with better sensitivity may reduce the standard deviation and the number of measurements necessary to demonstrate compliance to the point where it is more cost-effective to use the more expensive measurement system. For surveys in the early stages of the radiation survey and site investigation process, the measurement uncertainty and instrument sensitivity may become even more important. During scoping, characterisation, and remedial action support surveys, decisions about classification and remediation should be made based on a limited number of measurements. When the measurement uncertainty or the instrument sensitivity values approach the value of the derived concentration guideline level, it may become more difficult to make these decisions. From an operational standpoint, when operators of a measurement system have an a priori understanding of the sensitivity and potential measurement uncertainties, they will be able to recognise and respond to conditions that may warrant further investigation, e.g., changes in background radiation levels, the presence of areas of elevated activity, measurement system failure or degradation, etc.

The probability of making decision errors may be controlled by adopting a scientific approach, called hypothesis testing. In this approach, the survey results may be used to select between one condition of the environment (the null hypothesis) and an alternative condition (the alternative hypothesis). The null hypothesis is treated like a baseline condition that is assumed to be true in the absence of strong evidence to the contrary. Acceptance or rejection of the null hypothesis will depend upon whether or not the particular survey results are consistent with the hypothesis.

A decision error occurs when the decision-maker rejects the null hypothesis when it is true, or accepts the null hypothesis when it is false.

When the null hypothesis is rejected when it is true, this is sometimes referred to as a false positive error. The probability of making such a decision error, or the level of significance, is denoted by alpha (α). Alpha reflects the amount of evidence the decision-maker would like to see before abandoning the null hypothesis, and is also referred to as the *size* of the test.

When the null hypothesis is accepted when it is false, this is sometimes referred to as a false negative error. The probability of making such a decision error is denoted by beta (β). The term ($1-\beta$) is the probability of rejecting the null hypothesis when it is false, and is also referred to as the *power* of the test.

There is a relationship between α and β that is used in developing a survey design. In general, increasing α decreases β and vice versa, holding all other variables constant. Increasing the number of measurements typically results in a decrease in both α and β.

Five activities should be associated with specifying limits on decision errors:

- Determining the possible range of the parameter of interest; establishing the range by estimating the likely upper and lower bounds based on professional judgement;
- Identifying the decision errors and choosing the null hypothesis:
  - Defining both types of decision errors and establishing the true condition of the survey unit for each decision error;
  - Specifying and evaluating the potential consequences of each decision error;
  - Establishing which decision error has more severe consequences near the action level, consequences including health, ecological, political, social, and resource risks;
  - Defining the null hypothesis and the alternative hypothesis and assigning the appropriate term to the appropriate decision error;
- Specifying a range of possible parameter values, a gray region, where the consequences of decision errors are relatively minor; specifying a gray region will be necessary because variability in the parameter of interest and unavoidable imprecision in the measurement system may combine to produce variability in the data such that a decision may be "too close to call" when the true but unknown value of the parameter of interest is very near the action level;
- Assigning probability limits to points above and below the gray region that reflect the probability for the occurrence of decision errors;
- Graphically representing the decision rule.

The expected outputs of this step should be decision error rates based on the consequences of making an incorrect decision. Certain aspects of the site investigation process, such as historical site assessments, may not be so quantitative that numerical values for decision errors can be specified. Nevertheless, a "comfort region" should be identified where the consequences of decision errors are relatively minor.

2.7.2.7 Step 7: Optimise the design for collecting data

This step should produce the most resource-effective survey design that is expected to meet the Data Quality Objectives. It may be necessary to work through this step more than once after revisiting previous steps in the Data Quality Objectives Process.

Six activities should be included in this step:

- Reviewing the Data Quality Objectives outputs and existing environmental data to ensure they are internally consistent;
- Developing general data collection design alternatives;
- Formulating the mathematical expressions needed to solve the design problem for each data collection design alternative;
- Selecting the optimal design that satisfies the Data Quality Objectives for each data collection design alternative; if the recommended design will not meet the limits on decision errors within the budget or other constraints, the planning team will need to relax one or more constraints. Examples include:
    a. Increasing the budget for sampling and analysis;
    b. Using exposure pathway modelling to develop site-specific derived concentration guideline levels;
    c. Increasing the decision error rates, not forgetting to consider the risks associated with making an incorrect decision;
    d. Increasing the width of the gray region by decreasing the minimum value of the gray region;
    e. Relaxing other project constraints, e.g., schedule;
    f. Changing the boundaries; it may be possible to reduce measurement costs by changing or eliminating survey units that will require different decisions;
    g. Evaluating alternative measurement techniques with lower detection limits or lower survey costs;
    h. Considering the use of passive controls when releasing the survey unit rather than unrestricted release.
- Selecting the most resource-effective survey design that satisfies all of the Data Quality Objectives; typical sites (e.g., mixed-waste sites) may require the planning team to consider alternative survey designs on a site-specific basis.
- Documenting the operational details and theoretical assumptions of the selected design in the quality assurance project plan, the field sampling plan, the sampling and analysis plan, or the decommissioning plan, all of the decisions that will be made based on the data collected during the survey should be specified along with the alternative actions that may be adopted based on the survey results.

Key inputs for a final status survey design should include:

- Investigation levels and derived concentration guideline levels for each radio-nuclide of interest;
- Acceptable measurement techniques for scanning, sampling, and direct measurements, including detection limits and estimated survey costs;

- Identification and classification of survey units;
- An estimate of the variability in the distribution of residual radioactivity for each survey unit, and in the reference area if necessary;
- The decision-maker's acceptable a priori values for decision error rates (α and β).

2.8 Environmenta remediation plan

2.8.1 Environmental remediation objectives and criteria

A remediation programme should have clearly expressed objectives [3]. If remediation is justified and any clean-up action optimised, criteria are needed to target remediation activities, to assess performance as work proceeds, and to verify that the remediation has been achieved at its conclusion. These criteria may be expressed in terms of the residual dose, i.e., the projected dose from the future use of the remediated site, or in terms of concentration limits from which the residual dose, through a pathway analysis, can be calculated. Where necessary, re-entry criteria may be established by which it can be decided whether to allow the return of the population and/or reuse of the land for agriculture, etc.

A specific approach for the implementation of remediation criteria has been discussed in Section 2.2.2.3, definition of a remediation process, initial decision making, based on the form of the reference levels indicated in Table 2.1.

2.8.2 Remediation approaches and techniques

During or after preliminary site characterisation, an engineering study should be conducted to develop remediation options which address the specific contaminant problem and are aimed to reduce radiological and chemical exposure. Options should include engineering approaches and associated technologies. A preliminary selection of options may be made based on several factors including future land use, technical and institutional considerations, public acceptability, cost, regulatory requirements, etc. An overview of particular technologies is discussed in Section 4 of this document.

Further focused investigation of one or more particular method(s) may be conducted; this may include, for example, conducting a bench scale and pilot scale tests of a specific technology. These tests would be designed to collect sufficient information to develop, procure, and operate a full-scale system.

Once the clean-up criteria are confirmed, the preferred alternative should be selected, taking into account future land use constraints, if any, and the need for institutional control.

2.8.3 Implementing remediation actions

The implementation of remediation actions should include: procurement of the selected technology; preparation of the site; development of a health and safety plan; development of operations procedures; staff selection and training; completion of site clean-up; verification; waste disposal; and release of the site for any future use.

At completion of the remediation activities, the site should meet the remediation objectives set at the outset as demonstrated in final verification activities. Long-term monitoring may be necessary. Quality assurance protocols should have been applied to all programme activities.

2.8.4 Compliance with environmental protection

Participants in site characterisation work will be expected to comply, as a minimum, with the environmental legislation, regulations at all places of work and other guidelines specified in any scope of work [10].

Owners and operators of nuclear-licensed sites are mostly large organisations, and can be expected to hold, or have management systems designed to meet the requirements of environmental protection.

Such organisations will also be committed to continuous improvement programmes, and it may be expected that these organisations will require their consultants and subcontractors to meet specified requirements of environmental management competency. The adherence of suppliers to these requirements should also ensure:

- Compliance with corporate environmental policies
- Minimisation of liabilities (i.e., not to exacerbate risk from any existing contamination or create new contamination or impacts)
- Maintenance of integrated compliance with health, safety, security and environmental aspects
- Management of stakeholder involvement.

When producing specifications or evaluating tenders for site characterisation and site remediation works site owners and occupiers should ensure that the works comply with the requirements of the site environmental policy and environmental management system. In demonstrating that this is the case, consultants and sub-contractors should ensure that their own assessments are site-specific and activity-specific. Effective communication and flow of information between the client/liability holder and the consultant/contractor is necessary to demonstrate that the environmental protection systems of the two parties are compatible.

The key principles of compliance with an environmental management system are:

- The direct and indirect adverse environmental effects of site characterisation and remediation activities should be minimised. This should be demonstrated by provision of a safety, health and environment plan for performance of the work.
- Every individual should be suitably qualified, trained and experienced to carry out their work and to understand their responsibility for the environmental effects of their activities.
- Managers at all levels should understand their responsibilities for the environmental effects of the activities of the employees, contractors and visitors under their control.
- All staff should know the environmental objectives and targets relevant to their work, and assume personal responsibility for the environmental effects of their actions.
- Equipment and facilities used for site characterisation and remediation work should be appropriate for the job, adequately maintained and operated to a suitable system of work. This will minimise, as far as reasonably practicable, direct environmental effects.
- All staff should know the procedures for reporting accidents and emergencies that have environmental implications, and the actions to be taken to minimise the effect of an accident.
- Participation in audits, monitoring and review activities to check compliance with environmental legislation and management systems may be expected.

Identification and evaluation of potentially significant environmental effects should be undertaken in a risk assessment specific to a site characterisation activity. Such an assessment is likely to include consideration of the environmental aspects summarised in Table 2.8.

Table 2.8 Aspects of environmental protection appropriate to site characterisation activities

Aspect description	Example of activity or process	Mitigation
Waste management	Spoil generation and disposal	Minimisation by choice of technique Control of contaminated drilling returns
Water use	Water flush drilling	Avoid use
Materials storage and handling, including hazardous materials	Fuel storage	Store drums on appropriately sized bunded trays
Air quality	Emission from generators	Fit exhaust filters
Noise and vibration	Use of heavy plant	Refer to code of practice BS5228 - Noise control on construction and other open sites
Effluent including sewerage	Purged borehole water	Collection and disposal via authorised route
Contaminated land	Interconnection of aquifers due to poor borehole design	Borehole design to be approved by regulator
Ecology	Disturbed flora	Careful re-instatement of exaction locations
Odours	Equipment emissions	Site equipment so as to minimise impact, out of hours working
Transport	Vehicle movements and their emissions	Where appropriate ride a bicycle or electrical powered around site

An environmental protection checklist should comprise the following activities:

- Check contractual requirements.
- Check own organisational environmental requirements.
- Check and agree allocation of responsibilities.
- Estimate and review environmental impacts for the project.
- Produce environmental impacts for the project.
- Check personnel competence, equipment suitability and maintenance.
- Check procedures for monitoring and recording, audits and reviews, for communications of emergency incidents.

2.9 Waste management and transport of radioactive materials plan

2.9.1 Waste management

Both radioactive waste and non-radioactive waste will be generated during the execution of a site remediation programme. The management of these wastes should be addressed in project specific plans. These plans then need to be integrated with the site waste management procedures, and where management routes are not available, then new ones will need to be established.

For non-radioactive waste the development of a site waste management plan on construction sites is good practice, and on nuclear-licensed sites it is recommended. This plan should be integrated with radioactive waste management plans.

Further the management and transport of non-radioactive as well as of radioactive waste are subject to international and national regulations. It is therefore advised to contact the appropriate national agencies dealing with these topics, so that the plans are in compliance with the regulations.

This section addresses all important topics dealing with the waste management of non-radioactive and radioactive wastes.

2.9.1.1 Sources of waste

It is likely that both solid and liquid non-radioactive wastes as of radioactive wastes will be produced from the site investigation and remediation process.Typical solid wastes include:

- Solid wastes from initial site clearance activities, such as vegetation (which may need to be removed to allow adequate access to the site) and surface wastes (such as metallic items, which may interfere with geophysical surveys);
- Spoil that cannot be backfilled into boreholes or trial pits;
- Used personal protective equipment and used respiratory protective equipment;
- Disposable items used during sample collection, preparation and packaging;
- Waste from the site accommodation and hygiene facilities;
- Residues from samples sent for laboratory analysis.

Typical liquid wastes include:

- Water/liquids produced from wash-down facilities (i.e., water used for cleaning and decontaminating of site and sampling equipment);
- Water/liquids produced from operations in the hygiene and change facilities;
- Water/liquids produced from abstraction of groundwater from trial pits, trenches and boreholes on the site;
- Residues from samples sent for laboratory analysis.

2.9.1.2 Waste minimisation

In most countries in licenses requirements are set that licensees have to minimise the production of wastes and especially of hazardous and radioactive wastes.

Consequently, subject to achieving the objectives of the site remediation project, there may be a requirement to use intrusive techniques that minimise waste production, where their use will not compromise the objectives of the site remediation project.

If the remediation programme is dealing with a defense site, special regulations can be applicable. This has to be verified. However, on both categories of site it is good practice to consider options for minimising the generation of waste. It will also be necessary on all sites to segregate wastes into various waste streams defined by radioactivity so that they can be managed correctly. It may be appropriate (or a requirement specified by the client) to appoint a member of the project team with responsibility for minimising and segregating radioactive wastes. On some sites, this role is referred to as the waste minimisation officer.

2.9.2 Management of radioactive waste

2.9.2.1 Definition of radioactive waste classes by the IAEA

In the context of site investigations on potentially radioactively contaminated sites, wastes fall into two categories: radioactive waste and non-radioactive waste.

The definition of radioactive and non-radioactive wastes is given in national legislations and these can vary from country to country.

Exemption orders of both types of wastes exist that specify the conditions under which materials or wastes defined as radioactive can be "exempted", i.e., excluded from some or all of the regulatory provisions for radioactive materials. It is advised to check the national regulations on this topic.

The IAEA has defined the following radioactive waste categories (see Table 2.9) [53].

Table 2.9 Radioactive waste classes as proposed by IAEA

	Waste classes	Typical characteristics	Disposal options
1	Exempt waste (EW)	Activity levels at or below clearance levels [54], which are based on an annual dose to members of the public of less than 0.01 mSv	No radiological restrictions
2	Low and intermediate level waste (LILW)	Activity levels above clearance levels [54] and thermal power below about 2 kW/m^3	
2.1	Short lived waste (LILW-SL)	Restricted long lived radionuclide concentrations (limitation of long lived alpha emitting radionuclides to 4000 Bq/g in individual waste packages and to an overall average of 400 Bq/g per waste package)	Near surface or geological disposal facility
2.2	Long lived waste (LILW-LL)	Long lived radionuclide concentrations exceeding limitations for short lived	Geological disposal facility.
3	High level waste (HLW)	Thermal power above about 2 kW/m^3 and long lived radionuclide concentrations exceeding limitations for short lived waste	Geological disposal facility

Exempt waste (EW)

Exempt waste (EW) contains so little radioactive material that it cannot be considered 'radioactive' and might be exempted from nuclear regulatory control. That is to say, although still radioactive from a physical point of view, this waste may be safely disposed of, applying conventional techniques and systems, without specifically considering its radioactive properties [53].

Many studies have been performed on the subject of waste exemption. The IAEA provides recommendations on exemption from regulatory control and specifies unconditional clearance levels for radionuclides in solid materials based on limiting annual doses to members of the public to 0.01 mSv [54]. The recommended activity concentrations are dependent on the individual radionuclide and range from about 0.1 Bq/g to about 10^4 Bq/g. Because possible individual radiation doses are trivial at these concentrations, no particular attention needs to be paid to the radioactive properties of such waste.

Levels of activity concentration for exempt waste higher than those suggested in [54] may be established by the national authority on a case-by-case basis if specific national peculiarities are considered or defined requirements or conditions are given for the exemption of waste. The levels of activity concentration appropriate for conditionally exempt waste are highly dependent on the conditions for exemption. Actual values can be derived for individual cases.

It is important to obtain a consensus on the boundary for unconditionally exempt material which may be transferred from one country to another (e.g., for recycle/reuse). It would be of great value if the same limits could be adopted for different sites. This would greatly simplify exemption procedures and would increase the confidence of the public in such practices.

Low and intermediate level waste (LILW)

Low level waste has been defined in the past to mean radioactive waste that does not require shielding during normal handling and transportation [53]. Radioactive waste which required shielding but needed little or no provision for heat dissipation was classified as intermediate level waste. A contact dose rate of 2 mSv/h was generally used to distinguish between the two classes.

This distinction appears of secondary importance in the present context. Classification should be related to individual radionuclides, taking the various exposures and exposure pathways into account, such as inhalation (e.g., in the case of an incident) and ingestion (e.g., in the case of long term releases in the post-operational period of a repository). Thus, low and intermediate level waste may be subdivided into short-lived and long-lived waste. Additional considerations which must be taken into account in managing low and intermediate level waste are presented subsequently under 'Additional Considerations'.

Short-lived waste (LILW-SL)

Short-lived low and intermediate level waste (LILW-SL) contains low concentrations of long-lived radionuclides. The possible hazard represented by the waste can often be significantly reduced by administratively controlling waste as part of storage or after disposal. Although the waste may contain high concentrations of short-lived radionuclides, significant radioactive decay occurs during the period of institutional control. Concentrations of long-lived radionuclides that will not decay significantly during the period of institutional control are controlled to low levels consistent with the radiotoxicity of the radionuclides and requirements set forth by national authorities.

Because LILW-SL may be generated in a wide range of concentrations, and may contain a wide range of radionuclides, there may be a range of acceptable disposal methods. The waste form or packaging may also be important for management of this waste. Depending upon safety analyses and national practices, these methods may range from simple surface landfills, to engineered surface facilities, and to disposal at varying depths, typically a few tens of metres, or in deep geological formations if a co-disposal of short- and long-lived waste is anticipated. National practices may impose varying levels of isolation depending upon the hazard represented by different classes of radioactive waste.

From existing criteria it appears that a general boundary between near surface and geological disposal of radioactive waste cannot be provided, as activity limitations will differ between individual radionuclides or radionuclide groups and will be dependent on the actual planning for a near surface disposal facility (e.g., engineered barriers, duration of institutional control, site specific factors).

Long-lived waste (LILW-LL)

Long-lived low and intermediate level waste (LILW-LL) contains long-lived radionuclides in quantities that need a high degree of isolation from the biosphere [53]. This is typically provided by disposal in geological formations at a depth of several hundred metres.

The boundary between short-lived and long-lived waste cannot be specified in a universal manner with respect to concentration levels for radioactive waste disposal, because allowable levels will depend on the actual radioactive waste management option and the properties of individual radionuclides. However, in current practice with near surface disposal in various countries, activity concentration is limited to 4000 Bq/g of long-lived alpha emitters in individual radioactive waste packages, thus characterizing long-lived waste which is planned to be disposed of in geological formations. This level has been determined based on analyses for which members of the public are assumed to access inadvertently a near surface repository after an active institutional control period, and perform typical construction activities (e.g., constructing a house or a road).

Applying this classification boundary, consideration should also be given to accumulation and distribution of long-lived radionuclides within a near surface repository and to possible long term exposure pathways. Therefore, restrictions on activity concentrations for long-lived radionuclides in individual waste packages may be complemented by restrictions on average activity levels or by simple operational techniques such as selective emplacement of higher activity waste packages within a disposal facility. An average limit of about 400 Bq/g for long-lived alpha emitters in waste packages has been adopted by some countries for near surface disposal facilities.

In applying the classification system, attention should also be given to inventories of long-lived radionuclides in a repository that emit beta or gamma radiation. For radionuclides such as ^{129}I or ^{99}Tc, allowable quantities or average concentrations within a repository depend strongly on site specific conditions. For this reason, national authorities may establish limits for long-lived beta and gamma emitting radionuclides based on analyses of specific disposal facilities.

High level waste (HLW)

The high level waste (HLW) class largely retains the definition of the existing classification system [53]. This waste contains large concentrations both of short- and long-lived radionuclides, so that a high degree of isolation from the biosphere, usually via geological disposal, is needed to ensure disposal safety. It generates significant quantities of heat from radioactive decay, and normally continues to generate heat for several centuries.

An exact boundary level is difficult to quantify without precise planning data for individual facilities. Specific activities for these waste forms are dependent on many parameters, such as the type of radionuclide, the decay period and the conditioning techniques. Typical activity levels are in the range of 5×10^4 to 5×10^5 TBq/m^3, corresponding to a heat generation rate of about 2 to 20 kW/m^3 for decay periods of up to about ten years after discharge of spent fuel from a reactor. From this range, the lower value of about 2 kW/m^3 is considered reasonable to distinguish high level waste from other radioactive waste classes, based on the levels of decay heat emitted by high level waste such as those from processing spent fuels.

The suggested boundary levels for high level waste need not be distinct because of the general consensus that a high degree of isolation is necessary for management of radioactive wastes having very high concentrations of short- and long-lived radionuclides. National programmes exist to manage such radioactive waste.

Additional considerations

A number of additional important factors should be considered when addressing specific types or properties of radioactive waste [53].

Waste containing long-lived natural radionuclides

Many countries must address the disposal of very large quantities of waste containing long-lived natural radionuclides. Such waste typically contains natural radionuclides like uranium, thorium, and radium and is frequently generated from uranium/thorium mining and milling or similar activities. It may also include waste from decommissioning of facilities, where other isotopes may also be present. The characteristics of these wastes are sufficiently different from other wastes that they may require an individual regulatory approach.

Although these wastes do contain long-lived radionuclides, their concentrations are generally sufficiently low that either they can be exempted or disposal options similar to those for short-lived waste may be considered, depending on safety analyses.

Heat generation

Although heat generation is a characteristic of high level radioactive waste, other radioactive wastes may also generate heat, albeit at lower levels. Heat generation is dependent upon the type and content of radionuclides (half-life, decay energy, etc.). Furthermore, the heat removal situation is highly important (thermal conductivity, storage geometry, ventilation, etc.). Therefore, heat generation cannot be defined by a single value. The relevance of heat generation can vary by several orders of magnitude depending on the influencing parameters and the temperature limitations. Management of decay heat should be considered in a repository if the thermal power of waste packages reaches several W/m^3. Especially in the case of long-lived waste, more restrictive values may apply.

Liquid and gaseous waste

The treatment of liquid waste (which may contain paniculate solids) and gaseous waste (which may contain aerosols) aims at separating the radionuclides from the liquid or gaseous phase and concentrating them in a solid waste form. The separation is pursued until the residual concentration or total amount of radionuclides in the liquid or gaseous phase is below limits set by the regulatory body for the discharge of liquid or gaseous waste from a nuclear facility as an effluent. Treatment may include a storage period for radioactive decay.

Liquid and gaseous radioactive waste exceeding discharge limits set by national authorities should be conditioned for storage, transport and disposal. Only following sound safety analysis should radioactive waste in liquid or gaseous form be transported off the site or disposed of in terrestrial repositories in their original forms. Storage for decay at the facility of their origin may be considered as part of the conditioning process.

The classification of liquid and gaseous radioactive waste may be based on the different types of treatment that can be used, and on potential radiological, chemical and biological hazards. When solidified or conditioned for disposal these wastes fall under one of the solid radioactive waste classes.

2.9.2.2 Key issues for waste management

The key issues for waste management on radioactively and potentially radioactively contaminated sites are summarized below.

- *Averaging volume*. This is the volume of waste over which the activity concentration of radionuclides is averaged. Categorisation of waste (see below) is made on the basis of the averaging volume, which is therefore a key parameter in the design of a site characterization and any subsequent remediation. The averaging volume of any waste produced from the site characterisation or subsequent remediation should be agreed with the relevant environment agency during the survey design stage. In practice this agreement will be established on a case-by-case basis.
- *Waste minimisation*. Operators of nuclear-licensed sites will have both environmental policies and site licence conditions that state that waste production should be minimised. Strategies for intrusive investigations and for other aspects of the site investigation should be selected with this requirement in mind.
- *Categorisation of wastes*. Definition is firstly in terms of radioactivity but should also include other aspects, such as the water or leachable oil content of solid wastes and the hydrocarbon content of liquid wastes. Ensure that disposal routes are available for all wastes that will be produced.
- *Define responsibilities for wastes*. Define responsibilities for the characterisation, packaging and storage/disposal of radioactive and non-radioactive wastes. Note that this applies both to wastes produced on the site and to wastes arising from the laboratory analysis of samples.
- *Waste segregation*. Health physics monitoring during the site investigation should be used to make an initial segregation into the radioactive and non-radioactive waste streams required by the site operator. Waste segregation is crucial to minimise production of radioactive wastes.
- *Confirmatory analysis of wastes*. Prior to final sentencing of waste, laboratory analysis should be undertaken to confirm the waste category, and to ensure it conforms to acceptance criteria.
- *Waste disposal*. Ensure that wastes are disposed in accordance with site operating procedures (if available) and legislation. Ensure duty of care for non-radioactive wastes.

The level of relative enhancement of any wastes above background levels needs to be determined. Cases have arisen where elevated natural levels of radiation have resulted in problems over the sentencing of waste arising.

Some of the mentioned issues are dealt with in more detail below.

2.9.2.3 On-site facilities for management of radioactive wastes

Operational nuclear-licensed sites

Operational nuclear-licensed sites will have in general facilities for the management of both solid and liquid radioactive wastes. Typically on such sites, the site operator will retain responsibility for the storage and ultimate disposal of any solid radioactive wastes produced during the site investigation.

Under this arrangement, the contractor would be responsible only for the packaging of the solid radioactive wastes, in containers to be approved by the site operator. It would be for the site operator to ensure that disposal routes are available for both solid and liquid radioactive wastes; this may include obtaining variations to existing authorisations under the applicable regulations.

Facilities for the treatment and disposal of many liquid wastes are available on operational nuclear-licensed sites. Different categories of liquid waste are primarily defined by radioactivity limits. However, because the waste treatment plants will have been designed to treat the principal waste streams produced during routine operations on the site, and not with contaminated land investigations in mind, there may be the requirement to pre-treat site investigation wastes before disposal in the liquid effluent treatment plant. Pre-treatments may involve reducing suspended solid load, by processes such as flocculation/coagulation, settling and filtration, and reduction of dissolved or free-phase hydrocarbon or solvent contamination, by treatment with granular activated carbon. It is important to determine the waste acceptance criteria for liquid wastes, and hence the requirements for any pre-treatment, during the planning phase of the site investigation.

Non-nuclear-licensed sites

On non-nuclear-licensed sites where no facilities are available for the treatment or disposal of solid or liquid radioactive wastes, the site owner will need to make appropriate plans and arrangements, and obtain the necessary authorizations and agreements for waste accumulation and disposal. The treatment and packaging requirements for solid wastes will depend on the route for their eventual disposal. A mobile effluent treatment plant may be required if authorisation cannot be obtained for direct discharge of liquid wastes to the waste storage or treatment plant or into the environment.

2.9.2.4 On-site segregation of wastes for radioactivity

The radionuclide fingerprint of the potentially contaminated material must be known in order to select appropriate instruments and methodologies for assigning wastes to the different categories. Wastes in which fission products (such as ^{137}Cs) or radium are the principal contaminants can be segregated using certain hand-held gamma detectors, for example a 3 inch x 3 inch sodium iodide detector. Calibration of the detector for the particular nuclide and geometry (e.g., a semi-infinite plane or an excavator bucket full of waste) will be required.

It is not adequate or appropriate to segregate alpha- or beta-contaminated wastes using hand-held instrumentation. It will either be necessary to use an on-site laboratory to carry out gross alpha and gross beta screening analysis of representative samples of the waste or to categorise wastes after the laboratory radiochemical analyses of soil samples become available.

2.9.3 Management of non-radioactive waste

Non-radioactive wastes may be known as ‘controlled waste’ and includes waste arising from domestic, industrial and commercial premises, as well as hazardous waste. Non-radioactive wastes derived from site investigations are controlled waste. The ways of managing these wastes are rapidly changing, with more emphasis on reducing the volumes sent to landfill by recycling, and pre-treating that which is landfilled.

Site waste management plans (SWMPs) are designed to manage waste, improve environmental performance, help regulation and provide evidence to regulators and clients. Currently, site waste management plans can be voluntary codes of practice. However, legal requirements are rapidly changing in most countries, and legislation can be expected in the near future. Once site waste management plans become mandatory they are anticipated to apply to projects and will affect anybody in the construction chain. How such a site remediation project will be defined by this legislation is uncertain, but if site characterisation works are classed as part of major construction and demolition projects on radioactively contaminated sites then site waste management plans can be expected to be required, or adhered to as part of the management of a larger project.

2.9.3.1 Classification of non-radioactive waste

In most countries regulations exist for landfill waste dumps for pollution prevention and to control the non-radioactive waste disposal. These regulations will continue to develop and will have a significant impact on the management of wastes.

Main impacts on waste producers may be that:

- Certain kinds of wastes cannot be sent to landfill for disposal (e.g., liquids, chemical substances arising from research and development which are not identified, and explosive and reactive materials);
- Biodegradable wastes are to be increasingly diverted from landfills;
- Landfills are classified according to whether they can accept hazardous, non-hazardous or inert wastes. Wastes may only be accepted at a particular landfill if they meet the relevant waste acceptance criteria (WAC) for that class of landfill; and
- Most wastes must be treated before they can be landfilled.

The organization(s) that will take the responsibility for the wastes produced during site remediation should be identified at an early stage in the project. These are most likely to be the consultants managing the project, but in some circumstances it may be either the site-remediation sub-contractor or the site management.

The waste producer is responsible for ensuring that basic characterisation of the waste is undertaken to establish its key characteristics, as specified by regulations. In particular, details of the chemical composition and leaching behaviour of the waste may be required.

Once the waste is characterized, management options can be considered in accordance with the waste hierarchy. Waste minimisation, reuse, recovery and final disposal should be considered in that order. Where disposal by landfill is identified for all or part of the waste, the producer will need to consider appropriate treatment options.

In order to determine whether the waste is hazardous waste or non-hazardous waste the producer should first consult the national hazardous waste list (if existing) derived from the European Waste Catalogue. This may list all waste streams and may mark waste streams that are hazardous.

Having identified whether the material is hazardous or not, if the producer wishes to dispose of the material at landfill, further characterisation is likely to be required against the waste acceptance criteria (WAC) to determine if it is acceptable at a given landfill. The waste should then be periodically checked to ensure that those properties have not changed. When treated waste is consigned to a landfill, the landfill operator will carry out on-site verification at the site on each load to ensure that the waste is as described by the producer.

The full waste acceptance criteria consist of:

- A list of acceptable inert wastes;

- Leaching limit values; and
- Analysis of various organic compounds including mineral oil, polycyclic aromatic hydrocarbons and polychlorinated biphenyl, as well as total organic carbons and/or loss on ignition.

For inert wastes there may be a list of acceptable wastes. If the waste is a single waste stream comprising waste on the list of acceptable inert waste, and uncontaminated by other materials, then it may be accepted at an inert landfill without testing. For wastes that may be inert, but are not on this list, testing must be undertaken against leaching limit values, and also limit values for other criteria, including total organic carbon, to demonstrate that it is inert.

There are no leaching limit values for non-hazardous waste, because the primary requirement is to ensure that the waste is not hazardous. For hazardous wastes there may be a hazardous waste list. If the waste is on this list then, if it is to be disposed of at landfill, it needs to be subject to leaching tests and meet the limit values and other criteria in order to allow it to be disposed of off-site. Guidance on definition and classification of hazardous wastes has been provided in Section 2.9.4.

2.9.3.2 Treatment of non-radioactive wastes

Waste destined for landfill must be subject to prior treatment. Landfill regulations may provide definitions of treatments from which the following test (the ‘three-point test’) has been derived. Any potential treatment must fulfill all of these three criteria, but need only meet one of the four objectives of the third point:

- It must be a physical/thermal/chemical or biological process including sorting.
- It must change the characteristics of the waste.
- It must do so in order to:
    - Reduce its volume, or
    - Reduce its hazardous nature, or
    - Facilitate its handling, or
    - Enhance its recovery.

The waste producer makes the initial decisions about the management of their wastes and therefore in the best position either to treat or secure its treatment by others. If waste is to be sent to landfill after treatment then, depending on the treatment, testing to confirm whether the material should still be classified as hazardous waste must be carried out to establish its acceptability at landfill. Of particular relevant to site characterisation generated wastes is that simple physical dilution, without any concurrent chemical or physico-chemical changes, is not an acceptable treatment process. Therefore, the dilution of contaminated soil with other soils in order to lower the concentrations of contaminants of concern below those for hazardous waste is unacceptable. Mixing waste to achieve a physico-chemical change, in pursuance of the third criterion, may be acceptable.

2.9.4 Management of problematic waste and material generated during remediation of radioactively contaminated sites

Environmental remediation activities related to any nuclear licensed facility (e.g., NORM industry, nuclear power plants, defense sites, etc.) present several problems in the management of the generated waste and obsolete redundant material. The waste arising from environmental remediation is often different from the waste generated during normal operations or routine maintenance of the facility.

These differences may include its chemical, physical and radiological characteristics, the physical form and the general amounts or volumes. Owing to these specific characteristics, some of the waste could be considered as being problematic, for example waste for which application of routine methods of handling, treatment and conditioning is not appropriate and therefore requires special considerations for the selection of specific management options. For such environmental remediation waste and material proper planning and selection of appropriate waste management and material management options are of particular importance from the organizational, health physics, safety and economic points of view.

Some examples of the problematic nature of specific environmental remediation waste are as follows:

- High volume-low activity material may give rise to economic concerns over the disposal of the waste (e.g., contaminated soil). The volume of waste in this category is dependent on the national clearance levels.
- Some waste may be considered problematic because of the inventory of radionuclides that it contains (e.g., waste containing radionuclides of high radiotoxicity and mobile radionuclides such as ^{14}C and tritium).
- Some waste may be considered problematic because it is difficult to encapsulate in cementitious matrices (e.g., soil containing aluminium, beryllium and uranium – depleted metal). Corrosion of the material can lead to the generation of high levels of hydrogen, which can disrupt the encapsulation matrix and can introduce a risk of explosion. Also, expansion of the waste form can occur, due to the formation of corrosion products.
- Additional problems can occur in the encapsulation of waste material in a cementitious grout, in which the waste material can affect the product properties of the grout (e.g., high nitrate, fluoride and borate bearing liquid waste). The immobilization of phosphate, such as tributyl phosphate, or high levels of sodium hydroxide in some waste streams, can cause accelerated cement setting, leading to ‘flash’ setting of the waste form.
- Some types of waste can be problematic because of their physical nature (e.g., non-aqueous phase liquids such as oils, organic complexants and the degradation products of organic polymers). These components of waste may enhance the mobility of radionuclides in the disposal environment. They are difficult to immobilize because they are often just absorbed and not chemically bound within the immobilization matrix.
- Waste may also be considered problematic because it is hazardous due to either its physico-chemical properties or its inherent toxicity. These types of material represent a potential hazard to human health or the environment when improperly treated, stored or disposed of, or otherwise mismanaged. Among these types of waste the main concerns are on material that is hazardous and/or toxic by its chemical or physical nature. An analysis of the specific characteristics of such waste, and of its possible management options, is important for ensuring the safety of environmental remediation activities.

In this section problematic waste and material are identified as those that require special handling and treatment because of their unique combination of radioactivity, toxicity or chemical and physical hazards. This section reviews the origins of these types of waste and their characteristics, potential hazards and management options [55].

An integrated approach to the consideration of organizational principles, the regulatory background and the technical options for dealing with these types of waste and material is important in order to ensure the efficiency of the selected options, the safety of workers and public, stakeholders, and the protection of the environment.

Information already exists on the management of some problematic types of waste and material and on particular technologies and their application for handling, storage and processing. A review of the available information on this subject, analysis of related data and experience, and discussion of related problems would be of particular benefit for all parties planning environmental remediation activities.

The information summarized in this section will assist in the selection of adequate processes and technologies to solve particular waste management problems with different types of problematic waste and material during environmental remediation activities.

The overall approach (see Section 2.2.2.1) is not influenced by the requirements for the management of toxic and hazardous waste. However, the presence of these material types needs to be fully considered. In contrast with radioactive waste, which decays with time, delayed environmental remediation would not lead to a decrease in the associated hazards and toxicity of such waste; in fact the opposite is the case, in that delay may lead to decreasing integrity of the material and components, which may cause additional problems with the environmental remediation and management of the associated waste. This important factor should be taken into consideration when defining the environmental remediation strategy and making the selection of appropriate remediation options and associated techniques.

The choice of an environmental remediation option will mainly be based on technical, safety, economic and regulatory considerations. These considerations will enable the operator to select the most appropriate environmental remediation option. Although radiological hazards predominate in environmental remediation activities, toxic and other conventional hazards must be taken into account during the decision making process.

The definition of an environmental remediation and waste management strategy needs to fully consider the technical problems associated with the management and processing of all radioactive and hazardous waste. Experience of environmental remediation has shown that while the use of and requirements for personal protective equipment for radiological purposes during clean-up of sites may decline with time because of radioactive decay, the use of personal protective equipment for toxic and hazardous waste may remain constant or increase with time as material degrades.

For each option it is necessary to consider the volume and physico-chemical form of the toxic and hazardous material generated. 'Cradle to grave' processes should be available for the handling and treatment of all material (including waste) arising from any environmental remediation activity before these activities are undertaken. It should be kept in mind that in most countries no waste repository is available and that therefore safe interim storage facilities should be provided for the material until a suitable disposal option becomes available. Therefore, involved regulatory agencies should be consulted in an early stage and have to be taken in during the total planning process to get approval for selected options.

To determine a suitable environmental remediation strategy, information about the site and operational history is required (see Section 2.4, Historical site assessment). It has to be stressed, therefore, that record keeping during the operational life of a site and careful radiological and physicochemical characterization of waste and material are crucial.

For the purposes of this section the following definitions of hazardous and toxic waste and material are used:

- *Hazardous*. Waste and material that because of their quantity, concentration and/or physical, chemical or infectious characteristics may pose a substantial potential threat to human health or the environment when improperly handled, treated, stored or disposed of, or otherwise mismanaged.
- *Toxic*. Waste and material that contain certain substances determined to be harmful to human health in very small concentrations.

To distinguish between the two definitions, it is helpful to consider that all toxic waste is hazardous but not all hazardous waste is toxic.

There are some general considerations that are common to toxic and hazardous waste. The disposal of toxic waste in either shallow land burial or in deep geological facilities needs to consider the long term behaviour of the waste and has to respect the national regulations for its disposal. Special requirements may also be defined by regulatory authorities for the long term storage of hazardous waste if a disposal option is at present not defined or not available. As was indicated above, it should be considered that unlike the hazards related to radioactivity, the hazard from toxic waste will not reduce with time. However, some unstable toxic waste, mainly of an organic nature, could degrade while in storage or disposal, resulting in the generation of non-toxic products.

There are various national regulations concerning the limits for emission of toxic compounds, their concentration in drinking water, etc. These particular limits should be respected when preparing the safety analysis for toxic waste treatment, conditioning and disposal.

One of the possible options for the management of environmental remediation waste, including some hazardous components, is to consider recycling and reuse of components of the waste. Another option is the processing of this waste for storage and final disposal. These options are discussed in general in the following sections of this report in relation to particular types of hazardous material.

Table 2.10 Commonly occurring radiological hazards associated with problematic waste and material in a nuclear power facility

	Probability of commonly occurring radiological hazard		Comments
	Activation	Contamination	
Beryllium	High	Medium	The degree of contamination of the beryllium depends on whether it is cladded
Sodium and sodium-potassium alloys	High	Medium	Contamination in secondary circuit sodium is low and consists mainly of tritium
Cadmium	High	Low	When cadmium is used in fuel storage flasks it may be only slightly activated
Mercury	Low	High	Activated mercury may be used as shielding in research reactors or as target material in accelerators
Lead	Low	High	Where lead is activated it can be difficult to demonstrate compliance with clearance levels because of selfshielding effects
Cyanide	None	High	Cyanide is used for caesium removal purposes and hence is not activated
Decontamination chemicals	None	High	Some spent decontamination solutions may contain activation products
Asbestos	Low	Medium	Asbestos may be used as insulation material on reactor pressure vessels, but commonly the radiological hazard occurs from contamination on the surface
Polychlorinated biphenyls	None	Medium	Polychlorinated biphenyls are commonly found in oils, paints and other organic based material

All types of material arising during environmental remediation activities, including chemically toxic and other hazardous material, could be activated or radioactively contaminated depending on the nature of the nuclear facility in which the material originated and/or the purpose for which the material was employed. Therefore their treatment, conditioning and disposal consider both the radiological and non-radiological hazards associated with these types of material and waste [55]. Table 2.10 summarizes the commonly occurring radiological hazards associated with the problematic waste and material generated during decommissioning and of which the possibility exists that it has to be taken into account during environmental remediation.

In [55] information can be found about:

- Form of the problematic waste;
- Typical hazards;
- Possibilities for recovery and reuse;
- Waste treatment and management.

2.9.5 Waste transport and disposal

Wastes shall be disposed in accordance with the national relevant legislation and may impose duty of care on persons concerned with controlled and special waste. The duty should apply to any person who produces, imports, carries, keeps, treats or disposes of controlled or hazardous waste, or to a broker who has control of such waste. It requires that anyone who has a responsibility for controlled or hazardous waste ensures that it is managed properly and recovered or disposed safely. Under the duty of care, there are four main requirements:

1. To prevent any other person committing the offences of depositing, disposing or recovering controlled (or special) waste without a waste management licence, contrary to the conditions of a licence, or in a manner likely to cause environmental pollution or harm to health. This will be achieved by:
    a. The use of a reputable waste disposal contractor appropriately registered for disposal operations;
    b. Verification that the waste management licence permits the disposal operation to be undertaken;
    c. Conducting an audit trail on the disposal operation.
2. To prevent the escape of waste. This will be achieved by:
    a. The use of appropriate transport containers;
    b. Each container (sealed drum or closed skip) will be labelled in accordance with national and European regulations of dangerous goods.
3. To ensure that, if the waste is transferred, it goes only to an authorised person, or, to a person for authorised transport purposes.
4. This will be achieved by:
    a. The use of a reputable waste disposal contractor who is a registered waste carrier;
    b. Verification of the validity and currency of the waste carrier registration;
    c. Conducting an audit trail on the disposal operation.
5. When the waste is transferred, to ensure that there is also transferred a written description of the waste, a description good enough to enable each person receiving it to avoid committing any of the offences under (1) above and to comply with the duty at (2) above to prevent escape of waste.

This is achieved by raising a consignment note for each consignment of liquid or solid waste that is disposed. Written information regarding treatment should be contained on or with the Duty of Care transfer note.

2.9.6 Off-site road transport

2.9.6.1 Radioactive material movements

The transport of radioactive materials by road is subject to legislation relating both to radioactive content and to any chemical or physical hazards [29]. The legislation regarding radioactive material movements requires understanding of radiation protection issues. Specialist advice from a radiation protection adviser should be sought to ensure that all transfers of radioactive materials are in accordance with this legislation.

Transport regulations apply also to off-site transport by air, sea and rail and to shipment across international frontiers. However, these are of less relevance to contaminated land investigations, and are not discussed further in this guidance.

In the context of a site investigation, these regulations may be relevant to the movement of solid and liquid samples to a testing laboratory or archive and to the movement of waste to a disposal facility.

The consignor, who is responsible for transporting the radioactive material, in addition to the general duty to exercise reasonable care, must ensure that:

- If this is the first shipment using a specific type of package that the relevant authorizations have been obtained from the competent authority;
- The correct package type is used for the radioactive material (the total activity, external dose rate and surface contamination levels are appropriate to the package type);
- The package is correctly labelled;
- The package is transported in accordance with the legislation;
- The documentation complies with all the relevant legislation and relevant information is provided to the carrier;
- The consignor maintains a quality assurance programme;
- The consignee, who receives the radioactive material, is authorised to accept the radioactive material (i.e., it is a nuclear-licensed site or they have an authorisation to accumulate and dispose of radioactive material);
- The emergency arrangements are in place.

2.9.6.2 Nuclear materials

EURATOM safeguards apply to the civilian use of radioactive materials in the member states of the European Community.

One of the requirements is a system of accountancy and control of all nuclear materials subject to the legislation. “Nuclear materials” refers to any ore, source or special fissile material as defined in Part VI of the Commission Regulation (EURATOM) No 3227/76, 1976. For organisations handling only small quantities of these materials (such as potentially could be produced from a contaminated land investigation), only special fissile materials (^{239}Pu and uranium enriched in ^{235}U or ^{233}U) are subject to the legislation. Further, plutonium with an isotopic concentration of ^{238}Pu in excess of 80% by activity is exempted.

It is possible that samples produced from the investigation of a site contaminated with fissile radionuclides may require registration under the nuclear materials accountancy system (see above). It is not clear whether there is any “de-minimis” level below which the samples can be exempted from this system. Advice on the storage and transport of such material should be sought from the site operator who in turn will take advice from the regulator.

2.10 Stewardship

After remediation has been completed, the degree, extent and duration of control, if any, ranging from monitoring and surveillance to restriction of access, should be reviewed and formalised with due consideration of the residual risk [14]. The organisation responsible for the surveillance and verification of activities should be clearly identified [**Principle 4**].

There are several possible end points for the remediation process [12]:

- Use of the area may be unrestricted;
- Use of the area may need to be restricted in some or all parts and control may need to be exercised, for example, through a system of planning consents;
- Access to the area may need to be restricted and measures may need to be put into place to enforce this.

In each case, further surveillance and monitoring may be required to confirm the long term effectiveness of the programme of remediation, and additional controls may need to be imposed on the basis of the monitoring results.

The degree, extent and duration of control, if any, ranging from monitoring and surveillance to restriction of access, should be reviewed and formalised with due consideration of the residual risk.

So long-term stewardship results from the need to address the reality that 'clean-up' of facilities can not in all cases achieve conditions deemed acceptable for unrestricted use and will therefore require some form of management far into the future.

2.10.1 Defining stewardship

The long term and life cycle management of radiological liabilities requires certain provisions and institutions. In recent years the term stewardship has been coined to describe the various activities associated with the long term management of sites with radiological liabilities [16].

In general, 'long term stewardship' indicates the technical, societal and management measures needed to ensure the long term protection of humans and the environment at sites characterized by residual hazards after active remediation or assessment has been completed.

Different audiences have used the term 'long term stewardship' with different meanings. According to the Oxford English Dictionary, a steward is a person entrusted with the management of another's property. In this sense, stewardship in the present context means taking care of sites or land with radioactivity in the ground. More specifically, it refers to those instances or phases of such sites, where, for instance, active remediation has been completed, but residual radioactivity is left, not allowing the free release of the site or land.

Accordingly, the United States Department of Energy (USDOE) defines stewardship as:

> "*The physical controls, institutions, information and other mechanisms needed to ensure protection of people and the environment at sites where DOE has completed or plans to complete 'clean-up' (e.g., landfill closures, remedial actions, removal actions, and facility stabilization). This concept of long term stewardship includes, inter alia, land-use controls, monitoring, maintenance and information management*".

Long term stewardship may also be defined as:

> "*The implemented institutions, controls, information, and mechanisms necessary to protect the public and the environment from legacy waste, radioactively contaminated sites and/or groundwater, deemed impractical, unsafe, or too costly to remediate to free release standards* "[24].

Some other definitions can be read in a report by the National Research Council of the United States National Academies. This Council defined the roles of a long term steward of a site with long lived hazards as [56]:

- A *guardian*, stopping activities that could be dangerous;
- A *watchman* for problems as they arise, via monitoring that is effective in design and practice, activating responses and notifying responsible parties as needed;
- A *land manager*, facilitating ecological processes and human use;
- A *repairer* of engineered and ecological structures as failures occur and are discovered, as unexpected problems are found, and as (additional) re-remediation is needed;
- An *archivist* of knowledge and data, to inform future generations;
- An *educator* to affected communities, renewing memory of the site's history, hazards and burdens;
- A *trustee*, assuring the financial resources to accomplish all of the other functions.

The concept of long term stewardship is also known by several other names, depending on the organisation, for example:

- Long term surveillance and maintenance;
- Legacy management;
- Long term monitoring and surveillance.

The scope of a stewardship programme is outlined explicitly by the IAEA [6], [16]:

> "*The type, extent and duration of the restrictions and controls for site release can range from monitoring and surveillance to restriction of access to the site. They should be proposed by the operator on the basis of a graded approach and in consideration of factors such as the type and level of residual contamination after completion of clean-up; relevant dose constraints and release criteria; and the human and financial resources necessary for the implementation of the restrictions and controls. The restrictions proposed by the operator should be enforceable by the regulatory body and the clean-up plan should specify which entity will ensure that the restrictions are maintained*."

Depending on the prevailing regulatory framework under which clean-up is to be accomplished, either the state, regional, tribal, or federal organisations will have to bear the responsibilities and/or authorities for long-term stewardship.

Nevertheless, it would always be the objective of life cycle management to minimize the need for stewardship within an overall optimizing management approach.

However, developing successful monitoring, institutional controls, engineering controls, maintenance activities and information management to last for hundreds, even thousands of years required for these radioactively contaminated sites and structures is a huge challenge.

2.10.2 Integration of planning for stewardship into the remediation plan

Although the general consensus appears to be that remediation decisions and long term stewardship decisions are best made conjointly, this has not always been followed in practice. This bifurcation can result in stewardship plans that are difficult to implement and enforce, and disproportionately costly for the benefit they provide [140]. Ideally the remediation decision would be one step of the life cycle planning process, with the preference for a comprehensive plan that provides the greatest benefit-to-cost ratio over the life of the facility.

To complete a detailed remediation plan before operation is nearing completion, is recommended, but review and adjustment are likely to be necessary for practical reasons. Whatever stage in the process the site has reached, integration of the remaining steps into a life cycle management approach could improve short term decisions for long term benefits. For example, design decisions about the site layout can minimize both site disturbance and environmental impacts, while still providing operational efficiencies. If the site is in the remediation phase, considering the remaining life cycle in immediate decisions may indicate to decision makers, for instance, that slight increases in short term costs or worker risks may significantly reduce stewardship costs and minimize overall impacts.

In long term stewardship, the many decisions intended to minimize human health hazards and the environmental impacts that have been incurred earlier in the life cycle must be accepted (see Section 2).

The integration of planning for stewardship during the operational and remediation phases is not limited to physical actions. Other considerations may include the building up of trust funds for long term stewardship (see Section 5.2.10), avoiding foreclosing future options and taking contingencies into account when making decisions.

2.10.2.1 Maintenance/long term behaviour of engineering solutions

Design goals and boundary conditions of engineered solutions

Many opportunities exist to reduce long term stewardship costs, reduce environmental impacts and enhance the longevity of engineered features. Consideration of long term stewardship in engineering at the design stage, with periodic updating if and when required, is one of the critical areas to achieve this integration. A mentality of the minimally acceptable with the least short term cost could cloud leading decision making over the whole life cycle of the site.

Likewise the notion to remediate to background levels everywhere can also limit leading decision making by spending too much without gaining adequate benefit in performance or protection, while having an impact on the environment and potentially on worker safety.

While the ‘useful service’ or ‘design’ life of engineering solutions are certainly concepts that all design engineers are familiar with, the timescales are generally orders of magnitude shorter than those of interest in the present context. For most civil engineering structures, continuous or periodic maintenance is also implicitly assumed. Methods and concepts to predict the long term behaviour of near surface structures are still in their infancy, while the problem itself has been explicitly recognized in the context of the performance assessment for radioactive waste repositories.

Thus, the erosion resistance features can be modelled on the basis of short term data, but methods to assess the long term performance need to be developed on the basis of insight into geomorphological processes. Basin scale, statistical studies, rather than discrete mechanistic studies, might provide the necessary insight.

The long term stability of engineering structures has also to be assessed in view of the probability of major accidents such as seismic events. Over the last few decades, highly engineered capping designs have been developed, which are also commonly required by regulators with the intention of reducing radon emanations and external exposures to gamma radiation, as well as minimizing water infiltration. However, these designs are likely to retain their high sealing performance for only a limited period of time. Signs of deterioration in performance (an increase of permeability in the sealing layer) are usually already observable 5 to 10 years after emplacement. A good way forward to ensure long term stability of the capping appears to be an emulation of the natural soil structure as found in the vicinity of the remediated site. Although such ‘natural’ capping designs (with the use of long lasting natural materials and structures mimicking as far as possible the natural soil profile) are likely to have a lower immediate sealing performance than plastic liners, for instance, this will be outweighed by their long term stability.

Recent flooding events in various parts of the world often seem to indicate, inter alia, that the design basis, in particular with respect to the magnitude of infrequent events, is insufficient. Precise flood water level records only go back some 100 years, while anecdotal evidence may extend this to a few hundred years. Thus, a design basis may not capture an event that occurs, on average, every 1000 years. Similar effects may occur in areas other than flood defences.

Design for long term stability

In order to select and implement the most efficient design from the point of view of self-sustainability over the long term, learning from natural processes and environmental behaviour may be a valuable strategy. The paradigm is engineering with nature and not against it.

The natural evolution of soils and diagenesis also give valuable insights into the development of long term management plans. The contaminated material will not remain unchanged in the long term, and assessment of its evolution will give confidence in the project if diagenesis improves the retention of contaminants.

Limiting infiltration will reduce the need for seepage control downstream. Long term management of the quality of drainage or seepage from the site is best provided for by some form of passive water treatment. Active water treatment plants are labour and maintenance intensive, and there are no guarantees that the resources will be available over the longer term. Passive forms of treatment may include, for instance, either a limestone layer to prevent the formation of acid drainage or a wetland to polish seepage water before release to surface water courses [43].

Cappings and similar features are also intended to prevent bio-intrusion. The structure of the cover, as heavily engineered as it may be, may not be able to prevent root intrusion in the long term if it has not been designed to be compatible with the natural vegetation cover and plant succession typical of the surrounding environment.

The ecosystem around a remediated site is the result of a process lasting for centuries or millennia and is shaped by a wide variety of initial conditions and contributing factors, such as the initial rock type, climatic evolution, and surrounding flora and fauna. The result is a (dynamic) equilibrium between soil type, vegetation cover and climatic conditions. Any attempts to reconstitute an ecosystem at the site, such as revegetation; need to be as compatible as possible with the surrounding ecosystem(s).

The final use of the site needs to be compatible with the ecosystem in order to minimize pressure on the site due to human use. Any environmental impact study is intended to assess the potential of a site to be integrated into the surrounding environment. Indeed, the best shape for a remediated site is achieved when it is compatible with the surrounding geomorphology. This concerns in particular slope stability. From a geomechanical point of view, gentle slopes contribute to achieving low relief energy.

Natural geological processes achieve this over millennia, and engineered structures may benefit from observation of the evolving geomorphology and slopes around the environment of a site.

While completing engineering for remediation, consideration of the stewardship requirements on a site-by-site basis is recommended. In general, when considering stewardship the following points should be kept in mind:

- Designs with low inherent (potential) energy are preferred to designs with higher energies. This applies in particular to geomorphological relief energy: all above ground structures are subject to the forces of erosion and will eventually disappear, starting, of course, with any engineered capping. In addition, the surrounding environment may have a high relief energy, although the actual engineered structure may be below the surface (see Figure 2.12).

- Designs with a low likelihood of failure and limited effect if failure occurs are preferred to those that are less reliable: for example, self-sustaining systems and approaches such as waste rock or tailings cemented by geochemically stable secondary minerals or vegetated slopes similar to naturally sustainable slopes in the area would probably have a good chance of surviving the long durations required for long term stewardship.
- Designs that mimic diagenetic processes are preferred.
- Designs that maximize natural systems in the area and are compatible with the surrounding area are preferred. Experience with existing disposal cells and similar structures indicate that nature soon attempts to encroach on cells. This experience favours designs with an ecosystem type of approach rather than a barrier control one.
- Designs that are based on natural attenuation and retention are preferred [144].
- Designs that include redundancies in protection are preferred.

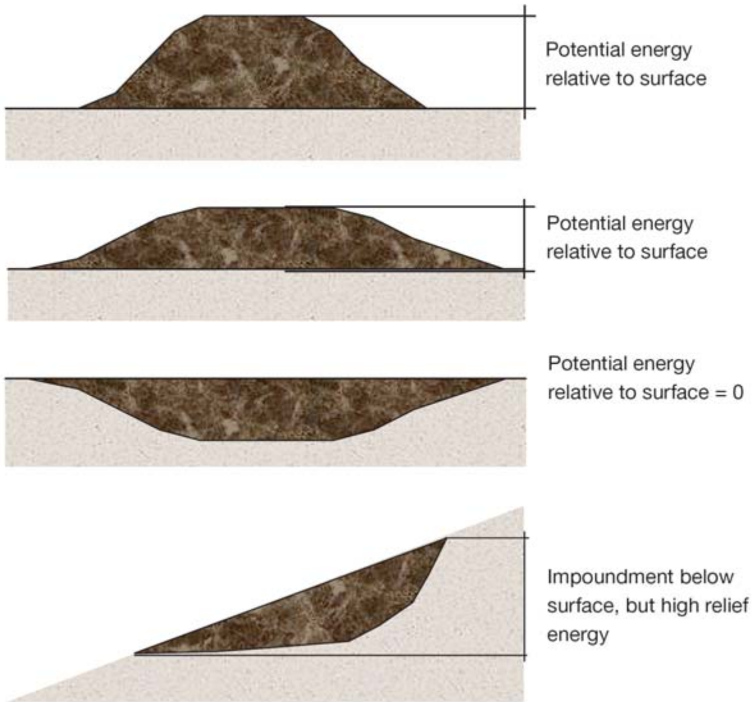

Figure 2.12 Diagrams illustrating the concept of inherent potential energy in the design of impoundments

A technical issue related to intergenerational communication is the longevity of permanent markers to warn future generations of previous land use and possible residual hazards, for example gravestones and other forms of visual sign. As this form of communication may be the final layer of defence for warning future populations, markers and signs must be developed with great care to ensure physical longevity. The problem of coding the information is discussed in Section 2.11.3.

2.10.3 Transition to the stewardship phase

When an extended period of institutional control is the selected management option for the site, the active remediation period will be followed by a period where control might be transferred to the steward, who might be another party. This would require appropriate planning and regulatory control [141]. The major milestone in this process is the decision that clean-up has been achieved.

Table 2.11 Criteria for the transition from closure to longterm stewardship [142]

Transition criteria	Description
Regulatory based transition criteria	Results of the periodic review indicate that the results of the remediation actions meet the plans. For sites where residues remain a post-closure plan has been approved, a survey plan recorded and the ompetent authorities notified of the volumes and types of residues present. Performance assessment has been made and analysis requirements have been met. Title, deeds, property transfer documentation and any deed restrictions or covenants have been put into place prior to the transition. The long term stewardship plan has been approved by the competent authorities.
Infrastructure transition needs	All required physical and administrative institutional controls are in good condition. All accesses and utilities required for the site have been maintained. Monitoring wells, monitoring equipment and ancillary equipment are in good condition. Monitoring data and maintenance records have been reviewed to determine the condition of the wells, and procedures are in place for maintaining and monitoring the performance of the equipment. Any leachate collection system, related monitoring equipment and ancillary equipment are in good condition. Groundwater remediation equipment is operational, maintained and monitored. Engineered caps or covers are in good condition. Monitoring data or the results of periodic reviews indicate that the cap is performing in accordance with closure requirements. Physical site boundaries have been located and are consistent with the legal description recorded with the appropriate authorities and any deed restrictions.
Record keeping	The project file contains management plans, i.e. sampling, quality assurance and quality control (QA/QC) and monitoring plans, and final decontamination and decommissioning reports. Monitoring data and maintenance records have been reviewed to determine the condition of the wells, and procedures are in place for conducting maintenance and monitoring performance of the equipment. Data necessary for long term stewardship have been identified and documented, and the data types have been defined. Institutional control requirements have, if required, been incorporated into the land use plan. Site documentation and project files contain the residual contaminant source term, contaminant concentration and location, and potential risks to human health and the environment. Site documentation and project files contain current as-built drawings of surface and subsurface site features, residue locations, engineered features, monitoring wells, access and physical institutional controls. Required land use restrictions have been properly recorded with the competent authorities. Historical and archaeological resources at or near the site have been located and documented. Ecological concerns that may require modification of long term stewardship activities have been documented. Safety analysis reports, emergency preparedness documents and management plans are all in existence.
Scope, schedule and budget	There is a transition schedule that includes adequate review periods for documentation, site inspections and development of additional documentation. The basis for the transition is included in the description of the proposed site. The resources and personnel that are critical to accomplishing the tasks that are required in the transition phase have been identified. There is a listing of baseline changes that have been approved or of any new contracts or modifications necessary before the transition can take place. The expectation that the site will continue to perform as designed over the design life period is inherent in the long term stewardship process. The proposed site scope has to be consistent with regulatory requirements.
Special conditions	Any special historical or cultural/archaeological resources are identified and documented as well as reviews required of the condition of historical or cultural resources under stewardship. Any special ecological concerns such as the management of threatened or endangered species are included in the scope and cost estimates. Special management conditions for sites exposed to natural hazards, such as flooding or earthquakes, are documented and incorporated into the management plans. Storm water requirements are incorporated into the long term stewardship plans.

Provisions need to be made for a scheduled and smooth transition period in order to ensure (also see Table 2.11) that:

- All the necessary responsibilities have been transferred and there are no uncertainties over which responsibilities belong to which party.
- All necessary records have been preserved.
- There is continuity of the post-remediation and compliance monitoring activities as well as maintenance of the necessary infrastructure.
- The engineered containments for the residual contamination continue to be maintained.
- There is uninterrupted compliance with site use restrictions and other controls to ensure the integrity of any engineered containments.

In reality, it may be a question of definition when the active remediation period ends and when a site is actually transferred into the long term stewardship phase. This may also occur at different times for different environmental compartments. For instance, at a given site a groundwater treatment scheme may continue long after the surface soil remediation has been completed. Thus, while the site use may be controlled under a stewardship programme, the underlying aquifers may still be actively remediated. If the groundwater remediation is carried out by the steward, it could be claimed, however, that this is part of the stewardship programme.

Several stewards may be involved for a given period of time with the same site: one could be a user of the surface area, while another organization is responsible for the monitoring of the groundwater and possibly its remediation.

The range of activities, decisions and related records for the transition of a USDOE site from closure to long term stewardship is discussed, for example, in [143]. The slow progress of remediation and towards stewardship has been a major concern at many sites, and strategies have been developed to accelerate this transition.

2.10.3.1 Consideration of non-radiological hazards

While this document is concerned with residual contamination from activities involving radioactivity, most, if not all, radiologically contaminated sites will also exhibit some level of non-radiological contamination. This comes primarily from the fact that many sites will have had a number of different processes occurring on them historically. Practices that would not be acceptable today may have led to chemicals and hazardous materials entering the soil, surface water and groundwater, for example due to inadequate containment, poor disposal practices or accidents. In the case of mining, for instance, operators may have not been aware of the hazard posed by certain constituents in the geological material they have been using.

There are a number of potential problems with sites exhibiting cocontamination [7]. For example, in many countries the legislation dealing with radiological and non-radiological contaminants may differ considerably, both in terms of environmental risk assessment and in authorization for disposal.

The environmental risk from non-radiological contaminants may in some cases be greater than that from the radiological species present, but this is often ignored due to the general perception of increased risk from radioactivity.

The presence of other contaminants alongside radionuclides may result in the latter’s mobilization or attenuation through changes in chemistry [144] It is only through a comprehensive knowledge of all contaminant species present that predictions of remediation success and engineering integrity can be made.

2.10.4 Provision of a skill base and retention of knowledge

Successful execution of stewardship requires a range of special skills and knowledge frequently akin to that required for the original operations at the site in question. However, closing down the original operations typically leads to key qualified staff seeking employment elsewhere. Assigned stewards have to develop strategies to retain qualified staff or a roster of qualified consultants and contractors.

The maturing market for environmental services from the mid-1990s onwards raises concerns over the availability of a suitable workforce to implement remediation and the early stages of stewardship programmes. If the nuclear industry itself has ceased to evolve or even exist in the future, there will also be the possibility that the qualified workforce will become depleted. It is important, therefore, that a small skill base be somehow retained for both the short and longer terms. As the land use will undoubtedly have changed, the skill base itself will need to change in an appropriate manner in order to manage the new facets of the site.

The shorter term aspects are again easier to cover. Reorientation programmes, such as that of the International Science & Technology Center (ISTC) [145] that aims to redirect Russian weapons scientists to civilian projects including environmental ones, may be useful. Similar activities are taking place in support of the redirection of the major US national laboratories. In USDOE complexes a range of strategic measures and incentives for employees are used:

- Establishing a database for all the activities covered by the US Office of Environmental Management for critical questions and initiating mechanisms to foster temporary assignments;
- Offering incentives to employees eligible for retirement to delay their departure so as to work at closure sites;
- Removing salary offsets for retirees and offering other incentives to reemploy retirees at closure sites.

2.10.4.1 Development of management tools

The fact that there are always alternative approaches to set up long term stewardship programmes necessitates quantitative comparisons of the various alternatives at both the planning and operational stages. A variety of such tools, including cost-benefit analysis, decision analysis and prioritization processes, are available but few of these are tailored to the specific needs of a long term stewardship programme.

In order to foster trust and ensure traceability of decisions on remediation work and other activities leading towards stewardship, all work should be carried out to internationally recognized standards, such as ISO 14000 [146], for which specific guidance would still need to be developed.

2.10.5 Start of a long term stewardship

Figure 2.13 shows the generic life cycle management of a (nuclear) facility [16], [56]. The early stages of the life cycle consist of identifying the need for an activity site and selecting the site as well as designing, constructing and operating the facility (e.g., a facility processing minerals causing a contamination of NORM or TENORM material (Technically Enhanced Natural Occuring Radioactive Material) or a nuclear facility.

At the end of the operational phase, the site undergoes decommissioning and active remediation. Decommissioning involves actions such as decontamination, demolition and dismantling of buildings and equipment, and sometimes waste conditioning depending on national regulations and licenses.

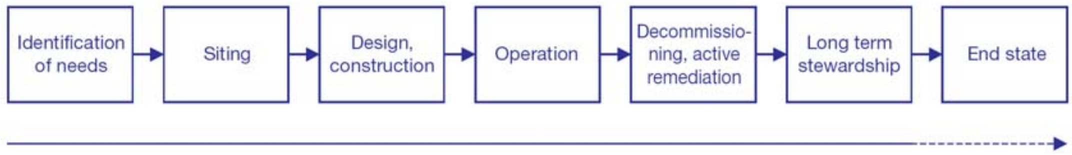

Figure 2.13 Life cycle management

During active remediation, engineered, physical and chemical measures (e.g., caps, liners, reactive barriers and micro-organisms) may be put into place to protect human health and the environment. In some countries, decommissioning and active remediation are considered as an integrated process. In these countries, the boundary between decommissioning and the onset of site remediation is blurred, and there might be different cycles of decommissioning and site remediation. In some countries, these cycles may last for decades to allow the decay of short-lived radioactivity and this process is called 'safestore'.

In these cases, there may be interim 'fit for purpose' land uses at the end of each cycle. In contrast, in other countries, decommissioning is completed before site remediation begins, so that the boundaries are clearly defined.

A site may also be split into sub-sites that are fit for free release and others that require institutional control. A suitable split may greatly facilitate a subsequent stewardship programme.

The determination of estimation of the time when remediation is complete and long term stewardship begins may differ between countries and may well vary for different types of sites within a country [16]. Many times the determination of when remediation is complete is based on when the regulator certifies or by some means designates that the remedial actions taken have met the originally established remedial objectives. Groundwater remediation in some cases tends to have very long remedial durations, which creates a unique timing issue over when remediation is complete and long term stewardship begins. The duration depends on the time needed for active water treatment. This is a critical issue to consider early in the remediation phase, especially if the parties responsible for remediation and long term stewardship are not the same entity or may change over time.

Long term stewardship begins after the end of decommissioning and active remediation [16]. The intermediate guarantee phase of several years that is sometimes imposed for engineered structures, etc., might be viewed as part of the active phase or already be part of the stewardship phase. Long term stewardship fundamentally does not encompass any active remediation. Hazards on the site will have been removed or been contained by engineered systems put into place during the active remediation phase, or natural processes, such as attenuation, dispersion or radioactive decay, will have been used to keep exposures below levels of concern. Long term stewardship primarily involves the care and maintenance of the site and any structures built as part of the remediation solution. Monitoring activities ensure that the remediation solution behaves as predicted and that any land use restrictions are complied with. In some cases, a permanent solution may have been deferred until a (more) suitable remediation technology has been developed, and the site has been put into a stewardship-like state in the interim period.

A long term stewardship programme is being developed during the active remediation and decommissioning phase, and addresses monitoring and maintenance as well as including provisions for corrective actions in case of deviation from the predicted behaviour of the site. The final end state is ideally the unrestricted release of the site. However, if any control measures remain necessary, long term stewardship needs to be put into place. If unrestricted release is not possible, the site can still be used for specific purposes (e.g., industrial use) but the steward needs to ensure that the restrictions are complied with.

2.10.5.1 Overview of long term stewardship drivers

Principal drivers for needing long term stewardship at a site may be a combination of:

- *Priorities* - Owner, local, federal priorities may not support funding for clean-up to free-release levels;
- *Long-lived contaminants* - Radionuclides, chemicals, and metals may not be easily or quickly broken down to safe constituents;
- *Lack of technology* - No further environmental benefit from remediation may be attainable with existing technology or asymptotic levels have been reached, e.g., groundwater and vadose zone;
- *Risk* – Short term human health or environmental risks of conducting remedial activities may outweigh the benefits of remediation.

2.10.5.2 Challenges of long term stewardship

The challenges of long term stewardship are associated with the time frames under consideration. Many regulations assign authority and responsibility for environmental contamination into the foreseeable future, i.e., decades, but residual contamination at facilities or sites may remain hazardous for a very long time. The objectives of long term stewardship should be to ensure adequately long-lived monitoring, institutional controls, engineering controls, maintenance activities and information management for the related radioactively contaminated sites and/or groundwater.

The societal aspects of long term stewardship may present several important challenges, such as building trust, communicating the nature of the risks and of the remediation and stewardship options, reconciling economic, management and technical issues with considerations of public values and beliefs, resolving ethical questions and engaging stakeholders in the decision making process, and thereafter retaining stakeholder commitment [16].

2.10.5.3 Components of long term stewardship

Many aspects of long term stewardship are intended to maintain the long term protectiveness of the remedy. Components of long term stewardship therefore should include:

- *Management* - Stewardship for radiological liabilities must be framed for very long time horizons. Given the long half-lives of many relevant radionuclides, and compared to the average human life, “long term” in essence means eternity. However, it is also clear that, during the life cycle of site management, the stewardship will encompass an extremely broad range of issues and activities [16].
- *Institutional/Administrative Controls* - Control exposure to hazardous substances by establishing (governmental) controls and providing legal enforcement tools. It is recommended that institutional control activities defined for a remediated site where restrictions are maintained after remediation has been completed should be included in a monitoring and surveillance plan that should be subject to periodical review and to approval by the competent authority.
- *Physical/Engineered Controls* - Implemented to treat or stabilize contamination, to physically contain or isolate waste, or to prevent access.
- *Monitoring and Maintenance* - Ongoing environmental monitoring to determine the effectiveness of the remedy, improve understanding of the contaminant interactions with the site, and support maintenance of engineered controls to guide decisions on when and how to modify long term stewardship activities.
- *Information Management Systems and Repositories* - Maintenance of environmental data and other information relevant to the remedy including public communication. When sites make the transition from clean-up to long term stewardship, site stewards and stakeholders should be given detailed information about the location and the

nature of residual hazards, the processes that generated them, and the engineered and institutional controls that are part of the remedy [**Principle 5**].

- *Periodic review of the remedy and, if needed, alteration of the remedy* - At regular intervals, for example, every five years, a review should be conducted to evaluate the implementation and performance of a remedy in order to determine if the remedy is or will be protective of human health and the environment.
- *Site access* - Restriction of access to contaminated sites and/or institutional control may be required to be maintained in cases of serious residual contamination [12].
- *Removal of restrictions* - If the monitoring and surveillance programme has verified the long term effectiveness of the remedial measures in eliminating unacceptable risks to human health and the environment, consideration should be given to removing any restrictions applied to the site and ending or reducing the extent of the monitoring and surveillance.

2.10.6 Societal and ethical challenges relating to long term stewardship

The societal aspects of long term stewardship may present several important challenges, such as [16]:

- Building trust at the stakeholders. Stakeholders in the specific case of long term stewardship may be different as during the remediation of the site and should be identified;
- Communicating the nature of the risks and of the remediation and stewardship;
- Defining societal criteria for defining and implementing stewardship strategies;
- Managing ethical questions and engaging stakeholders in the decision making process and thereafter retaining stakeholder commitment [16].
- Keeping stakeholders involved;
- Reconciling economic, management and technical issues with considerations of public values and beliefs.

Contaminated sites are socially constructed risks. As in the case of most socially mediated risks, the significance - and hence the acceptability - to an individual, to members of a community or to a society, of exposure (or a danger of exposure) to a dose, depends on how, by whom and why the dose has been produced. Correspondingly, in order to assess to what extent or on what basis the members of a society will judge acceptable (or not) a given strategy for management of high level long-lived radioactive residues, it is necessary also to consider the meanings and relationships (in social, economic, cultural and symbolic terms) that alternative remediation and stewardship strategies might establish between the people - individuals, classes, interest groups, succeeding generations and whole nations - implicated in the site stewardship process.

2.10.7 Optimisation of the remediation and long term stewardship process

In future all kind of public and private organisations will continue to spend a lot of financial means on the characterisation and assessment of contaminated environmental media and on the selection, construction, operation, maintenance, and monitoring of environmental remediation systems [28]. As the various environmental clean-up statutes and their implementing regulations evolved, the initial assumption was that these programmes could follow a basic “study, design, build” linear paradigm. However, years of experience has led to the realisation that the significant uncertainty inherent in environmental clean-up requires more flexible, iterative approaches that manage uncertainty. Uncertainty, as demonstrated by frequently missed target dates, has forced the development of mechanisms that allow for both the systematic re-evaluation of initial objectives and the continuous improvement and optimisation of remediation technologies and techniques. These mechanisms and re-evaluations are known collectively, or generally, as “remediation process optimisation” (RPO). With schedules for projects in the operating and maintenance or long term remedial action phase frequently being measured not merely in years, but in decades, remediation process optimisation is not a just option, but a necessity.

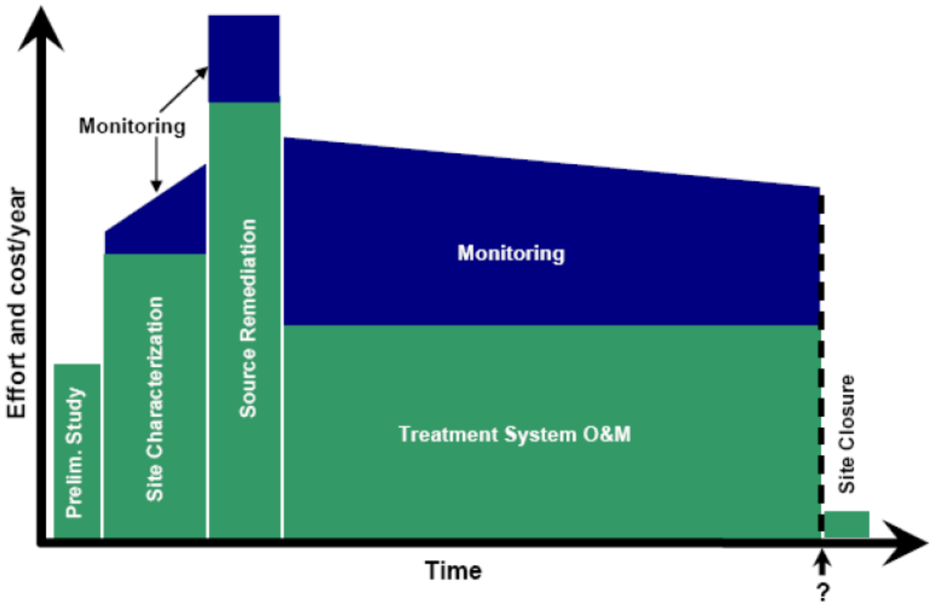

Figure 2.14 Effort versus time in typical remediation actions

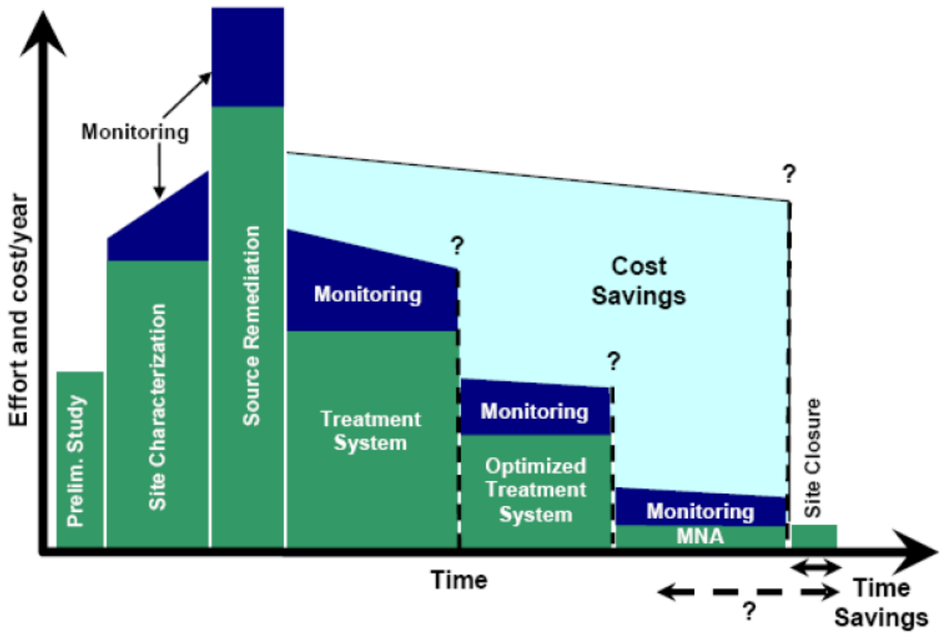

Figure 2.15 Effort versus time in remediation actions with remediation process optimisation (RPO)

In the initial stages of a remediation action, much of the effort is on characterisation and source remediation; limited effort is spent on monitoring. As the project matures, most of the resources are spent for monitoring and operations and maintenance. Figure 2.14 depicts effort and cost versus time for a typical conventional remediation action at a contaminated site. As shown by the dashed line, at most sites it cannot be assured how long it will take to reach closure.

A remediation process optimisation review is a way to evaluate the status of the remediation process and get an idea of when to expect closure. Instead of continuing with a long term operations and maintenance period, the cost as well as the time to completion can actually be reduced through the process of optimisation, as shown in Figure 2.15.

Depending on site-specific conditions, such a remediation process optimisation review could result in substantial savings.

The primary goal of remediation process optimisation should be to ensure that the remediation process is progressing toward site clean-up objectives that are both acceptable and feasible and that selected remediation approaches attain those objectives and remain protective of human health and the environment. Taking account of the general regulatory and technical framework for evaluating remediation processes, regardless of the type or complexity of the remedy, remediation process optimisation should not just look at the "how" of remediation, such as the technologies in place, but also at the "why," which may be described as the conceptual site model that considers all factors involved with the site remediation, such as the environmental and (current and future) land-use plans, site-specific chemical and geologic conditions, and the regulatory environment.

The regulatory environment establishes the need to review and possibly revise clean-up goals to ensure their continuous applicability. As a result, scientific advances and regulatory changes, such as the movement towards risk-based goals and re-evaluation of technologies deployed, are core features of a comprehensive remediation process optimisation review. Therefore, consideration should be given to the re-evaluation of remediation goals and ways that potentially inapplicable or unattainable goals can be updated based on these and other new regulatory approaches.

2.10.8 End of a long-term stewardship

The length of the long term stewardship phase depends on the half-lives of the residual radionuclides of concern [16], [56]. For some sites, where relatively short-lived radionuclides such as ^{137}Cs and ^{90}Sr are the problem, the period of stewardship can be of the order of hundreds of years. Where long-lived radionuclides, such as many of the isotopes of uranium, thorium and plutonium, are the problem, the stewardship period may have to last effectively for ever.

It can be noted that these considerations also become more and more important and receive increasing public attention in the case of 'conventional contaminants' such as heavy metals, persistent organic pollutants and other toxic or hazardous substances. The term 'long term' is interpreted differently in different countries.

Administrations in various countries have adopted for practical reasons certain time spans; thus a 1000 year basis may have been selected for engineering designs in this context.

2.11 Record keeping

2.11.1 General considerations

Future generations will command more knowledge and capability than the present generation [16]. However, knowledge and insight might also be lost.

The majority of texts on subjects, such as knowledge management, are concerned with the preservation of knowledge as a corporate (or group, such as the nuclear industry as whole) asset. In this sense, it is about ensuring that the knowledge of an individual is shared with others and about making this knowledge available at any time. In the present context the time horizon is much longer and may go well beyond the lifetime of individuals or corporations, even beyond the duration of a society. Moreover, site specific knowledge and information may be much more vulnerable to loss than are generic knowledge and capabilities.

Long term knowledge management and the intentional transmission of information will have to address four main issues:

1. How to transmit knowledge over long periods of time;
2. The kind of knowledge to be stored;
3. The types of data and information needed;
4. The types of storage media.

The first of the above issues is the most important and the most difficult to resolve.

2.11.2 Knowledge forms and knowledge sharing

Successful site remediation and stewardship, especially when with a multi-stakeholder base, needs to address a variety of challenges about knowledge sharing, i.e., its exchange and 'translation', allowing understanding between people in different occupations with different kinds of knowledge, and in their leisure as well as professional situations. In the science/environmental policy/sustainability fields there are many barriers to effective communication and sharing of knowledge. For example, within the scientific field, 'formal' scientists and technical experts do not always recognise and reciprocate the informal scientific knowledge, creativity and innovation existing at the grass-roots level of society.

Members of a community living in a given area may often have a rich informal knowledge of what has taken place in the past, of the functioning of ecosystems, of sources of risk and of hazards. Sometimes this knowledge is associated with traditional communities in an area. There is also informal knowledge in industrial contexts. Just as farmers may have good insights into local hydrology, workers in factories and mines may have intimate understandings of the workings of machines and of the properties of wastes and residuals. Awareness of what has really happened to wastes, and why, can be of great value for the design of remediation programmes and for the monitoring of contaminated sites.

For a variety of reasons, including proximity, the 'non-experts' can sometimes 'read' or 'observe' the world in ways that are not available to formal experts coming from outside. Dialogue and stakeholder consultation can, in principle, ally formal and informal expertise. Stakeholder deliberation may then, in a variety of ways, contribute to the identification of concepts and criteria for a socially satisfying solution. However, this type of pragmatic science based on observation and confronting local and day to day problems may not always be articulated or acknowledged. Policy makers and resource managers may sometimes evolve filters and structural barriers that prevent them from recognising the potential that exists for blending formal and informal science. One reason that informal knowledge may not be used is that the systems for training experts, as well as some bureaucratic tendencies, favour standardised solutions - and so they treat as inconvenient the specificities of sites and ecological (as well as social) heterogeneity. Incentives for investing in knowledge and technologies with a strong site specificity, and hence with limited potential for generalisation, may be very low.

Mobilising knowledge for sustainable development and stewardship requires attention to the forms of knowledge sharing, including their institutional, technical, economic, linguistic and cultural pre-conditions. Social trust and partnerships are constructed through dialogue and cooperation - among scientists and technical experts with policy makers, implementers and stakeholders - including experts with site specific (local) knowledge that complements methodological and coordination expertise. Knowledge as a resource must be accessible to the actors and pertinent to the context of their action.

Following these arguments, it is important to adopt a pluralistic approach to building the knowledge base. Science (understood as the activity of technical experts) should be considered as an important part of the relevant knowledge base that needs to be developed and mobilised in order to provide evidence in a decision or policy process. However, the ideal of rigorous scientific quality assurance should be complemented by a commitment to open public dialogue. Citizens and stakeholders should have a fundamental role in a knowledge partnership process. The strength and relevance of scientific evidence is amenable to assessment by citizens, who contribute to the framing of the issues and to judgements about the acceptability of proposed solutions. In this perspective, all parties should come to the dialogue ready to learn. Through this co-production of knowledge, the extended peer community should create a (deliberative) democracy of expertise.

2.11.3 Records

A ‘record’ is an item of information about a site in question. The information may be represented or coded in a variety of ways and on a variety of materials. Typical examples are text, numerical data, maps and drawings on paper, photographic images on film, or digitised information on magnetic (tapes and floppy disks) or optical (CDs and DVDs) storage devices (see Figure 2.16).

A second important property of a record is that it is not an end in itself but that it has a purpose. The purpose is to document and convey knowledge and information.

To ensure that records do not cause in future generations an effect opposite to the one that is intended, it is most important to put much emphasis on the transfer of information, for example, by means of education.

Figure 2.16 Monoliths used as markers to delineate a radioactive waste burial site: granite marker plot M, in the Palos Forest preserve, Cook County Forest preserve district, photograph courtesy of R. Del Tredici

2.11.3.1 The need for records

Records should serve two main purposes:

1. To provide possible and actual users of a site with information on possible or actual hazards;
2. To provide those in charge of controlling or mitigating such hazards with the necessary operational information.

Different stakeholders are likely to require different types of record. As a result, efficient and effective stewardship and the related decisions should only be based on documentation containing all the information relating to the site in question. It should constitute the institutional memory and cover the following fields and corresponding physical records:

1. Documents related to the decision making process, for example, working documents justifying the decision taken.

2. Historical records, for example, operational records that help people to understand the site and its surroundings and provide information on the origin of the potential hazards due to the site, decommissioning records, and records on remediation measures undertaken and remediation verification.

3. Records that document the current state of the site and are ‘live’ documents that are necessary during the next phase, for example, the transition phase or the stewardship phase of the life cycle period; in this case, environmental management plans, environmental monitoring results over time (such as groundwater quality and discharges) and inventories.

4. Records and maps of the site showing the geographical location, topography, geomorphology, site boundaries, geology, hydrogeology, hydrology, water balance, meteorological information (and changes over time), site investigations and characterisations (including those relating to any pre- and post-remediation activities).

5. Incident and accident records associated with potentially contaminating events, records of active and non-active waste disposal sites and chemical stores.

6. Factual records relating to environmental parameters used in contaminant fate and transport modelling, for example, rock porosity, hydraulic conductivity and sorption coefficients.

7. Interpretive records relating to the predictive behaviour of contaminants through time, quantitative risk assessments.

8. Official records of decisions, such as licences and permits, and legal opinions on applicable laws.

9. Copies and excerpts from official records deposited elsewhere, for example, in land registers, cadastres, deeds, registered mortgages, securities and deposits, registered land use restrictions and rights of way or access have been a long standing means of conveying important information on sites. They may record not only ownership but also other important information, including use restrictions and rights of access.

10. Church books and registers frequently date back to the early seventeenth century and may record events that are of interest in mining areas.

2.11.3.2 Records management challenges

At many contaminated sites, an extended period of time may be required in order to complete the active remediation, which may then be followed by institutional controls to allow passive remediation of the residual hazards. The storage of important site records must therefore be carried out for periods that may range from some decades to hundreds of years, or even thousands of years, though this is probably rather optimistic. Storing (physical protection) the records securely over these periods of time in itself is not sufficient, they must also be understandable and accessible (protection of the contents). There are many significant technological issues associated with long term storage of records, and many unknowns with regard to reasonable practices:

1. The current practices of storing records in hard copy form (e.g., paper) and in electronic form give rise to technological issues with regard to longevity.

2. The design and operation of records storage facilities to prevent loss events is of considerable importance. This is especially important in areas of the world where natural and human-made hazards are significant.

3. Accessibility to records requires sound approaches to their indexing. Because many sites requiring long term institutional controls may be large and complex, large volumes of records should be accessible over long time frames; hence indexing methods should be established with great care.

A decisive management issue is the classification of the importance of records, and the establishment of retention periods for the different classes of record. The development of classification criteria is not a simple matter: questions of relevance and quality arise, and may be viewed differently by different groups of stakeholders. Older records are often less in quantity and of lower quality than comparable newer records - in terms of the level of detail in the records. However, being the only records available for the period in question, they may still have to be retained.

Establishing and operating dedicated effective records management facilities may be costly and the need for them is often not very well appreciated by certain groups of stakeholders, in particular when they do not see any immediate benefit for themselves. Records are often deposited with existing (national) facilities, such as archives and libraries. Cataloguing and storage practices may need to be adapted to stewardship needs.

2.11.3.3 Types of data and information needed

Typically, data on the type of residual contamination (chemical and physical properties), its exact geographical location and the type of remedial and other countermeasures should be included. In addition, and in particular for sites where long term changes in chemical (seepage and groundwater) or geotechnical properties are to be expected, it may be important to retain specific monitoring data. However, different stakeholders may have different data and information needs. Views on types of record to be kept and to what extent may vary between the organisation responsible for the site and other stakeholders.

Experiences relating to information needs in existing projects have shown that:

- All current and future stakeholders will require information in summarised form.
- All stakeholders are concerned about loss of information and knowledge.
- Detailed data needs vary on the basis of responsibilities and are not entirely defined.
- A variety of stakeholders require access to photographs, aerial photographs, maps and other spatially related information.
- Access to post-closure monitoring data will be required should such monitoring be necessary.
- Access to pre-closure monitoring data will be necessary for those in charge of regulatory compliance verification.
- All stakeholders require access to data on monitoring institutional controls.
- Public stakeholders have a need for information related to the impacts of contaminants.
- The information needs of former site workers are rather distinct from the needs of other stakeholders, and are defined through regulations and/or litigation procedures.

Other experiences have identified a range of information types that typically would be searched for by stakeholders:

- Custody and long term care licensing;
- Site operations and treatment systems;
- Property information;
- Site surveillance/inspection reports;
- Legal documents;
- Site maintenance information;
- Site specific legal agreements;
- Community relations/public involvement;

- Institutional controls;
- Health and safety;
- Use and operations history;
- (National) environmental policy;
- Permits;
- Programmatic plans;
- Completion/closure reports;
- Physical site data;
- Waste management and disposal;
- Environmental data;
- Site specific technical studies;
- Radon and environmental hazards and related monitoring data;
- Correspondence on decisions;
- Groundwater and surface/leachate water monitoring;
- Quality assurance;
- Records.

The following spatially related information has been experienced to be of greatest interest:

- Monitoring locations;
- Site boundary;
- Institutional control boundary;
- Contaminant plume;
- Groundwater compliance monitoring network;
- Topographic contours;
- Aerial or satellite images;
- Potentiometric surface contours;
- Disposal cell boundaries;
- Monitoring well lithology and completion log.

The data needs and the interest in information may change over time, however. It is likely that the interest of the public may diminish after a few years, and only those data relevant to potential redevelopment may remain of interest.

2.11.3.4 Selection of records for retention

A major challenge in record keeping anywhere is the decision about which records to retain and which records could be disposed of. As has been discussed above, the importance that is attached to a certain record may change with time and depend on the stakeholder concerned.

A categorisation of records according to levels of importance, such as critical, necessary or useful, might be helpful in deciding which material requires most attention and in focusing resources on its preservation. A road map that indicates in which way the importance of a certain record changes with time might be a useful management instrument.

The timescale of retention of individual records would be determined by the needs of the stewardship programme. Certain records would be reclassified as time progresses; for instance, operational records would become historical records. A risk assessment may need to be undertaken in more complex cases to achieve a balance between the possible cost arising from no longer having certain records available and the cost of storing these records. It may actually be cheaper to store all records indiscriminately than to scrutinise them and make selections - with the risk of destroying some that may later be deemed valuable. For certain types of record there may be legal requirements to retain them for a specified period of time; for example, tax offices may require that documentation supporting tax returns be kept for a certain number of years, or a contractor may be required to retain certain records for warranty purposes.

In addition to the operator and their successors, for example the steward, the regulator may also have collected various types of record. Often, these duplicate records may have been generated or held by the operator and may provide a certain redundancy. Different rules and regulations for retention may apply for the regulator and other government authorities. Some governments may have a well established system for assessing and retaining records. The regulator may require the operator to prepare a summary report on records held.

2.11.3.5 Quality requirements and standards for record keeping

A number of generic quality requirements may be formulated that may serve as guidelines for records management and for the selection of record formats and materials. Records ideally should be:

1. Robust;
2. Independent of time, or flexible enough to cope with changes over time;
3. Not reliant on individuals, organisations or technologies;
4. Able to withstand catastrophic events and attempts at sabotage;
5. Reliable, i.e., capable of capturing, managing and delivering all the information that needs to be collected and collated;
6. Transparent, i.e., the structure of the information management system should be open and clear (not a ‘black box’), and software tools to be of the open source type and to allow export of data in a structured and standardised form;
7. Structured, i.e., records created with a contextual purpose in mind and containing metadata (data about data) should ensure that the context is clear in order to aid understanding.

The International Standards Organization has produced standards for information and document structures, records management and metadata structures that describe records. The International Council on Archives has produced standards designed to ensure that records are described, indexed and managed in a form that enables users to access records relative to their required context.

It is recognised that metadata are an essential instrument to ensure the integrity of records. Contextual information would be captured as an integral part of the management of records and the running of the archive. Contextual information should provide an excellent source of structural information that can be used to locate records from a range of different perspectives. It should provide links between ideas, relationships between records and a variety of associations between entities (people, organizations, etc.), records and publications. Contextual information is perceived as providing a road map to records and related information.

The collection and management of contextual information should not be the exclusive province of a sole archivist but rather the responsibility of all those involved in information creation, preservation, publication, management and use.

2.11.3.6 Records management strategies

It is quite conceivable that an agreement should be reached between the (former) operator, the steward and the regulatory authority as to where copies of all (historical) records should be collated and kept. A single institution may be made legally responsible for keeping the records, but this institution may delegate the actual record maintenance to another institution or outsource the work. In either case the ultimate responsibility would remain with the nominated steward.

During transition periods, the management of remediated sites may face certain continuity problems:

1. One extreme is the critical situation when a site has been forgotten because all records on it have been lost;
2. Private operators may not be able or willing to guarantee to remain responsible for the long term, especially if no specific financial arrangements are made and the scope and extent of liabilities are not clearly defined.

A proper and formalised information management strategy should help to minimise losses of crucial and valuable information and records, thus ensuring continuity. While loss of records may be common throughout the whole life cycle, records are particularly vulnerable during the transition phase from operation to stewardship. The reason typically is that the records may have little or no value to the outgoing operator and the steward may not yet have the necessary infrastructure and management structures in place. Major losses of records frequently occur where a period of loss of institutional control has occurred, for example during a period of neglect between the end of active operation and the onset of an orderly remediation programme, during instances of war or civil unrest and in the case of 'orphan' contamination. Experience shows that maintaining some activity on a site throughout its life cycle improves the probability of maintaining records. Alternatively, a depository for all collated records could be found until a final decision on the value of the records can be made on the basis of stewardship needs.

In addition to attempting to ensure the physical protection of records, various other strategies to protect the information they contain may be considered. Duplicate records at two or more separate locations are an obvious solution. Given the concern about the longevity and viability of private enterprises and even national institutions, a centralised facility to collect and preserve records may be considered. Such redundancy may also be valuable in the case of catastrophic events at the place where the records are kept. One of the locations may even be at international level, which would offer some protection against the effects of war or civil unrest in a region. In order to maintain the memory of a site, it should not be necessary to have all records as duplicates.

Within one country, different types of information pertaining to a given site may be held at different locations, for example, the land register, environmental agency or local authority, which may reduce the risk that a complete set of records is lost in a single incident. The various databases may be physically or conceptually interlinked to provide a comprehensive management system.

An important medium for preserving and transmitting generic information on sites and their spatial extents may be maps, including geological, hydrological and land use maps. Some of these maps, geological maps, may be standardised tools that have been in use for at least 130 years. Sites with restricted use could be indicated by special map signatures.

It is important that not only the records themselves be retained but also the means and tools for understanding them. In the case of analytical data, for instance, this would be information on sampling and analytical procedures. This also extends to the physical capability of reading, for example, digital records.

In addition to storing information, electronic databases may be used to communicate with stakeholders and the public in general. These databases may contain information not only on sites that still have residual contamination above levels of concern but also on sites that have been remediated to the current levels of no concern. There is value in retaining information on such sites for two reasons:

1. They could serve as examples or role models for successful implementation of a remediation programme.
2. The view of regulators of what constitutes a level of no concern can change (and has changed) over time. Sites that have been remediated to standards applicable at the time of remediation may later, with more stringent regulations, be considered contaminated again. In this way, some degree of institutional memory of these is preserved.

2.11.3.7 Recording media

Since records may have to be kept for very long periods, the media used for storage are of crucial importance. On the basis of past experience with record keeping, a few basic requirements on the media and technology for recording can be formulated. These requirements include that records ideally should:

- Be readable without the aid of proprietary technology;
- Be capable of duplication and transfer to new media without loss of information;
- Preserve the context surrounding the information contained and its use.

The advantages and disadvantages of different recording media are summarised in Table 2.12. However, as has been discussed above, not all records may need to be stored for a very long time. Therefore, the choice of recording medium can be made appropriate to the length of the required retention time. Records of only short term relevance may be stored on ordinary office paper or proprietary magnetic media, whilst those records that need to be preserved for a very long time would need to be made on special papers or even on such exotic materials as silicon carbide.

Table 2.12 Types of media and their respective advantages and disadvantages

Medium	Advantages	Disadvantages
Paper	Easily readable (by the current generation) Relatively robust Degrades slowly Relatively easy to duplicate Relatively inexpensive, so inexpensive to store duplicates in several places	Occupies significant space Inks and paper degrade in the long term Easily destroyed by fire and water
Film, photographic records	Relatively cheap Negatives require smaller storage space than paper	Media degrade Easily destroyed by fire and water
Microfiche	Storage space significantly smaller than that for many other media Can be read using relatively simple technology (magnifying glasses)	Degrades in the long term (though some fiche media have been developed that potentially last longer than paper) Requires a tool to be read
Digital records	Can be retrieved relatively easily, rapidly and from a number of areas Storage space (disks, servers, etc.) very small, and one source that is networked can be read by a number of readers Easy to attach metadata Easy to arrange contextually or by multiple contextual relationships Easy to copy	Require specialist software to be read Life expectancy of software very short Relatively sophisticated machines required to access records
Silicon carbide slabs	Very durable in the long term Corrosion resistant Wear and abrasion resistant Do not require sophisticated environmental controls to ensure no degradation	Require sophisticated equipment to form the record (e.g., laser engraving tools) Expensive

In addition to concerns over the long term stability of the base medium, the stability of the actual inscription and possible detrimental interaction of the chosen materials with the base medium need to be assessed. It is known, for instance, that certain inks will fade or that they will destroy the paper due to chemical reactions. Inks that form a stable inorganic compound (e.g., iron gallate or soot) after the medium has evaporated are preferable to those that rely on organic polymers. A concern is the cheap modern papers and computer inks that seem to be in general use currently to produce hard copy records. These papers may not be acid-free, and the inks or dyes are usually based on organic polymers or use binders such as those employed in laser printing technology.

Over the past two or three decades, digital data processing, and hence storage of digital records has become ubiquitous and it is now more prevalent than other forms of data storage. The main incentives have been the high data density that can be achieved, with the associated savings in storage space, the versatility of the digital format, which allows use of the stored information for a variety of purposes, and the ease of data retrieval for further use.

Given the rapid changes in information management technologies, preserving data is a major issue for a programme that must extend into the indefinite future. Many systems that were once considered high technology simply no longer exist. For instance, data stored on 5.25 in. floppy disks are now virtually useless, as very few users have been able to retain the necessary hardware (disk drives) and associated software. A similar future awaits the 3.5 in. floppy disk and other magnetic media (e.g., tape streamers) in the light of rewritable CDs and DVDs becoming common. Optical disk (CD and DVD) technology is also being challenged by issues such as media durability (disk delamination) and the changing wavelength of the light source used to read or write disks. The problem of rapid technological change and the associated technical obsolescence has been widely recognised and extensively discussed for many years, but without any agreement on how this can be resolved.

Considering data preservation, most newer digital media may be much less robust than printed books or other paper documents because:

a. They are less chemically stable than even poor quality paper.

b. They deteriorate more rapidly even when stored unused in good environments.

c. Digital data are machine dependent, i.e., they must move within machines to provide their information. Simply reading the data incurs wear on the media.

d. They are totally system dependent for retrieval of their information. When the system (hardware, software or both) is no longer sustained, the information will be lost unless it is migrated to a newer system.

e. Digital information technologies rely on ever greater data packing densities, making the information ever more vulnerable to large losses from small incidents.

f. Failure of many newer digital media is often unpredictable and sudden, and may result in total loss of the information recorded.

g. There is little experience with the maintenance and preservation of many newer types of media.

Technological obsolescence is a major concern, particularly since technical developments are not driven by, and do not take into consideration, long term information preservation needs:

a. Accessibility of digital information depends entirely on intricate edifices of hardware, operating systems, applications software and storage media.

b. Most systems are heavily proprietary, which leaves those concerned with long term preservation dependent on the marketplace.

c. Changes in technology are almost wholly driven by business and market forces; libraries, archives and other government institutions have virtually no influence on these developments.

d. Although there are many crucial standards, both formal and de facto, in the digital domain, developments in technology often outpace the standards setting process.

A data mining procedure, i.e., transformation of existing records into current and long term formats might be needed to preserve records. In other words, digital media typically have very high maintenance requirements compared with those of other media, for instance paper. When deciding on the medium, these disadvantages may need to be balanced against the advantages of ease of data retrieval. In general, it appears that digital media may be of more value for data preservation on the ten year time span than for the long term.

2.11.3.8 Coding of information

Preserving physical records is one thing, ensuring their readability another. Conceptually, reading is composed of two steps: the transformation of the stored information into a medium that is accessible to humans and the decoding of the information into a format that is understandable to them. Some storage media require only simple tools for retrieving information, for instance a projector or microscope suffices to read a microfilm, while magnetic storage devices require sophisticated and often proprietary hardware. The decoding required means, for instance, that textual information be available in a language that can be understood by the user. In addition, the conventions of formulas or drawings must be understood. Necessary decoding keys can often be obtained from the context but sometimes the context itself is coded.

Typically, redundancy and a widespread use of the coding system are likely to aid readability over prolonged periods of time. Thus, plain text is a good candidate. Bar codes, on the contrary, have very little redundancy and require a special key for deciphering. This key is not common cultural knowledge at the time they are created and may easily be lost.

Symbols and pictograms are another issue. People with limited experience of other cultural contexts and historical perspectives might easily overlook the fact that the understanding of the meaning of symbols might be lost or that the meaning itself might indeed change. For instance, in the Western world it is generally accepted that a bright red or yellow colour is often used in warning symbols. Colours, however, have different connotations in different cultures; the colour of mourning is black in the Western world while it is white in East Asia. Therefore, it is dangerous to take the meaning of symbols for granted and to rely on them for conveying particular messages.

2.11.3.9 Records storage facilities

A spatial separation between the locations where records are kept and the locations of any problems is usually necessary to provide for conditions conducive to records preservation and for reasons of accessibility. In other words, the records should normally be stored in an archive remote from the site under stewardship. Various proposals have been made to overcome the problem of providing for the long term stability of records stored at a given site. These include two dimensional bar codes and button memories.

In designing records management facilities the fact has to be taken into account that certain records, for instance those on monitoring and maintenance, are ‘living’ records. Their continuous, even if not daily, use requires ease of access while providing security for longer periods of time. Therefore, certain records may have to be in close physical proximity to the steward. A possible strategy for providing both easy access and security is to maintain duplicate records. In such a case, however, mechanisms for duplicating such records in a way that ensures an exact copy are required. Typically the primary working records are paper copies or digital files, while the archived records are often transferred onto microfiche in order to reduce space requirements.

Facilities for storage of records for the short or intermediate term (say up to 25 years) are typically located in suitable accommodation, for example, the basement of the buildings in which the record creating institution is based. Records of higher importance and of wider public interest are often transferred to a state archive after a certain period of time. Records that are deemed to be of historical interest are candidates for the public archives. This is particularly true when the record creating institution ceases to function. The laws of countries usually specify the time for which records have to be kept. In many cases it is unlimited, i.e., for the lifetime of the recording medium. In exceptional cases, restoration or other procedures to extend the lifetime, or measures to transfer the information to other media, are taken.

Records that are to be kept for an a priori unlimited period of time in some countries are copied onto microfiche, which is then stored, for instance, in underground mines or similar facilities. The reason for placing the microfiche underground is a comparatively low risk of fire, natural disasters and major accidents such as plane crashes.

There is not much experience yet on how well these facilities would function over the very long term. The only long term experiences with storage of written or printed records are with monastery or university libraries that have been in existence for close to a thousand years. Although their continuing existence is an example of continued institutional control, there are many more examples where such control has failed or the institutions have been deliberately dissolved.

2.11.4 Record keeping – Project files

Site owners/operators should prepare comprehensive records of the nature and extent of the contamination, the process of deciding how to manage the contaminated site, implementing the chosen strategy, validation, and interactions with stakeholders throughout the process, as well as of any lessons learned and changes made during the implementation [10].

Such records should also include descriptions of activities performed; data from the historical site assessment and monitoring and surveillance programmes; occupational health and safety records for the remediation workers; records of the types and quantities of waste produced and of their management and disposition; data from environmental monitoring; records of financial expenditures; records of the involvement of interested parties; records of any continuing responsibilities for the site; identification of locations that were remediated and those with residual levels of contamination remaining; specifications of any areas that remain restricted and the restrictions that apply; statements of any zoning and covenant restrictions or conditions; and statements of lessons learned [12].

Failures in the implementation of remedial measures may arise from a lack of consensus among interested parties, often in the negotiations during the decision making process regarding the implementation of the remediation plan. While some conflicts between interested parties are apparent at the outset of the decision making process, others may arise much later, for example during discussions in which the actual implications of alternative decisions are made explicit. All conflicts and their resolution in the decision making process should be documented.

The organisation responsible for maintaining and updating the records should be clearly designated and the provision of the necessary resources and notification of the competent authority should be considered.

In order to achieve the objectives, at the project outset, plans should be made for record keeping which are compliant with the quality management programme used for the site characterisation works. Consideration should be given at an early stage as to the longevity of the materials and devices to be used to store data, since these factors have time and cost implications for project deliverables.

A ‘Project Records File’ (PRF) should be set up for each site so that information about contaminated land can be held in a formalised structure. The ‘Project Records File’ should be part of the record management system of the organisation that owns or operates the site and should be accessible to stakeholders.

An example of a 'Project Records File' and some additional information is available in 0.

2.11.4.1 Site characterisation reporting

Delivery of investigation reports may be required for different purposes in order to serve different audiences. The reporting structure provided in Table 2.13 should be evaluated. Consideration should also be given to standardisation of the data format.

Table 2.13 Suggested reporting structure

Report	Audience
Summary Report	A brief non-technical summary of the whole investigation for a lay audience. Such a document is particularly useful to supply as part of stakeholder involvement.
Preliminary Investigation Report with Initial Conceptual Model	To be completed prior to the next stage of investigation, and useful for circulation to all technically involved parties, and to supply with tender documents for the next site investigation stage.
Exploratory and Main Report	It is recommended that reports from these investigations are split according to potential audiences.
Factual	From a business point of view the commissioning organisation may wish to release factual information only to potential buyers or developers and allow them to place their own interpretation and cost analysis on the findings.
Interpretative	The interpretative report can be produced giving details of the risk assessment and may be for a limited audience.
Supplementary Reports	These reports tend to be short and target particular issues, and there is no particular merit in splitting the facts from the interpretation

2.12 Archiving for future referencing

2.12.1 Introduction

During the life cycle of an active industrial site the site owners/operator should prepare comprehensive records of the nature of the industrial process and of important events. In the case of a nuclear facility or a facility that deals with radioactive material (e.g., NORM and TENORM), important events are dates at which licenses have been granted based on the national nuclear law or updates of these licenses, changes in industrial activities, receiving of radioactive materials, transporting of nuclear materials to third parties or to radioactive waste or chemical waste storage facilities, accidents, etc.

At the end of the life cycle, the site should be remediated for unrestricted or restricted re-use. Again, site owners/operator should prepare comprehensive records of the nature and extent of radioactive contaminations present before an environmental remediation, the process of deciding how to manage the contaminated site, implementing the chosen remediation strategy, validation, and interactions with stakeholders throughout the process, as well as of any lessons learned, changes made during the implementation and a detailed overview of remaining radioactive contaminations and/or hazardous materials including the eventual risk for the public and the environment.

All of these records should be 'in principle' available and easy accessable at the end of the remediation process or at the beginning of an eventual stewardship. Depending on the type of industry and the duration of its active live time, the amount of records can be overwhelming and can be stored at different media (see Section 2.11.3.6).

However, the following questions arise:

- For how long should records be kept available?

- Must all records be kept available for the same time period? If no,
- Which records for which time period?
- Must all records to be stored at one place? If no,
- Must from all records be a copy available? If no,
- Which records have to be copied for back-up?
- And where must the back-up(s) to be stored?

It is evident that some records are more important to others, as example a nuclear license is more important than the record of one of the many sample analyses made during the active period of the industrial activity at the site.

2.12.2 Objective and scope of the archive for future referencing

The objective of the 'Archive for future referencing' is that it should be able to be consulted by the public and all stakeholders in the nearby and long term future for answering questions dealing with:

1. assessment of the eventual risk of any remaining radioactive contamination and/or remaining hazardous materials according to new insights about risk assessments developed in the future,
2. the former radioactive contaminants and/or hazardous materials formerly present at the site and/or groundwater during the active industrial period,
3. the remaining radioactive contaminants and/or hazardous materials present at the site and/or groundwater after the environmental remediation period and during an eventual stewardship period,

and in this way preventing costly new site characterization and environmental remediation projects in the future.

To fullfil the objectives of this archive, the content of the 'Archive for Future Referencing' has to anticipate, as good as possible, on knowledge that will be generated and developed in the future on health physics and environmental risk assessment of radioactive contaminants and hazardous materials. It is evident that at this moment no depiction can be made hereof. Therefore the archive has to contain unambiguous information about:

- what type of industrial activities has been formely present at the site?
- what type of industrial activities has never been present?
- what type of radiological and hazardous contaminations has been formely present at the site?
- what type of radiological and hazardous contaminations is nowadays still being present?
- what type of radiological and hazardous contaminations has never been present?
- which amounts of radiological and hazardous materials have been transported and to which locations, e.g., other industries, waste storage facilities?
- the quality of the archived information,

and thus leaving no space for different interpretations.

An 'Archive for Future Referencing' should be set up for each site so that information about contaminated land can be held in a formalised structure. This archive can be part of the record management system of the organization that owns or operates the site. The organisation responsible for maintaining the permanent records and the 'Archive for Future Referencing' should be clearly designated. Special attention should be drawn to the (physical) quality of the archive. Media used for data storage tend to deteriate rapidly (see Section 2.11).

It is advised, as it can be benificary and cost saving from the start of an industrial activity, to set-up such an archive.This archive will contain only approved quality assured and quality controlled data dealing with human risk and environmental impacts. An organization aiming at *corporate socially responsibility* will be eager to show – by means of the archive – that it did everything possible to take care of the environment and stakeholders. The ‘Archive’ could be subdivided by area for complex sites or where site responsibility is split up to cope with fragmentation of landholding for de-licensing or redevelopment.

Site owners should hold this ‘Archive’ that can be readily accessed and updated for the duration of their ownership of the site and pass the records on to new owners. This course of action should be maintained if no form of national system is established for keeping records of contaminated land in the long term.

Local authorities and environment agencies may maintain registers of ‘special sites’ and of other land that has been designated as ‘contaminated or hazardous’. These registers are mostly not suitable for keeping or maintaining detailed records such as in an ‘Archive for Future Referencing’, however.

Therefore, a ‘National Archive’ (NA) could be established to provide a ‘Public Records Place of Deposit’ where data of historical and local interest could be managed effectively and made available to as wide an audience as possible. Site owners should remain entirely responsible for the management of records on their sites, however.

A fixed structure for an ‘Archive for Future Referencing’ is proposed in the following sections.

2.12.3 Archive contents

As this is the first attempt to create an ‘Archive for Future Referencing’, it has to be accepted that the ideas about the content are not yet fully mature and may change to newly developed insights in time.

The content of this archive should be condensed and should include all relevant information to fullfil the objective of the archive. The content should balance between incorporating the information itself or summarized or including only the reference where the information can be found. A very important aspect is how to transmit knowledge - information - over a long period of time (see Section 2.11.2 and 2.11.3) and to ensure that these records in future generations do not cause an effect opposite to the one that is intended.

The content of the archive should consist of the following sections:

1. Introduction and archive overview;
2. Historical information and current (last) use;
3. Environmental remediation process;
4. Remaining radiological contaminations and hazardous materials;
5. Miscellanous.

2.12.4 Introduction and archive overview

Since the potentional user of the archive may not be familiar with the site, its historical use and the performed environmental remediation activities, and may read or study it only many years after, the reader should be guided through the archive. A structured overview of sections, documents present in the archive will help the reader to fathom the archive more easily.

The content of section 1 of the archive should include the following:

1.1 Glossary of terms, acronyms and abbreviations. In this glossary, all terms, acronyms and abbreviations have to be collected and especially those that are more based on the national and local social ethical culture, due to the fact that these terms will have the highest chance to be subjected to a change in meaning in time.

1.2 Executive summary. This executive summary describes in a condensed way the aim and the main contents of this archive.

1.3 Structure and content of the archive to guide the reader. It is important that the reader should understand the key points and the information as intended by the authors.

1.4 Overview of reference documents and location, also from back-ups and numbered copies of this archive, where they have been stored originally or could be found.

1.5 Register of stakeholder organisations and contact persons in time.

2.12.5 Historical information

The information presented in this second section should deal with the outcome of the performed 'Historical site assessment', but in a condensed way and focused on information that could be used for upcoming health physics and environmental risk assessments.

The content of section 2 of the archive should include the following:

2.1 Property identifications.

- 2.1.1 Physical characteristics.
  - 2.1.1.1 Name of the site, owner(s)/operator(s) name, address(es).
  - 2.1.1.2 Location, street address, city, country, state, geograpic coordinates, land registry registration.
  - 2.1.1.3 Boundaries of the site.
  - 2.1.1.4 Topography minute quadrangle or equivalent.
  - 2.1.1.5 Stratigraphy.
- 2.1.2 Environmental setting.
  - 2.1.2.1 Geology.
  - 2.1.2.2 Hydrogeology.
  - 2.1.2.3 Hydrology.
  - 2.1.2.4 Meteorology.

2.2 Historical site assessment methodology.

2.3 History and last current usage.

- 2.3.1 History: years of operation; type of facilities; description of operation; regulatory involvement; permits and licenses; figures as accurate as possible about the maximum amount of present radioactive and hazardous materials in time and from which manufacturers these materials are ordered.
- 2.3.2 Current usage-type of facility: description of operation; permits and licenses; figures as accurate as possible about the type and maximum amount of present radioactive and hazardous materials in time and from which manufactures these materials are ordered; description of spills or releases; list of waste manifests; emergency or removal actions; quality management system in relation to known and potential contaminants and hazardous material.

2.4 Findings.

- 2.4.1 Known and potential contaminants and hazardous material.

2.4.2 Potential contaminated areas.

2.4.2.1 Impacted areas, known and potential.

2.4.2.2 Non-impacted.

2.4.3 Known and potential contaminated media.

2.4.4 Known and potential problematic and hazardous materials and waste.

2.4.5 Related environmental concerns.

2.5 Conclusions.

2.6 References: documents reviewed; references to other sources of information.

2.7 Appendixes.

2.7.1 Photo documentation log: original photographs of the site and pertinent site features.

2.7.2 List of accidents that affected the site and/or the environment including corrective measures.

2.7.3 List of annual radiological and chemical releases to the environment (e.g., aerosols, dust, surface and groundwater, etc.).

2.7.4 Statement or list of actions that exclude explicitly specific industrial or other activities that have never been performed at the site.

2.7.5 Statement or list of radionuclides and hazardous materials that exclude explicitly that they have been present at the site.

Important is by describing the historical and current information to include figures as accurate as possible dealing with the maximum amount present and the chemical composition and form from radioactive and hazardous materials in time and from which manufactures these materials were ordered. These figures can and will be used to perform risk assessments if needed.

2.12.6 Environmental remediation process

The information in section 3 summarizes the environmental remediation and restoration process.

The design of a remediation and restoration programme for radiological contaminated land is dealt with in detail in Section 2.2.

The content of section 3 of the archive should include the following:

3.1 Initial site characterization and established remediation criteria.

3.1.1 Initial site characterization: determined nature and extend of radiological contamination (and hazardous material); source term; geology; geochemistry; hydrology; nature and extent of the contaminated plume; exposure pathways.

3.1.2 Risks and environmental impacts: evalution of the environmental, occupational and public health and safety issues during remediation.

3.1.3 Developed site specific remediation criteria.

3.2 Identification of remediation options: selected remediation option; justification and optimization of remedial measures.

3.2.1 Overall protection of human health and the environment.

3.2.2 Compliance with applicable regulations.

3.2.3 Long term effectiveness and permanence.

3.2.4 Reduction of toxicity, mobility, or volume.

3.2.5 Short term effectiveness.

3.2.6 Implement ability.

3.2.7 Community and government acceptance.

3.2.8 Final disposal residues.

3.3 Remediation and restoration plan: implementation and execution of the remediation plan, performance assessment.

3.3.1 Horizontal and vertical extent of the plume and contaminant concentration gradients, including a mass balance calculation.

3.3.2 Rate and direction of contaminant migration.

3.3.3 Changes in contaminant concentrations or distribution over time.

3.3.4 Rates of contaminant mass removal and transition from advective removal to diffusion rate limited removal.

3.3.5 Effects of hydrological events, such as above average rainfall, on contaminant mass removal and changes to groundwater flow.

3.3.6 Calibration of model based on actual results and effects of changes of operational parameters to model predictions.

3.3.7 Effects on regional groundwater levels and the resulting impacts.

3.3.8 Effects of reducing or limiting surface recharge (if applicable).

3.3.9 Effects of re-injection (if applicable).

3.3.10 Effects of any modifications to the original remedial action.

3.3.11 Other environmental effects of remedial action, such as saltwater intrusion, land subsidence, and effects on wetlands or other sensitive habitats.

3.4 Appendixes.

3.4.1 Photo documentation log: original photographs of the site of contaminated, remediated and restored areas, etc.

3.4.2 Graphical presentations and/or lists with locations of radiological contaminated areas including specific details of contamination like specific radioactivity, amount of material, chemical composition, etc.

3.4.3 Overview of waste manifests: type and amount of radiological, chemical or hazardous waste; transporter; waste storage facility.

3.4.4 Overview of audit trials, findings, corrective measures.

2.12.7 Remaining radiological contaminations and hazardous materials

The information in section 4 summarizes the final site characterization process and the demonstration that the potential dose or risk from residual radioactive contamination is below the release criterion for the site and/or for each survey unit and meets the release criterion.

The design of a final site charaterisation process for radiological contaminated land is dealt with in Sections 2.7 and 3.3.10.6.

The content of section 4 of the archive should include the following:

4.1 Design of the final status survey: radioactive contaminants, background selection, data quality objectives, null and alternative hypotheses, radiological data collection; additional investigations to support the radiological site characterization; sample frequencies, locations and patterns, applied intrusive and non-intrusive methods, applied field and laboratory equipment.

4.2 Data interpretation and conclusions: analysis of samples, detection limits, process of determining that the data quality objectives are met, applied statistical methods; actions as a consequence of individual measurements are in excess of the investigation levels; any additional data, remediation, or re-surveys performed to demonstrate that issues concerning potential areas of elevated activity were resolved.

4.3 Data quality assessment process: data verification, data validation, data quality assessment.

4.4 Appendixes.

4.4.1 Graphical presentations and/or lists with locations with remaining radiological contaminated areas including specific details of contamination like specific radioactivity, amount of material, chemical composition, etc.

4.4.2 Overview of audit trials, findings, corrective measures.

2.12.8 Miscellaneous

The contents of the ‘Archive for Future Referencing’ should also be subjected to quality assurance and quality control. In this way, the organization can directly prove to stakeholders and also for the future (main aim of the archive) that all data provided in the archive are correct and have a high quality. In this way costly reinvestigations can be prevented.

It is also evident that any structured format of an archive cannot anticipate on all unique and specific environmental remediation projects. Therefore, in this section of the archive the owner/operator can archive information which from the point of view of this organization is relevant for future risk and environmental assessments.

2.13 Quality management plan

Throughout the site remediation process, it is necessary to have confidence that the procedures, as example used to collect samples and to determine contaminant levels, are fit for purpose or how to perform correctly the excavation in an area [10]. This is achieved by adherence method statements which form part of the quality management system set out in the quality management plan.

Method statements describe the procedures for carrying out the principal activities (such as drilling boreholes, collecting samples, managing wastes and decommissioning boreholes, etc.). Procedures described in method statements should be in accordance with project contractual requirements and technical objectives, and should take account of health and safety issues and the need to minimise environmental impacts. These documents will need to be supplied for approval prior to commencement of any works.

Organisations commissioning site characterisation work should preferably hold a company accreditation to EN ISO9001 for quality management systems. As a result, both the client and organisations providing services have responsibilities in ensuring the quality of site investigation work. Some issues to be considered in this area are:

- Qualifications and experience of personnel carrying out the work;
- Qualifications, accreditation and experience of subcontractors;
- Chain of custody procedures;
- Quality assurance/Quality control for sampling and analyses;
- Accurate record keeping and data storage; and

- Review and audit of all works carried out at all stages of the investigation, including reporting and interpretation.

It is essential that quality procedures are applied at all stages of the remediation project. The procedures used should be capable of ensuring the reliability and robustness of the remediation work carried out and the data produced.

General guidance on quality management can be found in the British Standards Institution publications, with information specific to contaminated land in [147], [148], [149], [150].

The quality management plan will and should be prepared and approved before works commence.

2.13.1 Quality assurance and quality control

The goal of quality assurance and quality control (QA/QC) is to identify and implement methodologies and procedures which limit the introduction of errors into the remediation process. For EURSSEM a system is needed to ensure that plans are of the type and quality needed and expected for their intended use in an environmental remediation process.

A *quality system* is a management system that describes the elements necessary to plan, implement, and assess the effectiveness of QA/QC activities. This system establishes many functions including: quality management policies and guidelines for the development of organization- and project-specific quality plans; criteria and guidelines for assessing data quality; assessments to ascertain effectiveness of QA/QC implementation; and training programs related to QA/QC implementation. A quality system ensures that EURSSEM decisions will be supported by sufficient data of adequate quality and usability for their intended purpose, and further ensures that such data are authentic, appropriately documented, and technically defensible.

Any organization collecting and evaluating methodologies, procedures or data for a particular program must be concerned with the quality of the results. The organization must have results that: meet a well-defined need, use, or purpose; comply with program requirements; and reflect consideration of health, environmental issues, cost and economics. To meet the objective, the organization should control the technical, administrative, and human factors affecting the quality of results. Control should be oriented toward the appraisal, reduction, elimination, and prevention of deficiencies that affect quality in a not wished manner.

Quality systems already exist for many organizations involved in the use of radioactive materials. There are self-imposed internal quality management systems or there are systems required by regulation or by another entity, which require a quality system as a condition of the operating license. These systems are typically called quality assurance programs. An organization may also obtain services from another organization that already has a quality system in place.

Table 2.14 illustrates elements of a quality system as they relate to the data life cycle. Applying a quality system to a project is typically done in three phases:

1. The planning phase where the different data quality objectives (DQOs) are developed for the actions of an environmental remediation project and documented in the quality assurance project plan (QAPP) [6];
2. The implementation phase involving the actions, e.g., the collection of data in accordance with approved procedures and protocols;

[6] EURSSEM uses, like MARSSIM, the term quality assurance project plan to describe a single document that incorporates all of the elements of the environmental remediation design. This term is consistent with ANSI/ASQC E4-1994 ([151]) and EPA guidance ([125][147][152]), and is recommended to promote consistency. The use of the term quality assurance project plan (QAPP) in EURSSEM does not exclude the use of other terms (*e.g.*,, decommissioning plan, sampling and analysis plan, field sampling plan, remediation plan, health physics and safety plan, etc.) to describe planning documentation as long as the information in the documentation supports the objectives of the work to be performed.

3. The assessment phase including the verification of actions and validation of survey results and the evaluation of the environmental data using data quality assessment (DQA) and audits.

Detailed guidance on quality systems is not provided in EURSSEM because a quality system should be in place and functioning prior to beginning environmental remediation activities [125], [151], [152].

Table 2.14 The elements of a quality system related to the data life cycle

Data life cycle	Quality system elements
Planning	Data quality objectives (DQOs) Quality assurance project plans (QAPPs) Standard operating procedures (SOPs)
Implementation	Quality assurance project plans Standard operating procedures Data collection Assessments and audits
Assessment	Data validation and verification Data quality assessment (DQA) Audits

A graded approach bases the level of controls on the intended actions and use of the results and the degree of confidence needed in their quality. Applying a graded approach may mean that some organizations make use of existing plans and procedures to conduct an environmental remediation/restoration. For many other organizations, the need for clean-up and restoration of contaminated facilities may create the need for one or more quality assurance project plans suitable to the special needs of environmental data gathering, especially as it relates to the demonstration of compliance with regulatory requirements. There may even be a need to update or revise an existing quality management system.

2.13.1.1 Development of a quality assurance project plan

The quality assurance project plan is the critical planning document for any environmental operation because it documents how quality assurance/quality control activities will be implemented during the life cycle of a project ([125], [147]). The quality assurance project plan is the blueprint for identifying how the quality system of the organization performing the work is reflected in a particular project and in associated technical goals. This section provides information on how to develop a quality assurance project plan based on the data quality objective process [153]. The results of the data quality objective process provide key inputs to the quality assurance project plan and will largely determine the level of detail in the quality assurance project plan.

As example, the consensus standard ANSI/ASQC E4-1994 ([151]) describes the minimum set of quality elements required to conduct programs involving environmental data collection and evaluation. Table 2.15 lists the quality elements for collection and evaluation of environmental data from ANSI/ASQC E4-1994. These quality elements are provided as examples that should be addressed when developing a quality assurance project plan.

Each of these quality elements should be considered during survey planning to determine the degree to which they will be addressed in the quality assurance project plan. Additional quality elements may need to be added to this list as a result of organizational preferences or requirements of federal and state regulatory authorities. For example, safety and health or public participation may be included as elements to be considered during the development of a quality assurance project plan.

Table 2.15 Example of quality assurance project plan elements for site surveys and investigations

	Quality Assurance Project Plan element
1	Planning and Scoping (reference the QA Manual for information on the quality system)
2	Design of Data Collection Operations (including training)
3	Implementation of Planned Operations (including documents and records)
4	Assessment and Verification of Data Usability

In Table 2.16 an example of a format for a quality assurance project plan for site surveys and investigation is presented.

Table 2.16 Example of a format for a quality assurance project plan for site surveys and investigations

Quality assurance project plan element	Content
Planning and scoping (reference the quality assurance manual for information on the quality system)	Project management Title and approval sheet Table of contents Distribution list Project/Task organization Problem definition/Background Project task description Quality objectives and criteria for measurement data Special training requirements/Certification
Design of data collection operations (including training)	Measurement/Data acquisition Sampling process design (Experimental design) Sampling methods requirements Sample handling and custody requirements Analytical methods requirements Quality control requirements Instrument/Equipment testing, inspection and maintenance requirements Instrument calibration and frequency Inspection/Acceptance requirements for supplies and consumables
Implementation of planned operations (including documents and records)	Assessment/Oversight Assessments and response actions Reports to management
Assessment and verification of data usability	Data validation and usability Data review, validation, and verification requirements Validation and verification methods Reconciliation with user requirements

Quality assurance project plans should be developed using a graded approaches as discussed in Section 2.13.1. In other words, existing methodologies, procedures, designs, etc. can be included by reference. This is especially useful for not too complicated environmental remediation programmes.

Quality assurance project plans should be developed to document the results of the planning phase of the data life cycle (see Sections 2.2.2 and 3.3). The level of detail provided in the quality assurance project plan for relevant quality elements is determined using the data quality objective process during planning activities. Information that is already provided in existing documents does not need to be repeated in the quality assurance project plans, and can be included by reference.

For example, the quality system description, personnel qualifications and requirements, and standard operating procedures for laboratory analysis of samples may simply be references to existing documents (*e.g.*, quality management plan, laboratory procedure manual). Standard operating procedures for performing direct measurements with a specific instrument may be attached to the quality assurance project plan because this information may not be readily available from other sources.

There is no particular format recommended for developing a quality assurance project plan. Table 2.16 provides an example of a quality assurance project plan format.

3 Characterisation of radioactively contaminated sites

3.1 Introduction

This section of EURSSEM provides detailed guidance on the characterisation of radioactively contaminated sites and/or groundwater.

This section is intended for a technical as well as a non-technical audience. However, some fundamental knowledge of radioactivity and experiences with radioactivity and health physics is recommended. Basic concepts may be found on the internet on such sites as:

- www.iaea.org
- www.safegrounds.com
- www.health-physics.com

Information about possible radioactive contaminants and origin are presented here and includes as well as nuclide specific information for soil as for groundwater, so that it is clear that radioactive contaminants are common and levels vary. As soon as such a level has been determined and superseding a regulatory action level[7], actions have to be performed to characterise the radiological contamination.

Before the main steps in the radiological characterisation process of sites and/or groundwaters are presented, key-terms applied in EURSSEM are introduced and defined. As mentioned before, EURSSEM incorporates information of the IAEA, the SAFEGROUNDS Learning Network and MARSSIM. Some of these terms may be or may be not familiar to the user[8].

Now the Radiation Survey and Site and/or Groundwater Investigation Process can be described. In Section 2 of EURSSEM, this process (e.g., planning) has been described at a high generic level, while in this section the guidance is in more detail at an operation level. In addition, changes to the overall survey design that account for site-specific differences would be presented as part of the survey plan. This plan should also demonstrate that the extrapolation from measurements performed at specific locations to the entire site or survey unit is performed in a technically defensible manner. It is obvious that the detailed performance-based guidance should not be uniformly applied at every site with a radioactive contamination. Therefore, this guidance contains the flexibility for users to develop a site-specific survey design to account for site-specific characteristics. Users should adopt, in agreement with stakeholders, those portions of EURSSEM that apply to their site.

To be able to understand the guidelines of the presented approach, first the definitions of the adopted key terms are presented.

3.2 Definition of key terms adopted in site characterisation

An important step in understanding the Radiation Survey and Site Investigation (RSSI) Process is accomplished by understanding the scope of this guideline, the applied terminology and concepts.

As the guidance set out in EURSSEM is based on important documents that have been produced by:

- The International Atomic Energy Agency (IAEA), (www.iaea.org),
- The SAFEGROUNDS Learning Network (www.safegrounds.com),
- The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM),

7 Action levels are in general nuclide specific and defined by the government.

8 The authors of EURSSEM have been avoiding the use of new terms. However, in the case that it is unavoidable, preference will be given to terms defined by the IAEA.

the same terminology has been adopted. In the case of different terms for the same object/purpose, preference is given to terms defined by the IAEA.

In 0 a glossary is given with (all) specific terms applied in site characterisation, remediation and restoration processes. This section explains some of the terms in the order of their appearance in the guidance.

The process described in EURSSEM begins with the premise that a release criterion has already been provided in terms of a measurement quantity. The methods presented in EURSSEM are generally applicable and are not dependent on the value of the release criterion.

A *release criterion* is a regulatory limit that can be expressed in terms of dose (mSv/y) or risk (cancer incidence or cancer mortality). A release criterion is typically based on:

- The total effective dose equivalent (TEDE), or
- The committed effective dose equivalent (CEDE), or
- Risk of cancer incidence (morbidity), or
- Risk of cancer death (mortality)

and generally cannot be measured directly. *Exposure pathway modelling* has to be used to calculate a radionuclide-specific predicted concentration or surface area concentration of specific nuclides that could result in a dose (total effective dose equivalent or committed effective dose equivalent) or specific risk equal to the release criterion. As an example, a specific approach for the implementation of remediation criteria may be summarised as indicated in the form of the reference levels indicated in Table 3.1 (see also Section 2.2.2.3).

In this manual, such a concentration is termed the *derived concentration guideline level (DCGL)*. Exposure pathway modelling is an analysis of various exposure pathways and scenarios used to convert dose or risk into concentration. In many cases DCGL's can be obtained from responsible regulatory agency guidance based on default modelling input parameters, while other users may elect to take into account site-specific parameters to determine DCGL's.

In general, the DCGL can be general (e.g., dose, surface contamination level) or nuclide specific.

The units for the DCGL will be the same as the units for measurements performed to demonstrate compliance (*e.g.*, Bq/kg, Bq/m², Sv/h, cps/m²).

Table 3.1 Examples of reference levels

Band No.	**Range of annual doses (to average member of the critical group)**	**Is remediation needed?**	
		With constraint	**Without constraint**
Band 6	> 100 mSv/a	Always	Always
Band 5	10 – 100 mSv/a	Always	Almost always
Band 4	1 – 10 mSv/a	Almost always	Usually
Band 3	0.1 – 1 mSv/a	Usually	Sometimes
Band 2	10 – 100 µSv/a	Sometimes	Rarely
Band 1	< 10 µSv/a	Almost never	Almost never

This allows direct comparisons between the survey results and the DCGL. A discussion of the uncertainty associated with using DCGL's to demonstrate compliance is included in 0.

An *investigation level* is a specific level based on the release criterion that, if exceeded, triggers some response such as further investigation or remediation. An investigation level may be used early in decommissioning to identify areas requiring further investigation, and may also be used as a screening tool during compliance demonstration to identify potential problem areas. A DCGL is an example of a specific investigation level. If the DCGL is not superseded, in principle no further investigations or remediation has to be performed. The derivation of DCGL's from a reference level is given in Section 3.10. Important by the derivation is to understand the assumptions that underlie this derivation. The derivation assumptions must be consistent with those used for planning a compliance demonstration survey. One of the most important assumptions used for converting a dose or risk limit into a specific concentration is the modelled area of contamination. Other considerations include sample depth, composition, modelling parameters, and exposure scenarios. EURSSEM defines two potential DCGL's based on the area of contamination:

- If the residual radioactivity (after remediation) is evenly distributed over a large area, EURSSEM looks at the average activity over the entire area. The term $DCGL_W$[9] (the $DCGL_W$ applies the **W**ilcoxon Rank Sum statistical test, as indicated in Section 3.10.5) is derived based on an average concentration over a large area, e.g., large number of measurements.
- If the residual radioactivity (after remediation) appears as small areas of elevated activity[10] within a larger area, typically smaller than the area between measurement locations, EURSSEM considers the results of individual measurements. The $DCGL_{EMC}$ (the DCGL used for the Elevated Measurement Comparison (EMC) (see Section 3.3.2.1 and Section 3.3.2.6) is derived separately for these small areas and generally from different exposure assumptions than those used for larger areas.

A *site* is any installation, facility, or discrete, physically separate parcel of land, or any building or structure or portion thereof, which is being considered for survey and investigation.

Area is a very general term that refers to any portion of a site, up to and including the entire site.

Decommissioning is the process of safely removing a site from service, reducing residual radioactivity through remediation to a level that permits release of the property, and termination of the license or other authorization for site operation. Although only part of the process, the term decommissioning is used in this sense for the Radiation Survey and Site Investigation (RSSI) Process.

A *survey unit* is a physical area consisting of structure or land areas of specified size and shape for which a separate decision will be made as to whether or not that area exceeds the release criterion. This decision is made as a result of the *final status survey* - the survey in the RSSI Process used to demonstrate compliance with the regulation or standard. The size and shape of the survey unit are based on factors, such as the potential for contamination, the expected distribution of contamination, and any physical boundaries (*e.g.*, buildings, fences, soil type, surface water body) at the site.

Measurement is used interchangeably to mean:

- The act of using a detector to determine the level or quantity of radioactivity on a surface or in a sample of material removed from a media being evaluated, or
- The quantity obtained by the act of measuring.

Direct measurements are obtained by placing a detector near the media being surveyed and inferring the radioactivity level directly from the detector response.

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9 The "W" in $DCGL_W$ stands for **W**ilcoxon Rank Sum test, which is the statistical test recommended in MARSSIM and EURSSEM for demonstrating compliance when the contaminant is present in background. The Sign test recommended for demonstrating compliance when the contaminant is not present in background also uses the $DCGL_W$.

10 A small area of elevated activity, or maximum point estimate of contamination, might also be referred to as a "hot spot." This term has been purposefully omitted from EURSSEM because the term often has different meanings based on operational or local program concerns. As a result, there may be problems associated with defining the term and reeducating EURSSEM users in the proper use of the term. Because these implications are inconsistent with EURSSEM concepts, the term is not used.

Scanning is a measurement technique performed by moving a portable radiation detector at a constant speed above a surface to semi-quantitatively detect areas of elevated activity.

Sampling is the process of collecting a portion of an (environmental) medium as being representative of the locally remaining medium. The collected portion, or aliquot, of the medium is then analyzed to identify the contaminant and determine the concentration. The word sample may also refer to a set of individual measurements drawn from a population whose properties are studied to gain information about the entire population. This second definition of sample is primarily used for statistical discussions.

Graded approach is the term adopted for the method that makes the best use of resources for decommissioning. EURSSEM places greater survey efforts on areas that have, or had, the highest potential for a radiological contamination. The final status survey uses statistical tests to support decision making. These statistical tests are performed using survey data from areas with common characteristics, such as contamination potential, which are distinguishable from other areas with different characteristics.

Classification is the process by which an area or survey unit is described according to radiological characteristics. The significance of survey unit classification is that this process determines the final status survey design and the procedures used to develop this design. Preliminary area classifications, made earlier in the process, are useful for planning subsequent surveys.

Non-impacted areas are areas that have no reasonable potential for residual radioactive contamination. These areas have no radiological impact from site operations and are typically identified early in the Radiation Survey and Site Investigation (RSSI) Process.

Impacted areas are areas with a reasonable potential for residual radioactive contamination and will have an impact from site operations. Impacted areas are further divided into one of three classifications:

Class 1 Areas: Areas that have, or had prior to remediation, a potential for radioactive contamination (based on site operating history) or known contamination (based on previous radiation surveys) above the $DCGL_W$. Meaning, that at this site radioactive contaminations are of were present above the release criterion. Examples of Class 1 areas include:

- Site areas previously subjected to remedial actions[11].
- Locations where leaks or spills are known to have occurred of radioactive materials.
- Former burial or radioactive waste disposal sites.
- Radioactive waste storage sites
- Areas with radioactive contaminants in discrete solid pieces of material and high specific radioactivity.

Class 2 Areas: Areas that have, or had prior to remediation, a potential for radioactive contamination or known contamination, but are not expected to exceed the $DCGL_W$. Meaning, that at this site radioactive contaminations are of were present that is not expected to exceed the release criterion. To justify changing the classification from a Class 1 area to a Class 2 area, there should be measurement data that provides a high degree of confidence that no individual measurement would exceed the $DCGL_W$. Other justifications for reclassifying an area as Class 2 may be appropriate based on site-specific considerations. Examples of areas that might be classified as Class 2 for the final status survey include:

- Locations where radioactive materials were present in an unsealed form.

[11] Remediated areas are identified as Class 1 areas because the remediation process often results in less than 100% removal of the determined radioactive contamination, even though the goal of remediation is to comply with regulatory standards and protect human health and the environment. The radioactive contamination that remains on the site after remediation is often associated with relatively small areas with elevated levels of residual radioactivity. This results in a non-uniform distribution of the radionuclide and a Class 1 classification. If an area is expected to have no potential to exceed the $DCGL_W$ and was remediated to demonstrate the residual radioactivity is as low as reasonably achievable (ALARA), the remediated area might be classified as Class 2 for the final status survey.

- Potentially contaminated transport routes.
- Areas downwind from stack release points.
- Upper walls and ceilings of buildings or rooms subjected to airborne radioactivity.
- Areas handling low concentrations of radioactive materials.
- Areas on the perimeter of former radioactive contaminated controlled areas.

Class 3 Areas: Any impacted areas that are not expected to contain any residual radioactivity, or are expected to contain levels of residual radioactivity at a small fraction of the $DCGL_W$, based on site operating history and previous radiation surveys. Examples of areas that might be classified as Class 3 include:

- Buffer zones around Class 1 or Class 2 areas.
- Areas with very low potential for residual radioactive contamination but insufficient information to justify a non-impacted classification.

Class 1 areas have the greatest potential for contamination and therefore receive the highest degree of survey effort for the final status survey using a graded approach, followed by Class 2, and then by Class 3. Non-impacted areas do not receive any level of survey coverage because they have no potential for residual contamination. Non-impacted areas are determined on a site-specific basis. Examples of areas that would be non-impacted rather than impacted usually include residential or other buildings that have or had nothing more than smoke detectors or exit signs with sealed radioactive sources.

Background reference area: If the radionuclide of potential concern is present in background, or if the measurement system used to determine concentration in the survey unit is not radionuclide-specific, background measurements are compared to the survey unit measurements to determine the level of residual radioactivity. The *background reference area* is a geographical area from which representative reference measurements are performed for comparison with measurements performed in specific survey units. The background reference area is defined as an area that has similar physical, chemical, radiological, and biological characteristics as the survey unit(s) being investigated but has not been contaminated by site activities (*i.e.*, non-impacted). It is evident, that in highly populated or industrial areas no background reference areas can be found. In EURSSEM guidance is given how to adopt the area to investigate with radioactive contaminants also as background reference area.

Data Life Cycle is the term for the process of planning the survey, implementing the survey plan, and assessing the survey results prior to making a decision.

The Data Quality Objectives (DQO) Process is used in the survey planning to ensure that the survey results are of sufficient quality and quantity to support the final decision.

Quality Assurance and Quality Control (QA/QC) procedures are performed during implementation of the survey plan to collect information necessary to evaluate the survey results.

Data Quality Assessment (DQA) is the process of assessing the survey results, determining that the quality of the data satisfies the objectives of the survey, and interpreting the survey results as they apply to the decision being made.

A systematic process and structure for quality should be established to provide confidence in the quality and quantity of data collected to support decision making. The data used in decision making should be supported by a planning document that records how quality assurance and quality control are applied to obtain type and quality of results that are needed and expected. There are several terms used to describe a variety of planning documents, some of which document only a small part of the survey design process. EURSSEM uses the term *Quality Assurance Project Plan* (QAPP) to describe a single document that incorporates all of the elements of the survey design.

Site: Any installation, facility, or discrete, physically separate parcel of land, or any building or structure or portion thereof, that is being considered for survey and investigation.

3.3 Design of field-based site characterizations; data quality objective process

The first step in designing effective field-based site characterisations is planning [2], [10], [39]. The data quality objective (DQO) process is a series of planning steps based on the scientific method for establishing criteria for data quality and developing survey designs.

Characterization surveys may be performed to satisfy a number of specific objectives. Examples of characterization survey objectives should include actions as:

- Determining the nature and extent of radiological contamination;
- Evaluating remediation alternatives (*e.g.*, unrestricted use, restricted use, on-site disposal, off-site disposal, *etc.*);
- Input to pathway analysis/dose or risk assessment models for determining site-specific DCGLs (*e.g.*, Bq/kg, Bq/m^2);
- Estimating the occupational and public health and safety impacts during decommissioning;
- Evaluating remediation technologies;
- Input to final status survey design.

Planning radiation surveys using the DQO Process improves the survey effectiveness and efficiency, and thereby the defensibility of decisions. This minimizes expenditures related to data collection by eliminating unnecessary, duplicative, or overly precise data. Using the DQO Process ensures that the type, quantity, and quality of environmental data used in decision making will be appropriate for the intended application. EURSSEM supports the use of the DQO Process to design surveys for input to both evaluation techniques (elevated measurement comparison and the statistical test). The DQO Process provides systematic procedures for defining the criteria that the survey design should satisfy, including what type of measurements to perform, when and where to perform measurements, the level of decision errors for the survey, and how many measurements to perform.

The third step of the Data Quality Objectives (DQO) Process involves identifying the data needs for a survey. One decision that can be made at this step is the selection of direct measurements for performing a survey or deciding that sampling methods followed by laboratory analysis are necessary.

This decision is driven by "identifying the data needs" for the survey being performed and this includes:

- Area of survey coverage for surface scans based on survey unit classification (Section 3.3.2.8);
- Radionuclide(s) of interest (Section 3.3.3 and Section 3.3.4);
- Specific background for the radionuclide(s) of interest (Section 3.3.5);
- Derived concentration guideline level (DCGL) for each radionuclide of interest (Section 3.3.6);
- Target detection limits for each radionuclide of interest (Section 3.3.7);
- Type of samples to be collected (Section 3.4);
- Sampling locations and frequencies (Section 3.5);
- Type of measurements to be performed (Section 3.6 and Section 3.7);
- Selection of equipment (Section 3.8);

- Selection of applicable analyse methods (Section 3.9);
- Data interpretation (Section 3.10);
- Type and frequency of field QC measurements to be performed (Section 3.3.9 and Section 3.10.8);
- Measurement tracking and documentation requirements (Section 2.11 and Section 3.11);
- Cost of the methods being evaluated (cost per measurement as well as total cost) (0).

Some of this information will be supplied by subsequent steps in the DQO process, and several iterations of the process and will be further discussed and may be needed to identify all of the data needs. Consulting with a health physicist or radio-chemist may be necessary to properly evaluate the information before deciding between direct measurements or sampling methods to perform the survey. Many surveys will involve a combination of direct measurements and sampling methods, along with scanning techniques, to demonstrate compliance with the release criterion.

The level of effort associated with planning a survey is based on the complexity of the survey and the objective of the survey(s) (see Section 3.3.10). In general a final site survey will be the most extensive survey to be executed at a site and the guidelines given in the next sections are then most appropriate and a carefull consideration should be made during the design what to include and what to exclude explicitely.

Large, complicated sites generally receive a significant amount of effort during the planning phase, while smaller sites may not require as much planning. This graded approach defines data quality requirements according to the type of survey being designed, the risk of making a decision error based on the data collected, and the consequences of making such an error. This approach provides a more effective survey design combined with a basis for judging the usability of the data collected.

The survey methods used to evaluate radiological conditions and develop answers to these questions depend on a number of factors including: contaminants, contaminant distribution, acceptable contaminant levels established by the regulatory agency(ies), future site use, and physical characteristics of the site.

The remediation or decommissioning process assures that residual radioactivity will not result in individuals being exposed to unacceptable levels of radiation or radioactive materials. Regulatory agencies establish radiation dose standards based on risk considerations and scientific data relating dose to risk. Residual levels of radioactive material that correspond to allowable radiation dose standards are calculated (derived) by analysis of various pathways and scenarios (direct radiation, inhalation, ingestion, *etc.*) through which exposures could occur. These derived levels, known as derived concentration guideline levels (DCGLs), are presented in terms of surface or mass activity concentrations. DCGLs usually refer to average levels of radiation or radioactivity above appropriate background levels. DCGLs applicable to miscellaneous surfaces, e.g., pavements, are expressed in units of activity per surface area (typically Bq/m^2or $dpm/100\ cm^2$. When applied to soil and induced activity from neutron irradiation, DCGLs are expressed in units of activity per unit of mass (typically Bq/kg).

3.3.1 Major factors in site characterisation

Major factors in site characterisation, to be taken into account, include:

- Classification of the site. The classification is crucial to the survey design because the classification determines the level of survey effort based on the potential contamination and should involve reviewing all available information, e.g., a performed historical site assessment.

- Characterisation can be a large consumer of project resources. Mistakenly, its practical importance to solving the problem may not always be understood or appreciated. In some instances, the characterisations may be the "last word" measurements (e.g., for peripheral areas) and, as such, their credibility is vital.
- The amount of characterisation should be proportionate to the extent of the likely remediation effort. Over-characterisation can result in a disproportionate fraction of the budget being spent on measurements, leaving insufficient means to carry out acceptable remediation.
- Characterisation should be adequate to allow a properly designed remediation; one that does not involve excessive amounts of unnecessary effort or environmental damage.
- Characterisation efforts should be sufficient to demonstrate the existence of clean areas and to provide credible assurances that un-remediated areas are safe.
- Characterisations should have a sufficiently broad focus that any other unknown contaminants are detected at a stage when they can be dealt with efficiently.
- The characterisation, in the first instance, and the subsequent remediation should not make things worse by ill-advised first attempts that magnify or spread the problem. A guiding principle can be "first, do no harm".

The nature and amount of radionuclides present will probably need to address the full three dimensional distribution of radioactive contamination. There are many possible contamination scenarios, including:

- A superficial distribution of deposited activity.
- Activity which has been deposited on the ground surface and which has migrated into the ground.
- Activity which has been buried or covered (e.g., by ploughing or building operations).
- Activity which is to a greater or lesser extent distributed through a substantial depth of soil (e.g., waste tips).
- Activity which is deeply buried (e.g., due to leakage from underground storage tanks or drains (pipelines) which have carried active material).
- Activity distributed as hot particles which are individually hazardous.
- Activity which is uniform over large areas or volumes; and localized hot-spots.

Sometimes there may be *a priori* reasons to believe that the distribution is known, or can be established with little effort. In other cases, determination of the distribution will be a major part of the characterisation. Gamma emitting nuclides found near to the surface may be amenable to measurement by non-invasive means, whereas deeply buried material will usually require more complex and costly methods.

Figure 3.1 shows an estimated correlation between the various site characterisation methods [2]. As can be seen, there is a significant unit cost difference in price between in situ spectrometry and laboratory soil sample analysis. This difference is mainly due to the additional time and effort required for sample processing and measurement. There is some variability in this cost estimate, which is dependent on the radionuclide measured and the local factors such as cost of labour and analysis.

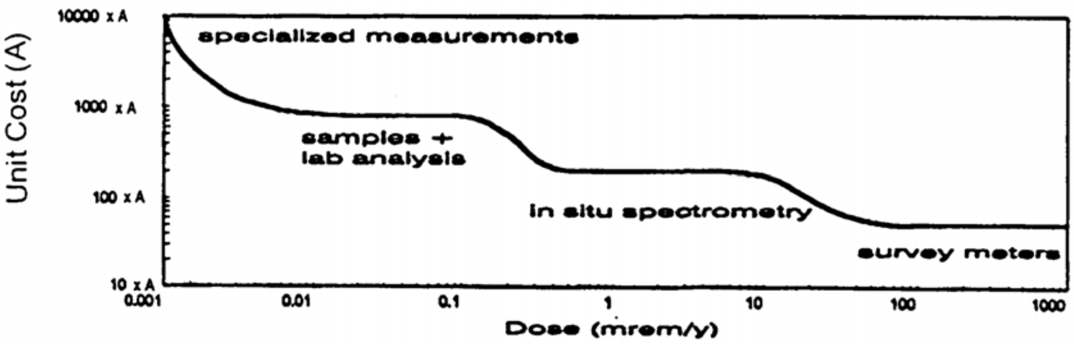


Figure 3.1 General pattern of measurement methods and their costs as a function of level of radiation/radioactivity being measured. Unit cost A is equivalent to US $1

3.3.2 General site characterisation survey design aspects

There is great variability in the details of characterization approaches appropriate to specific problems and sites. Differences among sites due to the heterogeneous character of the natural environment and to the nature and history of contamination are enough to require different approaches. However, the varieties of other important influences on the remediation problem definitely require that a characterization approach be designed to address all such issues. The guidance here focuses on the important elements that any strategy developed for characterisation of a specific site should consider. It also addresses the value of flexibility and phasing of study components to allow revision of the strategy as new information becomes available. Characterisation data are an important element in making effective remediation decisions. Clear specifications of the objectives and strategies for the characterization are important.

In the developed sampling and analysis plan, due consideration should be given to:

- *Spreading contamination*. Characterisation practices should be designed in such a way as not to contribute to the further spread of contamination at the site, or off-site. This is of particular concern when dealing with radioactive contamination. For example, contamination can be spread through uncontaminated aquifers as a result of poor drilling and well completion practices. Care should be exercised so that on-site workers do not inadvertently carry radioactive contamination off the site through inadequate decontamination processes.
- *Accessibility*. During the planning process it is necessary to consider access logistics, including the ability to physically gain entry to the site, especially for any equipment that is brought in (e.g., drilling rigs, cone penetrometer trucks). It should also be considered whether there are any overhead or underground utilities which may impact the investigation. It may be necessary to limit access to a contaminated area to only specially trained site workers and to allow for a decontamination zone for equipment and personnel.
- *Jurisdictional concerns*. Before initiating field work, it is essential to obtain any approvals necessary to access the area to be characterized. Authorization may be required from governmental or private parties. In addition, it may be necessary to obtain certain permits for digging, drilling, or installing any groundwater wells. A check list of requirements should be prepared to ensure preparedness.

Further, a field-based site characterisation has to fulfil the following (suggested) decision sequence to determine the appropriate investigation strategy for a site:

Decision 1: Is there enough information to meet project objectives (for risk assessment, established data quality guideline level(s), options comparison, preferred option implementation or verification and validation)?

If not, the objectives of the next phase of the investigation should be defined. If yes, the next phase of the characterization, remediation and restoration process should be defined.

Decision 2: For what should the (new) samples (soil, water, gas, etc.) to be collected be specified to obtain enough information to meet project objectives and what is the specification for the analyses?

These samples have to provide additional information for one or more specific pathways of the conceptual model. Therefore specific requirements have to be set for the analysis results of those samples (e.g., sample size, accuracy, etc.) to obtain the correct and needed information.

Decision 3: What locations should be sampled, how many and with what frequency samples should be taken?

Selection of the sample locations and the frequency of sampling have to fulfill the requirements to meet objectives, e.g., conceptual model.

Decision 4: From what depths should the samples (soil, water, gas, etc.) be collected, and what are the instrumental requirements?

Selection is made at which depths (e.g., surface, 10 cm, etc.) the samples should be collected and the specific instrumental requirements defined to meet the required analysis results.

Decision 5: What form (non-intrusive and/or intrusive) investigation is necessary to obtain the specified samples to meet project objectives?

Selection is made which non-intrusive and/or intrusive method(s) will be applied to collect the samples.

Decision 6: What techniques and (monitoring) installations/instrumentation should be employed to obtain the required analyse result from the samples (soil, water, gas, etc.)?

Selection of the appropriate analyse technique (non-destructive and/or destructive) to obtain an analysed result that fulfils the requirements.

Decision 7: What quality measures will be employed to ensure accurate data from the point of sample collection or monitoring to the laboratory and the data interpretation?

What are quality control and quality assurance measures?

Each decision should be documented so that other stakeholders can understand why the design was selected. Examples of linkage between site investigation design aspects and conceptual models are presented in Table 3.2.

In the case that more than one initial site conceptual model for a site or part of a site has been developed, site characterisation data should be obtained to test the various models and discriminate between them. Some of these models may be rejected because they are inconsistent with the new data, and uncertainty in the remaining model(s) will be reduced.

In many site characterisations, it is appropriate to phase the investigations. More detailed characterisations are deferred until the results of earlier phases of work have been evaluated. This approach ensures that the later investigations are focused on relevant areas with the appropriate degrees of accuracy and confidence employed.

Table 3.2 Examples of linkages between site characterisation design aspects and conceptual model

Survey design to address potential contamination through identified pathway	Pathway identified in the conceptual model
- Air quality sampling. - Surface sampling for radioactive and non-radioactive contaminants on an appropriate sampling pattern. - For other contaminants, addressed by intrusive investigations on an appropriate sampling pattern.	Diffuse airborne contamination.
- Walk over radiation surveys. - Soil vapour survey. - Surface and shallow sampling adjacent to roads.	Spillage from vehicles during transport operations.
- Walk over radiation surveys. - Soil vapour survey. - Surface and shallow sampling to roads. - Trial pits/boreholes located position of known buildings.	Disposals/spillages/losses associated with former buildings.
- A drain survey, including sampling of drain sediments. - Trial pits/boreholes located along the line of the drain.	Leakage from drains.
- Walkover geophysics survey prior to intrusive sampling, in order to detect disturbed ground, buried objects and services. - Soil vapour survey. - Walkover radiation surveys. - Intrusive investigations at positions identified by geophysical survey.	Burial of waste materials.
- Biota, e.g., meat, fish, diary products, vegetables, fruit, horticulture products, mushrooms, etc.	Food chain.

3.3.2.1 Site classification by contamination potential

Classifying a site/survey unit is crucial to the survey design because this step determines the level of characterisation/survey effort based on the potential for contamination. Sites are initially classified as impacted or non-impacted based on existing information and can be re-classified based on new information, e.g., preliminary investigation, historical site assessment.

Non-impacted areas have no reasonable potential for residual contamination and require no further evidence to demonstrate compliance with the release criterion. When planning the final status survey, impacted sites may be further divided into survey units. If a survey unit is classified incorrectly, the potential for making decision errors increases. For this reason, all impacted areas are initially assumed to be Class 1 (see Section 3.2 and 0). Class 1 areas require the highest level of survey effort because they are known to have contaminant concentrations above the release criteria, or the contaminant concentrations are unknown.

Information indicating the potential or known contaminant concentration is less than the release criteria can be used to support re-classification of an area or survey unit as Class 2 or Class 3 (see Section 3.2).

There is a certain amount of information necessary to demonstrate compliance with the release criterion. The amount of this information that is available and the level of confidence in this information are reflected in the area classification. The initial assumption for affected areas is that none of the necessary information is available. This results in a default Class 1 classification. This corresponds with the statement of the null hypothesis that the survey unit is contaminated, and represents the most efficient case for the regulator. For this reason, the recommendations for a Class 1 final status survey represent the minimal amount of information necessary to demonstrate compliance.

Not all of the information available for an area will be collected for purposes of compliance demonstration. For example, data will be collected during characterization surveys to determine the extent, and not necessarily the amount, of contamination. This does not mean that the data do not meet the objectives of compliance demonstration, but may mean that appliance of statistical tests would be of little or no value because the data have not been collected using appropriate protocols or design. Rather than discard potentially valuable information, EURSSEM allows for a qualitative assessment of existing data (see Section 2.4, Historical site assessment).

Non-impacted areas represent areas where all of the information necessary to demonstrate compliance is available from existing sources. For these areas, no statistical tests are considered necessary. A classification as Class 2 or Class 3 indicates that some information on describing the potential for contamination is available for that survey unit. The data collection recommendations are modified to account for the information already available, and the statistical tests are performed on the data collected during the final status survey.

As previously stated, the conservative assumption that an area receives a classification of Class 1 is only applied to impacted sites. The historical site assessment (see Section 2.4) is used to provide an initial classification for the site of impacted or non-impacted based on existing data and professional judgment.

3.3.2.2 Identification of survey units

A survey unit is a physical area consisting of structures or land areas of specified size and shape for which a separate decision will be made as to whether or not that area exceeds the release criterion. This decision is made as a result of the final status survey. As a result, the survey unit is the primary entity for demonstrating compliance with the release criterion.

To facilitate survey design and ensure that the number of survey data points for a specific site is relatively uniformly distributed among areas of similar contamination potential, the site is divided into survey units that share a common history or other characteristics, or are naturally distinguishable from other portions of the site.

A site may be divided into survey units at any time before the final status survey. For example, a historical site assessment or scoping survey results may provide sufficient justification for partitioning the site into Class 1, 2, or 3 areas (see Figure 3.2 for an example). Note, however, that dividing the site into survey units is critical only for the final status survey - scoping, characterization, and remedial action support surveys may be performed without dividing the site into survey units.

A survey unit should, in principle, not include areas that have different classifications. The survey unit's characteristics should also be generally consistent with exposure pathway modelling that is used to convert dose or risk into radionuclide concentrations. For indoor areas classified as Class 1, each room may be designated as a survey unit. Indoor areas may also be subdivided into several survey units of different classification, such as separating floors and lower walls from upper walls and ceilings (and other upper horizontal surfaces) or subdividing a large warehouse based on floor area.

Table 3.3 Suggested areas for survey units

Classification	**Suggested Area**	
	Land areas	**Structures**
Class 1	Up to 2,000 m^2	Up to 100 m^2 floor area
Class 2	2,000 to 10,000 m^2	100 to 1,000 m^2
Class 3	No limit	No limit

Survey units should be limited in size based on classification, exposure pathway modelling assumptions, and site-specific conditions. However, due to new instrumental developments for scanning surveys and insights the areas are increasing in practice. The suggested areas for survey units are indicated in Table 3.3.

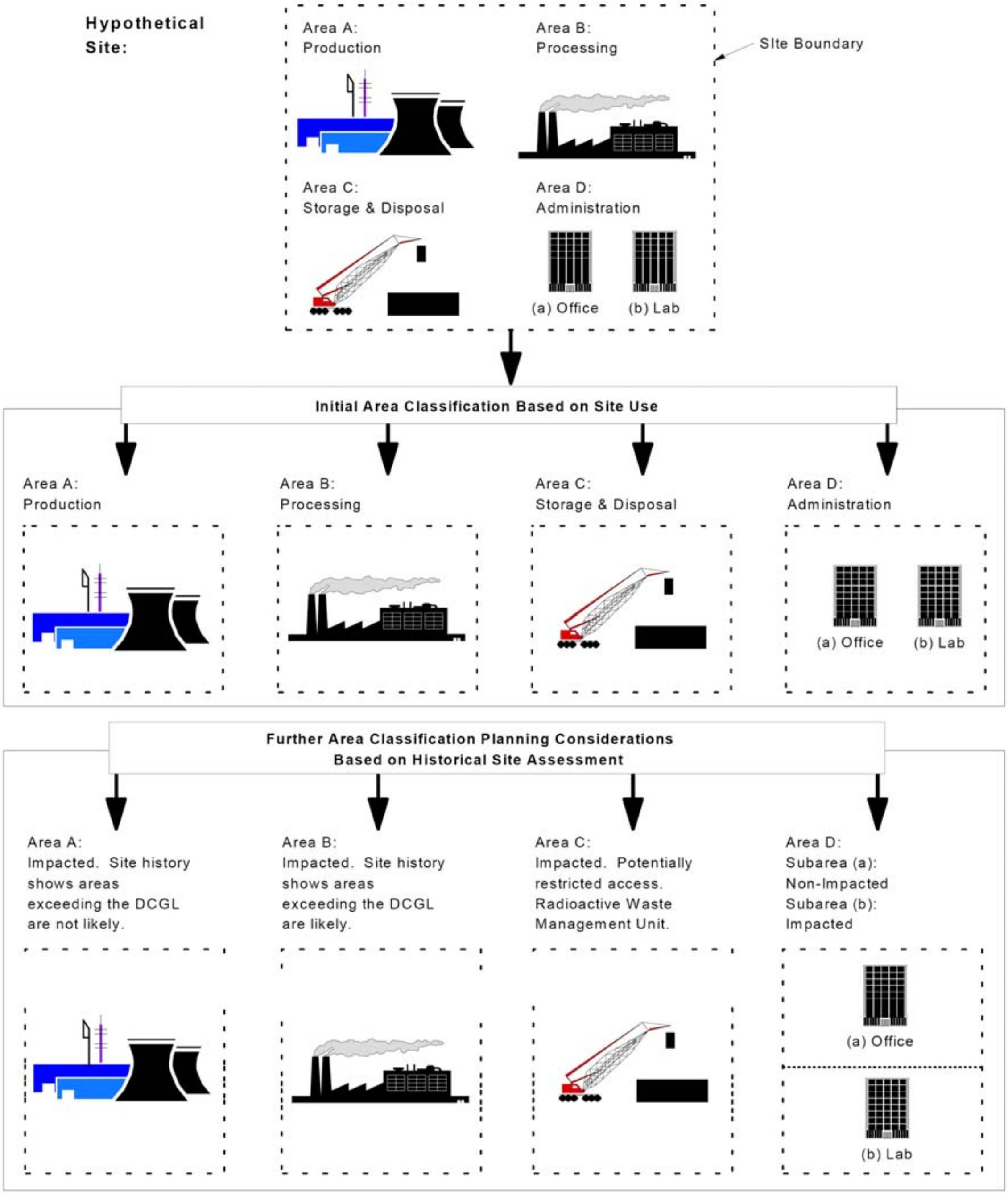


Figure 3.2 Example showing how a site might be classified prior to clean-up based on preliminary investigations, historical site assessment and supplementary investigations

The limitation on survey unit size for Class 1 and Class 2 areas ensures that each area is assigned an adequate number of data points. The rationale for selecting a larger survey unit area should be developed using the Data Quality Objective Process (Section 3.3) and fully documented. Because the number of data points (determined in Section 3.5) is independent of the survey unit size, disregarding locating small areas of elevated activity, the survey coverage in an area is determined by dividing the fixed (minimum) number of data points obtained from the statistical tests by the survey unit area. That is, if the statistical test estimates that 20 data points are necessary (minimum) to demonstrate compliance, then the survey coverage is determined by dividing 20 by the area over which the data points are distributed.

Special considerations may be necessary for survey units with structure surface areas less than 10 m^2 or land areas less than 100 m^2. In this case, the number of data points obtained from the statistical tests is unnecessarily large and not appropriate for smaller survey unit areas. Instead, some specified level of survey effort should be determined based on the DQO process and with the concurrence of the responsible regulatory agency. The data generated from these smaller survey units should be obtained based on judgment, rather than on systematic or random design, and compared individually to the DCGLs.

An important consideration is that the above applied statistical method does not take into account the perception of different stakeholders. Therefore, it can be necessary to increase the number of data points to satisfy these stakeholders. It is advised to discuss and agree with the stakeholders first on the methodology to apply to calculate the number of data points and second on the calculation of this number.

The criteria used for designating areas as Class 1, 2, or 3 should be described in the final status survey plan. Compliance with the classification criteria should be demonstrated in the final status survey report. A thorough analysis of the historical site assessment (HAS) findings (Section 2.4) and the results of scoping and characterization surveys provide the basis for an area's classification. As a survey progresses, re-evaluation of this classification may be necessary based on newly acquired survey data.

Example 3.1: Contamination identified in a Class 3 area

If contamination is identified in a Class 3 area, an investigation and re-evaluation of that area should be performed to determine if the Class 3 area classification is appropriate. Typically, the investigation will result in part or all of the area being reclassified as Class 1 or Class 2. If survey results identify residual contamination in a Class 2 area exceeding the DCGL or suggest that there may be a reasonable potential that contamination is present in excess of the DCGL, an investigation should be initiated to determine if all or part of the area should be reclassified to Class 1. More information on investigations and reclassifications is provided in Section 3.3.2.8.

3.3.2.3 Factors influencing the site characterisation design quality

The quality of the site characterisation arises primarily from:

- The survey/investigation design errors.
- Measurement errors.

3.3.2.4 Survey design errors

Survey design errors occur when the survey design is unable to capture the complete extent of variability that exists for the radionuclide distribution in a survey unit. Since it is impossible in every situation to measure the residual radioactivity at every point in space and time, the survey results will be incomplete to some degree. It is also impossible to know with complete certainty the residual radioactivity at locations that were not measured, so the incomplete survey results give rise to uncertainty. The greater the natural or inherent variation in residual radioactivity, the greater the uncertainty associated with a decision based on the survey results. The unanswered question is: “How well do the survey results represent the true level of residual radioactivity in the survey unit?”

Examples of possible areas of uncertainty are given in Table 3.4. Outstanding uncertainty should be recorded related to precision, bias, representativeness, completeness, comparability and sensitivity in order that the significance can be treated in the subsequent assessment of the data.

Table 3.4 Examples of uncertainties arising during site investigation, and possible actions that can be taken to reduce uncertainties in the site charaterization and remediation [10]

Site characterization activity	Examples of uncertainty	Possible action to reduce uncertainty
Preliminary investigation: - desk study	Access or supply of historical information on site history limited by site owner/occupier, leading to failure to identify potential radioactive and chemical contaminants, jeopardishing health, safety and environmental management and scope of investigation (conceptual model uncertainty).	Assume worst-case history, particularly for defense sites, and take client thorough an interative process to try to establish all relevant sources of information. Prepare contingency plans for health, safety and environmental management and site investigation procedures.
	Inadequate information retained by client in plans and demolition records. Potential presence of in-situ buried structures (e.g., foundation, services) on the site (conceptual model uncertainty).	Incorporate an exploratory investigation stage, using non-invasion geophysical surveying. Limited intrusive investigations to prepare main investigation plans.
	Poor conceptual model developed and/or lack of link with subsequent survey design. Results in poor quality investigation and poor quality health, safety and environmental management (conceptual model uncertainty).	Consult conceptual model checklist to ensure adequacy of model. Review conceptual model and site investigation objectives at regular intervals throughout project.
	Failure to set objectives, e.g., required risk target.	Ensure that risk targets are set. Use conceptual model of site and required level of confidence in output to design an appropriate sampling strategy.
	Failure to appreciate chemical and radioactive characteristics of waste that will be produced, possibly leading to production of waste (e.g., mixed radioactive and organics-contaminated waste) for which no regular disposal route exists.	Evaluate potential characteristics of waste, and ensure that disposal routes available.
Preliminary investigation: - site reconnaissance	Failure to appreciate requirement of site operating procedures. Could limit technical scope of investigation (e.g., cannot investigate close to services) or could cause extensive delays to project schedule.	Ensure that, during site visit, appropriate personnel are interviewed who can brief and supply contractors with necessary site operating instructions and documentation.
Site investigation: - exploratory - main - supplementary	Uncertainty in conceptual model and therefore poor understanding of contamination occurrence.	Use a phased investigation approach, real-time sampling to focus investigation, collect large number of samples, and or use Triad or Optimised Contaminated Land Investigation approaches.
	Failure to locate services, both inside and outside site boundary. This could lead to damage to services, possibly resulting in injury/death to site personnel and/or disruption to site operations. Extensive delays and project schedule uncertainty.	Ensure that excavation procedures on the client's site are in accordance with site procedures and health, safety and environmental guidance. For off-site excavations, ensure that national utilities are contacted.
	Inconsistent positioning information, leads to uncertainty in locations of contaminated ground, sampling points, services, etc. (data uncertainty).	All investigations or surveys should be topographically surveyed to ordnance datum and national grid reference. The accuracy of the survey surveying method should be reported.
	Poor quality management of investigation resulting in unreliable data (e.g., poor sampling and logging data). Further verification works may then be necessary to satisfy stakeholders (data uncertainty).	Ensure that all work is undertaken in accordance with quality management system.
	Uncertainty in analytical data (data uncertainty).	Check QA/QC procedures, analyse more samples, duplicate analyses, use different preparation methods, use different analytical methods with lower limits of detection, look for related contaminants.

Measurement errors create uncertainty by masking the true level of residual radioactivity and may be classified as random or systematic errors. Random errors affect the precision of the measurement system, and show up as variations among repeated measurements. Systematic errors show up as measurements that are biased to give results that are consistently higher or lower than the true value.

A quality control (QC) program can both lower the chances of making an incorrect decision and help the data user understand the level of uncertainty that surrounds the decision. Quality control data are collected and analyzed during implementation of the site characterisation to provide an estimate of the uncertainty associated with the survey results. Quality control measurements (scans, direct measurements, and samples, etc.) are technical activities performed to measure the attributes and performance of the survey. During any survey, a certain number of measurements should be taken for quality control purposes.

3.3.2.5 Design considerations for sites with a relatively uniform distribution of contamination

The survey design for areas with relatively uniform distributions of contamination is primarily controlled by classification and the requirements of the statistical test. The guidance and recommendations provided for Class 1 survey units are designed to minimise the decision error. Guidance and recommendations for Class 2 or Class 3 surveys may be appropriate based on the existing information and the level of confidence associated with this information.

The first consideration is the identification of survey units. The identification of survey units may be accomplished early (*e.g.*, scoping) or late (*e.g.*, final status) in the survey process, but must be accomplished prior to performing a final status survey. Early identification of survey units can help in planning and performing surveys throughout the Radiation Site Survey Investigation Process. Late identification of survey units can prevent misconceptions and problems associated with reclassification of areas based on results of subsequent surveys. The area of an individual survey unit is determined based on the area classification and modelling assumptions used to develop the release criteria or derived concentration guideline level ($DCGL_W$). Identification of survey units is discussed below.

Another consideration is the estimated number of measurements to demonstrate compliance using the statistical tests. Section 3.5 describes the calculations used to estimate the number of measurements. These calculations use information that is usually available from planning or from preliminary surveys (*i.e.*, scoping, characterization, remedial action support).

The information needed to perform these calculations is: 1) acceptable values for the probabilities of making Type I (α) or Type II (β) decision errors, 2) the estimates of the measurement variability in the survey unit (σ_s) and the reference area (σ_r) if necessary, and 3) the shift (Δ).

EURSSEM recommends that site-specific values be determined for each of these parameters. To assist the user in selecting site-specific values for decision error rates and Δ, EURSSEM recommends that an initial value be selected and adjusted to develop a survey design that is appropriate for a specific site. An arbitrary initial value of one half the $DCGL_W$ is selected for the lower bound of the gray region. This value is adjusted to provide a relative shift (Δ/σ) value between one and three as described in Section 3.5.1.1. For decision error rates, a value that minimizes the risk of making a decision error is recommended for the initial calculations. The number of measurements can be recalculated using different decision error rates until an optimum survey design is obtained. A prospective power curve (see 0, Section A.2 and 0, Sections D1.3 and D2.4) that considers the effects of these parameters can be very helpful in designing a survey and considering alternative values for these parameters, and is highly recommended.

To ensure that the desired power is achieved with the statistical test and to account for uncertainties in the estimated values of the measurement variability's, EURSSEM recommends that the estimated number of measurements calculated using the formulas in

Section 3.5 be increased by 20%. Insufficient numbers of measurements may result in failure to achieve the DQO for power and result in increased Type II decision errors, where survey units below the release criterion fail to demonstrate compliance.

Once survey units are identified and the number of measurements is determined, measurement locations should be selected. The statistical tests assume that the measurements are taken from random locations within the survey unit. A random survey design is used for Class 3 survey units, and a random starting point for the systematic grid is used for Class 2 and Class 1 survey units.

3.3.2.6 Design considerations for small areas of elevated activity

Scanning surveys are typically used to identify small areas of elevated activity. The size of the area of elevated activity that the survey is designed to detect affects the release criteria $DCGL_{EMC}$, which in turn determines the ability of a scanning technique to detect these areas. Larger areas have a lower $DCGL_{EMC}$ and are more difficult to detect than smaller areas.

The percentage of the survey unit to be covered by scans is also an important consideration. 100% coverage means that the entire surface area of the survey unit has been covered by the field of view of the scanning instrument. 100% scanning coverage provides a high level of confidence that all areas of elevated activity have been identified. If the available information concerning the survey unit provides information demonstrating that areas of elevated activity may not be present, the survey unit may be classified as Class 2 or Class 3. Because there is already some level of confidence that areas of elevated activity are not present, 100% coverage may not be necessary to demonstrate compliance. The scanning survey coverage may be adjusted based on the level of confidence supplied by the existing data. If there is evidence providing a high level of confidence, that areas of elevated activity are not present, 10% scanning coverage may meet the objectives of the survey. If the existing information provides a lower level of confidence, the scanning coverage may be adjusted between 10 and 100% based on the level of confidence and the objectives of the survey. A general recommendation is: always try to minimize the decision error. In general, scanning the entire survey unit is less expensive than finding areas of elevated activity later in the survey process. Finding such areas will lead to performing additional surveys due to survey unit misclassification.

Another consideration for scanning surveys is the selection of scanning locations. This is not an issue when 100% of the survey unit is scanned. Whenever less than 100% of the survey unit is scanned, a decision must be made on what areas are scanned. The general recommendation is that, when large amounts of the survey unit are scanned (*e.g.*, > 50%), the scans should be systematically performed along transects of the survey unit. When smaller amounts of the survey unit are scanned, selecting areas based on professional judgment may be more appropriate and efficient for locating areas of elevated activity (*e.g.*, drains, ducts, piping, ditches). A combination of 100% scanning in portions of the survey unit selected based on professional judgement and less coverage (*e.g.*, 20-50%) for all remaining areas may result in an efficient scanning survey design for some survey units.

3.3.2.7 Determining survey and investigation levels

An important aspect of a (e.g., final status) survey is the design and implementation of investigation levels. Investigation levels are radionuclide-specific levels of radioactivity used to indicate when additional investigations may be necessary. Investigation levels also serve as a quality control check to determine when a measurement process begins to get out of control. For example, a measurement that exceeds the investigation level may indicate that the survey unit has been improperly classified - definitions of applied area classes are given in Section 3.2 - or it may indicate a failing instrument.

When an investigation level is exceeded, the first step is to confirm that the initial measurement/sample actually exceeds the particular investigation level. This may involve taking further measurements to determine that the area and level of the elevated residual radioactivity are such that the resulting dose or risk meets the release criterion[12]. Depending on the results of the investigation actions, the survey unit may require reclassification, remediation, and/or resurvey. Table 3.5 illustrates an example of how investigation levels can be developed.

Table 3.5 Example of final status survey investigation levels

Survey unit classification	Flag direct measurement or sample result when:	Flag scanning measurement result when:
Class 1	> $DCGL_{EMC}$ or > $DCGL_W$ and > a statistical parameter-based value	> $DCGL_{EMC}$
Class 2	> $DCGL_W$	> $DCGL_W$ or > MDC
Class 3	> fraction of $DCGL_W$	> $DCGL_W$ or > MDC

When determining an investigation level using a statistical-based parameter (*e.g.*, standard deviation) one should consider:

- Data quality objectives for this survey objectives;
- Underlying radionuclide distributions and an understanding of corresponding types (*e.g.*, normal, log normal, non-parametric);
- Statistical descriptors (*e.g.*, standard deviation, mean, median), population stratifications (*i.e.*, are there sub-groups present?);
- Other prior survey and historical information. For example, a level might be arbitrarily established at the mean + 3 standard deviation of the survey unit, assuming a normal distribution. A higher value might be used if locating discrete sources of higher activity was a primary survey objective.

By the time the final status survey is conducted, survey units should be defined. Estimates of the mean, variance, and standard deviation of the radionuclide activity levels within the survey units should also be available.

For a Class 1 survey unit, measurements above the $DCGL_W$ are not necessarily unexpected. However, a measurement above the $DCGL_W$ at one of the discrete measurement locations might be considered unusual if it were much higher than all of the other discrete measurements performed during a survey. Thus, any discrete measurement that is *both* above the $DCGL_W$ and above the statistical-based parameter for the measurements should be investigated further. Any measurement, either at a discrete location or from a scan that is above the $DCGL_{EMC}$ should be flagged for further investigation.

For Class 2 or Class 3 areas, neither measurements above the $DCGL_W$ nor areas of elevated activity are expected. Any measurement at a discrete location exceeding the $DCGL_W$ in these areas should be flagged for further investigation. Because the survey design for Class 2 and Class 3 survey units is not driven by the elevated measurement criterion (EMC), the scanning minimum detectable concentration (MDC) might exceed the $DCGL_W$. In this case, any indication of residual radioactivity during the scan would warrant further investigation.

The basis for using the $DCGL_{EMC}$ rather than the more conservative criteria for Class 2 and Class 3 areas should be justified in survey planning documents. For example, where there is high uncertainty in the reported scanning MDC, a more conservative criterion would be warranted.

12 Rather than, or in addition to, taking further measurements the investigation may involve assessing the adequacy of the exposure pathway model used to obtain the DCGL's and area factors, and the consistency of the results obtained with the Historical Site Assessment and the scoping, characterization and remedial action support surveys.

Similarly, data quality assessment (DQA) for scanning may warrant a more conservative flag, as would greater uncertainty from historical site assessment or other surveys on the size of potential areas of elevated activity. In some cases, it may even be necessary to agree in advance with the regulatory agency responsible for the site on which site-specific investigation will be used if other than those presented in Table 3.5.

For a Class 3 area, there is a low expectation for residual radioactivity. It may be prudent to investigate any measurement exceeding even a fraction of the $DCGL_W$. The level selected in these situations depends on the site, the radio-nuclides of concern, and the measurement and scanning methods selected. This level should be set using the DQO Process during the survey design phase of the Data Life Cycle. In some cases, the user may also wish to follow this procedure for Class 2 and even Class 1 survey units.

3.3.2.8 Development of an integrated site characterisation strategy

The final step in survey design is to integrate the different selected survey techniques (see Section 3.6 and 3.7) with the number of measurements and measurement spacing (see Section 3.5). This integration along with the guidance provided in other portions of this manual produce an overall strategy for performing the survey. Table 3.6 provides a summary of the recommended survey coverage for structures and land areas. This survey coverage for different areas is the subject of this section.

Table 3.6 Recommended survey coverage for structures and land areas

	Structures		**Land Areas**	
Area classification	**Surface scans**	**Surface activity measurements**	**Surface scans**	**Soil samples**
Class 1	100%	Number of data points from statistical tests (Sections 3.5.1.1); additional measurements may be necessary for small areas of elevated activity (Sections 3.5.1.1).	100%	Number of data points from statistical tests (Sections 3.5.1.1); additional measurements may be necessary for small areas of elevated activity (Sections 3.5.1.1).
Class 2	10 to 100% (10 to 50% for upper walls and ceilings) Systematic and judgmental	Number of data points from statistical tests (Sections 3.5.1.1);	10 to 100% Systematic and judgmental	Number of data points from statistical tests (Sections 3.5.1.1);
Class 3	Judgmental	Number of data points from statistical tests (Sections 3.5.1.1);	Judgmental	Number of data points from statistical tests (Sections 3.5.1.1);

To account for assumptions used to develop the $DCGL_W$[13] and the realistic possibility of small areas of elevated activity, an integrated survey design should be developed to include all of the design considerations. An integrated survey design combines a scanning survey for areas of elevated activity with random measurements for relatively uniform distributions of contamination. Table 3.7 presents the recommended conditions for demonstrating compliance for a final status survey based on classification.

Random measurement patterns are used for Class 3 survey units to ensure that the measurements are independent and meet the requirements of the statistical tests. Systematic grids are used for Class 2 survey units because there is an increased probability of small

13 Note that the DCGL itself is not free of error. The assumptions made in any model used to develop DCGLs for a site should be examined carefully. The results of this examination should determine if the use of site-specific parameters results in large changes in the DCGLs, or whether a site-specific model should be developed to obtain DCGLs more relevant to the exposure conditions at the site. 0 provides additional information about the uncertainty associated with the DCGL and other considerations for developing an integrated survey design using the DQO Process.

areas of elevated activity. The use of a systematic grid allows the decision maker to draw conclusions about the size of any potential areas of elevated activity based on the area between measurement locations, while the random starting point of the grid provides an unbiased method for determining measurement locations for the statistical tests.

Table 3.7 Recommended conditions for demonstrating compliance based on survey unit classification for a final survey

Survey unit classification		**Statistical test**	**Elevated measurement comparison**	**Sampling and/or direct measurements**	**Scanning**
Impacted	Class 1	Yes	Yes	Systematic	100 % Coverage
	Class 2	Yes	Yes	Systematic	10-100 % Systematic
	Class 3	Yes	Yes	Random	Judgmental
Non-impacted		No	No	No	None

Class 1 survey units have the highest potential for small areas of elevated activity, so the areas between measurement locations are adjusted to ensure that these areas can be identified by the scanning survey if the area of elevated activity is not detected by the direct measurements or samples.

The data quality objectives of the scanning surveys are different. Scanning is used to identify locations within the survey unit that exceed the investigation level. These locations are marked and receive additional investigations to determine the concentration, area, and extent of the contamination.

For Class 1 areas, scanning surveys are designed to detect small areas of elevated activity that are not detected by the measurements using the systematic grids. For this reason, the measurement locations and the number of measurements may need to be adjusted based on the sensitivity of the scanning technique (see Section 3.5.1.1). This is also the reason for recommending 100% coverage for the scanning survey. 100% coverage means that the entire surface area of the survey unit is covered by the field of view of the scanning instrument. If the field of view is two meters wide, the survey instrument can be moved along parallel paths/spacing of two meters apart to provide 100% coverage. If the field of view of the detector is 5 cm, the parallel paths/spacing should be 5 cm apart.

Scanning surveys in Class 2 areas are also performed primarily to find areas of elevated activity not detected by the measurements using the systematic pattern. However, the measurement locations are not adjusted based on sensitivity of the scanning technique, and scanning is only performed in portions of the survey unit. The level of scanning effort should be proportional to the potential for finding areas of elevated activity based on the conceptual model. In Class 2 survey units that have residual radioactivity close to the release criterion a larger portion of the survey unit would be scanned, but for survey units that are closer to background scanning a smaller portion of the survey unit may be appropriate. Class 2 survey units have a lower probability for areas of elevated activity than Class 1 survey units, but some portions of the survey unit may have a higher potential than others. Judgmental scanning surveys would focus on the portions of the survey unit with the highest probability for areas of elevated activity. If the entire survey unit has an equal probability for areas of elevated activity, or the judgmental scans don’t cover at least 10% of the area, systematic scans along transects of the survey unit or scanning surveys of randomly selected grid blocks are performed.

Class 3 areas have the lowest potential for areas of elevated activity. For this reason, EURSSEM recommends that scanning surveys be performed in areas of highest potential (*e.g.*, corners, ditches, drains) based on professional judgment. Such recommendations may be typically provided by a health physics professional with radiation survey experience.This provides a qualitative level of confidence that no areas of elevated activity were missed by the random measurements or that there were no errors made in the classification of the area.

The sensitivity for scanning techniques used in Class 2 and Class 3 areas is not tied to the area between measurement locations, as they are in a Class 1 area (see Section 3.5.1.1). The scanning techniques selected should represent the best reasonable effort based on the survey data quality objectives. Structure surfaces are generally scanned for alpha, beta, and gamma emitting radio-nuclides. Scanning for alpha emitters or low-energy (< 100 keV) beta emitters for land area survey units is generally not considered effective because of problems with attenuation and media interferences. If one can reasonably expect to find any residual radioactivity, it is prudent to perform a judgmental scanning survey.

If the equipment and methodology used for scanning is capable of providing data of the same quality as direct measurements (e.g., detection limit, location of measurements, ability to record and document results), then scanning may be used in place of direct measurements. Results should be documented for at least the number of locations estimated for the statistical tests. The same logic can be applied for using direct measurements instead of sampling. In addition, some direct measurement systems may be able to provide scanning data.

As previously discussed, investigation levels are determined and used to indicate when additional investigations may be necessary or when a measurement process begins to get out of control. The results of all investigations should be documented in the final status survey report, including the results of scan surveys that may have potentially identified areas of elevated direct radiation.

Land area surveys

Class 1 areas

100% scanning coverage of Class 1 land areas is recommended. Locations of scanning survey results above the investigation level are identified and evaluated. Results of initial and follow-up direct measurements and sampling at these locations are recorded. Soil sampling is performed at locations identified by scans and at previously determined locations (Section 3.5.1.2). Where gamma emitting radio-nuclides are contaminants, in situ gamma spectroscopy may be used to confirm the absence of specific radio-nuclides or to demonstrate compliance.

Direct measurement or sample investigation levels for Class 1 areas should establish a course of action for individual measurements that approach or exceed the $DCGL_W$. Because measurements above the $DCGL_W$ are not necessarily unexpected in a Class 1 survey unit, additional investigation levels may be established to identify discrete measurements that are much higher than the other measurements. Any discrete measurement that is both above the $DCGL_W$ and exceeds three standard deviations above the mean should be investigated further (see Table 3.5). Any measurement (direct measurement, sample, or scan) that exceeds the $DCGL_{EMC}$ should be flagged for further investigation. The results of the investigation and any additional remediation that was performed should be included in the final status survey report. Data are reviewed as described in Section 3.10.8.4, additional data are collected as necessary, and the final complete data set evaluated as described in Section 3.10.3 or Section 3.10.4.

Class 2 areas

Surface scans are performed over 10 to 100% of open land surfaces. Locations of direct radiation above the scanning survey investigation level are identified and evaluated. If small areas of elevated activity are identified, the survey unit should be reclassified as “Class 1” and the survey strategy for that survey unit redesigned accordingly.

If small areas of elevated activity above DCGL values are not identified, direct measurement or soil sampling is performed at previously determined locations (Section 3.5.1.2). Where gamma emitting radio-nuclides are contaminants, in situ gamma spectroscopy may be used to confirm the absence of specific radio-nuclides or to demonstrate compliance. Data are reviewed as described in Section 3.10.8.4, additional data are collected as necessary, and the final complete data set evaluated as described in Section 3.10.3 or Section 3.10.4.

Investigation levels for Class 2 areas should establish levels for investigation of individual measurements close to but below the $DCGL_W$. The results of the investigation of the positive measurements and basis for reclassifying all or part of the survey unit as Class 1 should be included in the final status survey report.

Class 3 areas.

Class 3 areas may be uniformly scanned for radiations from the radio-nuclides of interest, or the scanning may be performed in areas with the greatest potential for residual contamination based on professional judgment and the objectives of the survey. In some cases a combination of these approaches may be the most appropriate. Locations exceeding the scanning survey investigation level are evaluated, and, if the presence of contamination not occurring in background is identified, re-evaluation of the classification of contamination potential should be performed.

Investigation levels for Class 3 areas should be established to identify areas of elevated activity that may indicate the presence of residual radioactivity. Scanning survey locations that exceed the investigation level should be flagged for further investigation. The results of the investigation and basis for reclassifying all or part of the survey unit as Class 1 or Class 2 should be included in the final status survey report. The data are tested relative to the pre-established criteria. If additional data are needed, they should be collected and evaluated as part of the entire data set. Soil sampling is performed at randomly selected locations (Section 3.5.1.2); if the contaminant can be measured at DCGL levels by in-situ techniques, this method may be used to replace or supplement the sampling and laboratory analysis approach. For gamma emitting radio-nuclides, the above data should be supplemented by several exposure rate and/or in-situ gamma spectrometry measurements. Survey results are tested for compliance with DCGLs and additional data are collected and tested, as necessary.

Structure Surveys

Class 1 areas

Surface scans are performed over 100% of structure surfaces for radiations which might be emitted from the potential radionuclide contaminants. Locations of direct radiation, distinguishable above background radiation, are identified and evaluated [42]. Results of initial and follow-up direct measurements and sampling at these locations are recorded and documented in the final status survey report. Measurements of total and removable contamination are performed at locations identified by scans and at previously determined locations (Section 3.5.1.2). Where gamma emitting radio-nuclides are present, in-situ gamma spectroscopy may be used to identify the presence of specific radio-nuclides or to demonstrate compliance with the release criterion.

Direct measurement or sample investigation levels for Class 1 areas should establish a course of action for individual measurements that approach or exceed the $DCGL_W$. Because measurements above the $DCGL_W$ are not necessarily unexpected in a Class 1 survey unit, additional investigation levels may be established to identify discrete measurements that are much higher than the other measurements. Any discrete measurement that is both above the $DCGL_W$ and exceeds three times the standard deviation (s) of the mean should be investigated further (Section 3.3.2.7). Any measurement (direct measurement, sample, or scan) that exceeds the $DCGL_{EMC}$ should be flagged for further investigation. The results of the investigation and any additional remediation that was performed should be included in the final status survey report. Data are reviewed as described in Section 3.10.8.4, additional data are collected as necessary, and the final complete data set evaluated as described in Section 3.10.3 or Section 3.10.4.

Class 2 areas

Surface scans are performed over 10 to 100% of structure surfaces. Generally, upper wall surfaces and ceilings should receive surface scans over 10 to 50% of these areas. Locations of scanning survey results above the investigation level are identified and investigated. If small areas of elevated activity are confirmed by this investigation, all or part of the survey unit should be reclassified as Class 1 and the survey strategy for that survey unit redesigned accordingly.

Investigation levels for Class 2 areas should establish a course of action for individual measurements that exceed or approach the $DCGL_W$. The results of the investigation of the positive measurements and basis for reclassifying all or part of the survey unit as Class 1 should be included in the final status survey report. Where gamma emitting radio-nuclides are contaminants, in-situ gamma spectroscopy may be used to identify the presence of specific radio-nuclides or to demonstrate compliance with the release criterion. Data are reviewed as described in Section 3.10.8.4, additional data are collected as necessary, and the final complete data set evaluated as described in Section 3.10.3 or Section 3.10.4.

Class 3 areas

Scans of Class 3 area surfaces should be performed for all radiations which might be emitted from the potential radionuclide contaminants. EURSSEM recommends that the surface area be scanned. Locations of scanning survey results above the investigation level are identified and evaluated. Measurements of total and removable contamination are performed at the locations identified by the scans and at the randomly selected locations that are chosen in accordance with Section 3.5.1.2. Identification of contamination suggests that the area may be incorrectly classified. If so, a re-evaluation of the Class 3 area classification should be performed and, if appropriate, all or part of the survey unit should be resurveyed as a Class 1 or Class 2 area. In some cases the investigation may include measurements by in-situ gamma spectroscopy at a few locations in each structure in a Class 3 area. A gamma spectroscopy system might even be an appropriate substitution for surface scans.

Because there is a low expectation for residual radioactivity in a Class 3 area, it may be prudent to investigate any measurement exceeding even a fraction of the $DCGL_W$. The investigation level selected will depend on the site, the radio-nuclides of concern, and the measurement and scanning methods chosen. This level should be determined using the DQO Process during survey planning. In some cases, the user may wish to follow this procedure for Class 2 survey units.

The results of the investigation of the measurements that exceed the investigation level and the basis for reclassifying all or part of the survey unit as Class 1 or Class 2 should be included in the final status survey report. The data are tested relative to the pre-established criteria. If additional data are needed, they should be collected and evaluated as part of the entire data set.

3.3.2.9 Other survey designs

The survey design in EURSSEM is based on six principal steps. Although the process is described sequential, EURSSEM is *not intended* to be a serial process that would slow site clean-ups. Rather, EURSSEM supports existing programs and encourages approaches to expedite site clean-ups. Part of the significant emphasis on planning in EURSSEM is meant to promote saving time and resources.

There are a number of approaches designed to expedite site clean-ups and characterisations. These approaches/methodologies can save time and resources by reducing sampling, preventing duplication of effort, and reducing inactive time periods between steps in a clean-up process. While differing in details, these methodologies have some common features:

- Decision making processes that affect sampling are determined before going to the field, but actual sampling decisions of "where" and "how many" are made in the field in "real time" by experts on the basis of evolving sampling results (such sampling and analysis plans are known as "dynamic" or "flexible" sampling plans).

- Regulator approval for the "science-based" approach over the traditional step-by-step approach in which regulators approve each phase of sampling before it is undertaken.
- Use of a suite of non-invasive and minimally-invasive technologies and field screening supported, when possible, by high quality on-site sample analysis with smaller amounts of verification sample analysis in off-site laboratories.
- Technology for efficient management, visualization, and interpretation of data to facilitate on-site, "real time" decision making.

Summaries of alternate clean-up approaches/methodologies are given below:

- *Observational approach.* The observational approach draws on tenets of geotechnical engineering in which it is accepted that the subsurface environment can never be reasonably sampled enough to create a conceptual model that contains no uncertainty. Geotechnical engineering deals with this uncertainty by designing subsurface building structures based on the "nominal" conditions and preparing contingency plans to handle the uncertainties should they be encountered in construction. This approach uses an iterative process of sample collection and real-time data evaluation to characterise a site. This process allows early field results to guide later data collection in the field. Data collection is limited to only that required for selecting a unique remedy for a site[14].The application of this approach to remediation of contaminated site stresses accelerating characterization to determine only the nominal conditions needed for design of a specific remediation system and providing remedial contingency designs to be employed should nominal conditions not pertain. Applications of the observational approach have been made to both radiological and non-radiological contamination problems [39], [57], [58], [59].
- *The Superfund Accelerated Clean-up Model (SACM),* which includes a module called integrated site assessment, has as its objectives increased efficiency and shorter response times [60], [61], [62].
- *Tri-Parti Agreement Negotiation Approach.* At DOE's Hanford Site, the parties to the Tri-Party Agreement negotiated a method to implement the CERCLA process in order:
    1. To accelerate the assessment phase;
    2. To co-ordinate RCRA and CERCLA requirements whenever possible, thereby resulting in cost savings. The Hanford Past Practice Strategy (HPPS) was developed in 1991 to accelerate decision making and initiation of remediation through activities that include maximizing the use of existing data consistent with data quality objectives[15].
- Streamlined approach for environmental restoration (SAFER). The US Department of Energy created the so-called SAFER approach (streamlined approach for environmental restoration) which combined the bias for implementing remediation with accelerated characterization that relies heavily on the data quality objective (DQO) approach. The results of applications have been faster and less costly characterization (and potentially smaller total remediation costs) [63], [64].
- *Expedited site characterization (ESC)* stresses taking a multi-disciplinary team of technical experts to the field to minimize the number of phases of characterization. The team members are very well versed in the site history, have an initial conceptual model of the site environment, are equipped with a suite of non-invasive and invasive

14 Information on the Observational Approach recommended by Sandia National Laboratories is available on the internet at http://www.em.doe.gov/tie/strechar.html.

15 Information on the Hanford Past Practice Strategy is available on the internet at http://www.bhi-erc.com/map/sec5.html.

technologies, and are prepared to carry out a dynamic sampling effort that may be adjusted daily as sampling results become available. ESC has been particularly effective in accelerating and improving the characterization of the subsurface environment in cases of groundwater contamination. An appropriate combination of geological, geophysical, hydrogeological, and geochemical investigations is bought to bear concurrently as the study identifies and focuses on critical parameters [30], [65], [66], [67], [68].

- *Adaptive sampling and analysis* (or, as sometimes referred to as ASAP, for "adaptive sampling and analysis programme developed at the Environmental Assessment Division (EAD) of Argonne National Laboratory[16]".) fuse soft data (for example, historical records, aerial photos, non-intrusive geophysical data) with hard sampling results to estimate contaminant extent, measure the uncertainty associated with these estimates, determine the benefits from collecting additional samples, and assist in siting new sample locations to maximize the information gained. ASAP exploits the opportunity for in-the-field decision making when field analytical and screening instrumentation can provide rapid results regarding contamination levels. The decision-making regarding sample location and number is facilitated by a decision support system that uses the results of radiological or chemical analyses and other site information to estimate the extent of contamination [69]. It also calculates the level of uncertainty associated with the estimate of extent. The system provides visualization of the data, contamination extent, and uncertainty. Just as important, it indicates where the next sampling should occur to have the greatest impact on reducing the uncertainty in the estimate of the extent of contamination. The system successively updates the prediction of new sampling locations after each set of new data is gathered and the estimate of contamination is refined. In several cases of soil contamination, rapid rounds of iterative sampling guided by the adaptive sampling and analysis system have resulted in delineation of contamination with costs as low as 25-40% of the originally predicted sampling and analysis costs for a traditional uniform-grid sampling programme [70], [71], [72], [73], [74].

3.3.3 Radioactive contaminants

Some objectives of the different surveys include identifying site contaminants, determining relative ratios of contaminants, and establishing DCGLs and conditions for the contaminants which satisfy the requirements of the responsible agency(ies). Identification of potential radionuclide contaminants at the site is generally performed through laboratory analyses, such as alpha and gamma spectrometry. These analyses are used to determine the relative ratios of the identified contaminants, as well as isotopic ratios for common contaminants like uranium and thorium.

Most of this section is based on general technical and statistical concepts for the characterisation of radioactively contaminated sites and/or groundwater for remediation purposes, however, much of the guidance can still be applied to other types of regulations or standards. The purpose of this paragraph is to provide the information required to understand the investigation process described in this section. This information:

- Summarises and defines the differences between natural, cosmogenic and anthropogenic radioactivity to understand the differences in origin of the radioactive contaminants.
- Deals with types of (possible) radioactively contaminated sites and/or groundwaters and with possible sources of contamination.

[16] Information on the Argonne National Laboratory adaptive sampling programs can be obtained on the internet at http://www.ead.anl.gov/~web/newead/prgprj/proj/adaptive/adaptive.html.

3.3.3.1 Natural, cosmogenic and anthropogenic radioactivity

Many materials contain some radioactivity, although typically at such a low level that sensitive instruments are required to detect them. The radioactivity occurs in the form of radionuclides derived from two sources:

- Natural ionising radiation pervades our environment, naturally occurring radionuclides, which can further be classified as either primordial radionuclides (with half-lives comparable to the age of the earth) or cosmogenic radionuclides (produced by the interactions of cosmic radiation with matter).
- Anthropogenic radionuclides, i.e., those produced by man, can be, as a result of site-specific activities, resulting in radioactive contamination. Notwithstanding this, anthropogenic radionuclides are widely distributed in the environment as a result of different mankind actions.

3.3.3.2 Natural or primordial radionuclides

The most commonly encountered naturally occurring radionuclides are in the decay series originating from ^{238}U, ^{235}U and ^{232}Th. The dominant naturally occurring isotope of uranium is ^{238}U (99.28% natural abundance by mass). ^{235}U constitutes essentially all of the remaining 0.72% by mass of natural uranium. The activity ratio of ^{238}U /^{235}U is approximately 22.

Crystal rocks, on average, contain approximately 25 Bq/kg ^{238}U (equivalent to 2 ppm U) and 30 Bq/kg ^{232}Th (equivalent to 7 ppm Th). Some rocks, such as the granites, can contain significantly higher levels of U: typically of order 16 ppm (200 Bq/kg ^{238}U). The activity of uranium in soils is also variable, and is influenced by the nature of the parent material, the mineralogy of the soil and the geochemical conditions in the soil column.

In the context of this guidance, as examples:

- A key long-lived member of the ^{238}U decay chain is ^{226}Ra that was used extensively to produce luminising paint. ^{226}Ra decays to ^{222}Rn, a short-lived radioactive gas which, in turn, decays to stable lead via a series of short-lived, predominantly alpha-emitting, radionuclides.
- ^{40}K is a lighter radionuclide and has a half-life of $1.28x10^9$ years, with an isotopic abundance of 0.0118%. This leads to natural potassium being radioactive, and having an activity of approximately 30 kBq/kg.

Data for concentrations of significant primordial radionuclides in soil is presented in Table 3.8.

Table 3.8 Concentration in soil of significant primordial radionuclides in Bq/kg

Radionuclide	**Median value in Europe (Bq/kg)**	
	Mean	Range
^{40}K	400	140 – 850
^{238}U	35	16 – 110
^{226}Ra	32	17 – 60
^{232}Th	30	11 – 64

3.3.3.3 Cosmogenic radionuclides

The interactions between neutrons and protons associated with cosmic radiation and atoms of nitrogen, oxygen and argon produces a series of radionuclides, the most abundant of which are ^{39}Ar, ^{14}C, ^{7}Be and ^{3}H (see Table 3.9).

The equilibrium activity of these cosmogenic radionuclides is controlled by their production rate in the atmosphere and their residence times in the atmosphere, in the oceans and in the sub-surface.

All living matter contains carbon of which a proportion is ^{14}C. The relative concentration of ^{14}C is approximately 0.23 kBq/kg of carbon. On the death of the organism, continued accumulation of ^{14}C, and the remaining unsupported ^{14}C decays (with a half-life of 5’730 years); Tritium (^{3}H) is produced naturally in the atmosphere by interactions of fast neutrons with nitrogen.

Table 3.9 Concentration of cosmogenic radionuclides in the troposphere

Radionuclide	Concentration in troposphere (mBq/m^3)
^{3}H	1.4
^{7}Be	12.5
^{14}C	56.3
^{39}Ar	6.5

3.3.3.4 Anthropogenic radionuclides

Anthropogenic radionuclides are produced as a result of (see also Section 3.3.3.1):

- Nuclear fission: the splitting of a heavy nucleus, such as uranium or plutonium, by spontaneous reaction, bombardment with neutrons or bombardment with charged particles. This is the process that occurs in a nuclear reactor to generate energy.
- Activation: the result of irradiation by neutrons. Many radionuclides for medical and industrial use are also produced by this process. Further, in a nuclear reactor, these reactions occur with the fuel, leading to the production of different isotopes, e.g., americium, and with the structural components (e.g., steels and graphite), leading to the production of unstable isotopes such as ^{60}Co and ^{14}C.

3.3.3.5 Summarising considerations

Each nuclide is characterised by the name (or symbol) of the element and the nuclide’s atomic mass; for example Nitrogen-14 (^{14}N) or strontium-90 (^{90}Sr). Nuclides of the same element with different atomic masses for example, uranium-235 (^{235}U) and uranium-238 (^{238}U) are known as isotopes of the element. Most elements have more than one known isotope, so the total number of nuclides is several times greater than the number of elements.

Most nuclides found in nature are stable, but some nuclides that occur naturally as well as some produced by humans, exhibit the property known as radioactivity. These nuclides are referred as radionuclides.

A nuclide that is radioactive is unstable. The atomic nucleus spontaneously decays, that is it changes into the nucleus of a different nuclide, emitting radiation in the process. This is a random process that cannot be predicted exactly, but the average rate at which nuclei decay and the type of radiation they emit are both characteristic of the radionuclide.

The rate at which a radionuclide decays is called its activity and is equal to the average number of decays per second. The unit of activity is decays per second, which SI-unit is given the special name Becquerel (Bq). 1 Bq is defined as: 1 decay per second.

1 Bq is a very small level of activity, so values are often quoted in multiples such as kBq (10^3), MBq (10^6) and GBq (10^9), although background radiation activities might be expressed in smaller units such as mBq (10^{-3}).

A related measure of the rate at which a radionuclide decays is the half-life, also a constant characteristic of the radionuclide. This is the average time it takes for one-half of the atoms in a sample of the radionuclide to decay. After two half-lives, one-quarter of the atoms will remain, after three half-lives there will be one-eighth left, and so on. After 10 half-lives, the activity will reduce to about one-thousandth of the initial value. Half-lives of known radionuclides range from tiny fractions of a second to many millions of years.

A radionuclide will eventually decay into a stable nuclide, this may take one step or many steps. For some natural radionuclides this “decay chain” can extend through many intermediate radioisotopes, known as daughters, before a stable state is achieved. In some situations the relative half lives of parent and daughter radionuclides are such that daughter radionuclides can quickly accumulate and end up being the same activity as the parent. This is known as secular equilibrium. This is particularly important for some radionuclides such as ^{137}Cs. ^{137}Cs (parent-nuclide) is a beta emitter, however its daughter-nuclide ^{137m}Ba is a gamma emitter. Parent- and daughter-nuclides are often treated together when they occur in secular equilibrium.

3.3.4 Radioactively contaminated sites, sources of contamination and radionuclides of concern

3.3.4.1 Radioactively contaminated sites

The use of radioactive materials for a variety of purposes has resulted in contamination of sites and/or groundwaters (i.e., land areas, including structures, waste dumps, soils, rocks, biota, surface and groundwaters, etc.) throughout the world. The radionuclides involved may have been produced for a variety of reasons, including scientific research, industry, medicine or warfare. Another possibility is that they are simply an unnatural concentration of the naturally occurring radioactive elements. The affected sites can range from small localized areas in urban environments to larger areas encompassing many tens or hundreds of square kilometers.

The source of the radioactive contamination may be from a known activity at the site and the radionuclides involved may be known. Records may give information about the radionuclides involved and their likely disposition and chemical state. Alternatively, a chance discovery may have revealed the presence of contamination and no other information is available. It might be that the site is populated and immediate steps must be taken to ensure no harm is done, or it could be that people are easily excluded and there is adequate time to undertake investigations.

These and other differences mean that each site and/or groundwater must be treated as a unique situation taking into account its own particular circumstances. In general, all potentially contaminated sites and/or groundwaters will need an evaluation (characterization) based on the principles given herein. In minor cases of contamination, many steps can be treated summarily, but usually all will still have to be dealt with.

Some examples of radioactively contaminated sites and/or groundwaters that might be encountered are given below. The list is not exhaustive but is intended to show the wide range of problems that might be found; they can vary in extent from large land sites to relatively small sites such as a manufacturing facility.

- *Nuclear power production and nuclear fuel cycle activities*. The various stages of the nuclear fuel cycle and the operation and decommissioning of nuclear reactors all have the potential to create contaminated sites. The contamination may include mill tailings; spillage of uranium ore end product at the mine and in transport; waste from enrichment and fuel fabrication operations; fission product and actinide waste streams from reprocessing of fuel elements; radioactive effluents from normal operations of nuclear power plants; wastes produced during decommissioning of reactors; and major releases under accident conditions, e.g., contamination from uranium ore and yellowcake handling, ^{137}Cs contamination of river banks following accidents at a nuclear power plant, contamination problems occurring on railway property due to rain run-off of fission product contaminants from fuel transportation containers.

- *Production and use of radioactive substances for medical, research or industrial purposes*. Radioactive materials have been used widely since their discovery for a variety of scientific, medical and industrial uses. In some cases, either through ignorance, carelessness, or accident, sites have been left contaminated with residues of the operations. Such sites include factories where radium was used in luminescent paint and thorium was used in thorium coated gas mantles. Other locations where radionuclides have been handled have the potential for leaving contamination and the possible widespread dispersal of radium contamination in the surrounds of production plants.
- *Mining and chemical processing associated with uranium and thorium impurities*. Because uranium and thorium are present in many ores containing other useful minerals, the mining of these ores and the processing to recover materials such as copper, gold, niobium, coal and monazite will generally produce waste streams containing significant amounts of radioactivity. These have the potential to result in unacceptably contaminated sites. Examples are contamination from the processing of monazite ores, contamination issues arising from naturally occurring radioactive materials (NORM) found in coal slag piles, or by-products of the fertilizer industry - technically enhanced naturally occurring radioactive materials (TENORM). However other activities would also result in the accumulation of NORM or TENORM, such as:
    - Oil and gas extraction.
    - Fertiliser production.
    - Phosphoric acid production.
    - Iron and steel production.
    - Cement industry.
    - Ceramics industry.
- *Military activities and the production, testing and use of nuclear weapons*. The manufacture of nuclear weapons involves the handling, transport and storage of large quantities of radioactive materials. The testing of weapons may involve nuclear yield and the release of fission products and activation products, or may involve the deliberate dispersal of radioactive materials in the environment. Some military use is made of depleted uranium which may contain fission products if obtained from reprocessed fuel. All of these activities have, in the past, resulted in contaminated sites, many of very large areas.
- *Major incidents*. In the course of nuclear weapons production and transport, there have been several severe accidents resulting in considerable contamination. These include: Windscale Pile 1, Kyshtym (1957), Palomares (1966) and Thule (1968). The spread of contamination by accident or by human ignorance are illustrated by the cases of the Chernobyl reactor (1986) and Goiania (1987).
- *Authorised dispose of wastes to approved landfill sites containing low levels of radioactivity*. Moreover, wastes with very low levels of radioactivity can also be disposed of in general waste, including consumer products like smoke detectors, leading to the generation of landfill emissions containing radioactivity, such as tritium in leachate. Some landfill sites may have in the past accepted wastes from naturally occurring radioactive material (NORM) and technically enhanced naturally occurring radioactive material (TENORM) industries resulting in elevated levels of natural radionuclides in the emissions.

In Table 3.10 examples are given of typical radioactively contaminated sites found worldwide as well as details of expected radionuclide contaminants.

Table 3.10 Examples of typical radioactively contaminated sites found worldwide

Type of contaminated site	Radionuclides present and comments
Radium luminising works	^{226}Radium + Daughters Radon (^{222}Rn)(+D) emanation from the underlying ground could present a significant inhalation hazard. This hazard would need to be assessed and engineered solutions adopted. Radium compounds may be soluble in water and if so, the ground water pathway could be significant.
Thorium gas mantel works	^{232}Thorium + Daughters Thoron (^{220}Rn)(+D) emanation from the underlying ground could present a significant inhalation hazard. This hazard would need to be assessed and engineered solutions adopted.
Phosphate fertiliser production	^{238}U + Daughters are most significant contaminants, ^{232}Th + progeny.
Nuclear weapons test site	Contaminants are mainly long-lived fission products and original fissile components of test weapons. Many species are only significant in the first year or so after the creation of this type of contamination. Some radionuclides have short lived daughters in secular equilibrium.
Coal ash/slag from coal-fired power stations	Levels typically low compared with U mining or nuclear accidents. Volumes may be very large. Radon emissions may be significant. Present containments may be rudimentary or non-existent.
Nuclear power plant sites and environs	Levels may vary from generally low but widespread to locally high specific activity. Off-site releases may be trough gaseous, liquid or particulate routes. In most circumstances, fission or steel activation products, and tritium, would be expected to be the most significant isotopes.
Mining, milling and processing of copper (and other) ores having high U7Th impurities	Radionuclides of the U decay series may be found: for instance, in waste rock piles and slags. Sites may be contaminated especially by ^{210}Pb/^{210}Po particulate. Ores include copper, tin, silver, gold, niobium and monazite.
Nuclear weapon and fuel fabrication plant (uranium enrichment and lithium production) also fuel reprocessing plants	Contaminants are mainly from uranium and plutonium fuel and fission products (generally with half lives of at least 1 year).

3.3.4.2 Radionuclides of concern

The radioactive contaminants associated with a given contamination problem may be quite site specific. The classes of radionuclides that may be encountered include fission products, activation products, uranium and other naturally occurring radionuclides, other man-made radioisotopes, transuranics, tritium, and so on. In Table 3.11 radionuclides are presented that may be present at a radiologically contaminated site and/or groundwater. It has to be noted that this table tries to be complete, but due to the large differences in industrial processes it can not be guaranteed. The comments on mobility given below are intended to be used as guidelines rather than as absolute criteria. Certainly, for elements other than those listed, mobility should be assessed on a case-by-case basis.

Table 3.11 Radionuclides of concern found at radioactively contaminated sites worldwide

Radionuclide	Type of contaminated site and/or groundwater	Comments
^{14}C	Groundwater	The most common mode of ^{14}C production is by an n-p reaction on ^{14}N, although it is also a low yield fission product and can also be produced by activation of ^{13}C or ^{17}O. One of the most common sources of ^{14}C in radioactive wastes stems from its use as a tracer for a wide variety of studies of biological systems and of organic compounds. The common inorganic forms of ^{14}C in radioactive wastes are as carbonates; in acidic media, it can be lost to the atmosphere as $^{14}CO_2$, but in neutral to alkaline systems, the ionic forms of $H^{14}CO_3^-$ or $^{14}CO_3^{2-}$ will dominate. These anionic species normally exhibit little in the way of chemical interactions with geologic materials, and they tend to migrate at groundwater velocity, although there has been laboratory evidence for some isotopic exchange

Radionuclide	Type of contaminated site and/or groundwater	Comments
		with solid carbonates. When present in radio labelled organic compounds, as found in certain waste sources, the radiocarbon may also be transported at, or nearly at, groundwater velocities; this can be the result of subsurface degradation which may convert such compounds to inorganic forms (e.g., mobile carbonates).
Caesium	Groundwater	Among anthropogenic radioisotopes, one of the best examples of an element that very rarely exhibits appreciable subsurface mobility is caesium. This is evident by the prolonged surface retention of ^{137}Cs deposited from atmospheric weapons tests over 30 years ago, and by the continued contamination of surface soils by radioactive caesium released during the Chernobyl incident. One study showed ^{137}Cs was rapidly fixed by clay minerals and organic matter present in soil and, as a result, only about 1-10% remained in a mobile form.
^{60}C	Groundwater	Although cobalt is a transition metal and would normally be expected to be present as a cation in aqueous solutions (and hence interact appreciably with geologic solids), experience at Chalk River has shown that an appreciable fraction of the ^{60}Co released from an aqueous wastewater infiltration pit is present as an anionic complex. The evidence also indicated that this is due to presence of an organic complexing agent that is naturally present in the aquifer. This complexed ^{60}Co is subsequently transported at rates that approach or equal those of water movement through the subsurface. High ^{60}Co mobility was also observed down-gradient of a solid waste management area at Chalk River; for that case, there is no information of the ^{60}Co form. Anionically complexed cobalt was also observed in experimental studies following tracer injections into a sand aquifer in Great Britain. Rapid movement of ^{60}Co has not been observed in the surficial sands at Chemobyl, however, so cobalt complexation does not appear to be a universal phenomenon.
Fissile components of test weapons	Nuclear weapons test site	See "Fission products (long-lived)".
Fission products (long-lived)	Nuclear weapons test site	Many species are only significant in the first year or so after the creation of this type of contamination. Some radionuclides have short-lived daughters in secular equilibrium.
Fission products (steel activation products, tritium).	Nuclear power plant sites	Radioactive contamination levels may vary generally low but widespread to locally (relative) high specific activity. Off-site releases may be through gaseous, liquid or particulate routes.
Fission products (steel activation products, tritium).	Nuclear power plant environment	See "Nuclear power plant sites".
^{3}H	Nuclear power plant sites	See "Nuclear power plant sites".
^{3}H	Groundwater	Although tritium may be present in wastes that are spilled or disposed of on surface or in the subsurface in a variety of chemical forms, tritiated water is by far the most common compound. Because the tritium is present as water, it is transported in the subsurface at the same rate as all other water in the system. In combination with its high mobility, the half-life of tritium (12.4 years) is long enough that transport over appreciable distances can occur. In heavy water moderated reactors, tritium is a very abundant isotope, and it would be a key radionuclide in any fusion power systems.
"Immobile" elements	Groundwater	The quotation marks are intended to stress the qualified nature of this list, because there are almost always some cases where chemical conditions are so extreme that at least limited transport has been observed.
Iodine	Groundwater	In most cases, iodine can be expected to be present as an anionic species (iodide or iodate) and hence to be highly mobile. The half-lives of many of the common radioactive isotopes are too short to be groundwater

Radionuclide	Type of contaminated site and/or groundwater	Comments
		contaminants of concern. Iodine-129 (^{129}I) can be of potential concern, but its volatility during spent fuel reprocessing operations (which are the source of most of this isotope) has meant that it has either been dispersed to the atmosphere or, in more modem facilities, it has been collected by stack gas filtration and the spent filters have been stored with care.
Niobium and Zirconium	Groundwater	Long-lived radioisotopes of these two elements are generated by neutron activation of reactor components. Because they are most common in materials that were designed to be inherently very resistant to corrosion, information on their behaviour in the subsurface is limited. Rapid and strong sorption to a wide variety of geologic materials appears to be the rule rather than the exception, however.
Other nuclides	Groundwater	In general, any other radionuclides that form anionic species under aquifer conditions can be expected to migrate at velocities approaching those of the water movement in the underground system. Ruthenium and antimony isotopes frequently exhibit rapid migration, or at least do so for a fraction of their inventory; but the half-live of the common radioisotopes of these elements is one year or less, making them less likely to be of substantial concern.
Plutonium	Groundwater	Apart from evidence for a very limited colloid formation under some geochemical conditions, the subsurface (and general environmental) mobility of plutonium appears to be extremely limited due to its normally being present in the form of highly insoluble compounds. The high toxicity assigned to plutonium, however, offsets the reduced risks due to the low mobility and makes it a high risk whenever it exists in the subsurface.
Radium and Thorium	Groundwater	Among the naturally occurring radioisotopes, cases of groundwater contamination by radium and thorium are very rare. Normally, these elements are present in the form of insoluble compounds. Extremely acidic conditions have been known to mobilize them, but reductions to concentrations likely to result in satisfactory water quality can be achieved by remediating (neutralizing) the groundwater's acidity.
^{226}Ra + daughters	Radium luminising works	^{222}Rn (radon) emanation from the underlying ground could present a significant inhalation hazard. This hazard would need to be assessed and engineered solutions adopted. Radium compounds may be soluble in water and if so, the groundwater pathway could be significant.
^{226}Ra and ^{210}Pb	Groundwater	These nuclides are commonly found in drinking water at very low levels, typically in the range 0 -180 and 40 – 200 mBq/liter.
^{90}Sr	Groundwater	This abundant fission product has been identified as a key radionuclide in groundwaters that have been contaminated by accidental releases of, for example, nuclear wastes containing fission products, to surface waters or from waste management/disposal areas. Substantial subsurface migration of ^{90}Sr has been observed at Chernobyl, Hanford, Oak Ridge, and Chalk River. Strontium is a member of the alkaline earth family and is normally present in aqueous solutions as a divalent cation. As such, one would anticipate that it would interact with geologic solids, exhibiting sorptive behaviour, and at all of the sites listed above this has indeed occurred with ^{90}Sr. Sorption occurs to only a limited degree, however, and much of the transfer to aquifer solids is reversible. Thus, strontium has frequently exhibited rates of subsurface movement that are a few per cent of the velocity of the transporting water.
Thorium	Groundwater	See “Radium and Thorium”.
^{232}Th + daughters	Thorium gas mantel works	^{220}Rn (radon) emanation from the underlying ground could present a significant inhalation hazard. This hazard would need to be assessed and engineered solutions adopted.
^{235}U and ^{238}U	Groundwater	Uranium contamination of groundwater is most commonly associated with uranium mine and mill tailings, and with wastes arising from fuel refining operations. Uranium is a polyvalent element and, under reducing conditions, its solubility is usually extremely low, being controlled by the precipitation of UO_2. Under oxidizing conditions, and where carbonate species are abundant in solution, the anionic uranyl carbonate species,

Radionuclide	Type of contaminated site and/or groundwater	Comments
		which normally undergoes little interaction with solid phases, may form. Consequently, uranium migration can be limited in some circumstances and it can be significant in others. It is therefore important to assess the ambient geochemistry when assessing uranium mobility.
Uranium and plutonium fuel and fission products	Nuclear weapons and fuel (reprocessing) fabrication plant.	The radioactive contaminants are mainly from uranium enrichment and lithium production, generally with half lives of at least 1 year.
U/Th (high impurities)	Mining, milling and processing of ores, like copper, tin, silver, gold, niobium, monazite, etc.	Radionuclides of the U decay series may be found: for instance, in waste rock piles and slags. Sites and/or groundwater may be contaminated especially by $^{210}Pb/^{210}Po$ particulate.
^{238}U + daughters	Phosphate fertiliser production	Most significant contaminants, also ^{232}Th + progeny.
^{238}U + daughters	Coal ash/slag from coal-fired power stations	Radioactive contamination levels are typically low compared with uranium mining or nuclear accidents. Volumes may be very large. Radon emissions may be significant. Present containments may be rudimentary or non-existent.
Zirconium	Groundwater	See "Niobium and Zirconium".
Zirconium	Mining, milling and processing of ores.	See "U/Th (high impurities)".

3.3.4.3 Background radioactivity and selecting background reference areas

It is important to distinguish between radioactive contaminations resulting from:

- Human activities on the site.
- The background level of radioactivity, which arises from natural radioactivity in the soils and rocks, and in some cases from former human activities.
- Levels of man-made radionuclides originating from sources unrelated to the site (for example, atmospheric fallout from the Chernobyl accident).

Background levels of radioactivity will vary spatially both from one site to another and within the same site. In addition, background levels of radiation can vary over time as well. The principal factor that controls the background level of natural radionuclides at a site is the level of radioactivity in the rock from which the soil was derived. Natural series radionuclides can also be concentrated in different parts of the soil column and weathering profile, typically associated with iron oxides, clay minerals and organic material. Therefore, it is to be expected that background levels of naturally occurring radionuclides in the rocks and soils will vary with depth.

Many sites contain areas of made ground; that is, material that has been imported onto the site, or moved from another area of the site, to fill depressions and raise ground level. Some types of made ground, such as ash and metallurgical slag materials, contain elevated levels of naturally occurring radionuclides. Others, such as imported sand and clay, may have levels of radioactivity below that of the natural soil at the site. This may make determination of background levels difficult, where the usual practice would be to go to a known, uncontaminated area nearby to determine the local background rate. This method might not take account of the content of any made ground on the site. Variations in natural background level may be detected by some walkover radiation surveys and should be taken into account when deriving background levels for the site (see Section 3.3.3).

The level for action must be distinguishable from background, otherwise it may be difficult to suitably differentiate for clean-up.

Levels of atmospheric fallout-derived radionuclides (for example, ^{3}H and ^{137}Cs) are influenced largely by altitude and rainfall patterns. In general atmospheric fallout has arisen from the testing of nuclear weapons and from more recent events, principally the Chernobyl accident.

Levels of radioactivity in the environment can be influenced by past or present authorised radioactive discharges into the atmosphere and aquatic systems. The impact of marine discharges can extend some distance away from the site due to the accumulation of material in sediments over an extended period of operations.

Levels of radioactivity may also occur at significant levels due to the naturally-occurring uranium, thorium, and actinium series; ^{40}K; ^{14}C; and tritium.

Care has to be taken with discharges in the past. These discharges may be allowed according to the applicable laws at that time and therefore they may be not subjected to the present regulations.

External radiation dose rates from the background levels of radioactivity in rocks and soils depend on the levels and nature of the radioactivity. Typical background dose rates are 0.05-0.1 μSv/h.

Radio-nuclide concentrations in background water samples should be determined for a sufficient number of water samples that are upstream and downstream of the site or in areas unaffected by site operations. Consideration should be given to any spatial or temporal variations in the background radio-nuclide concentrations.

Careful assessment of the background to provide a baseline is required, together with the enhancement as a direct result of the practices carried out on the site.

3.3.5 Establishing background environmental quality

For the reasons discussed earlier, it is important to establish the background level of radioactivity in soils and waters at the site. Once the background concentrations have been measured, then the definition of "background" has to be agreed with regulators before decisions can be taken on land management.

It would be possible to define background as the average activity of all samples analysed; however, the disadvantage of this approach on a heterogeneous site (i.e., where natural radioactivity and fallout-derived radioactivity vary spatially) is that it could be unnecessarily cautious. For example, it could lead to a recommendation to remediate an area that had not been contaminated by site activities.

A more pragmatic approach may be to define "background" in terms of the activity below which a certain percentage of the distribution lies. Clearly, the percentile chosen would need to be justified.

As discussed in Section 3.3.1, background levels of radioactivity will vary (i) from site to site and (ii) spatially in 3-dimensions within a site. Concentrations of naturally occurring radionuclides will be strongly influenced by the composition of the rocks and soils, and by the extent of near-surface weathering effects.

Anthropogenic radionuclides derived from global fallout are (with the exception of tritium) unlikely to penetrate significantly below surface soils; it would therefore be inappropriate to use the background levels of such radionuclides in surface soils to derive a background for deeper soils and rocks.

Background levels can be established by applying a reference area. Reference areas provide a location for background measurements which are used for comparisons with survey unit data. The radioactivity present in a reference area would be ideally the same as the survey unit had it never been contaminated. If a site includes physical, chemical, geological, radiological, or biological variability that is not represented by a single reference background area, selecting more than one reference area may be necessary.

The following approaches exist:

- No reference area is needed;
- A second area - reference area - that has similar physical, chemical, geological, radiological, and biological characteristics as the survey unit being evaluated;
- The site under investigation can, under certain conditions, also serve as reference area.

3.3.5.1 No reference area needed

No reference area is needed if the radiological contaminant of concern is not present in the background or the radiological contaminant is present in such a small fraction of the derived concentration guideline level ($DCGL_w$) (*e.g.*, < 10%) value as to be considered insignificant.

The survey unit radiological conditions may be compared directly to the specified DCGL and reference area background surveys are not necessary. If the background is not well defined at a site, and the decision maker is willing to accept the increased probability of incorrectly failing to release a survey unit (Type II error), the reference area measurements can be eliminated and a one-sample statistical test performed as described in Section 3.10.2.

3.3.5.2 Second area as reference area

In order to determine background levels of radioactivity at a site, it is therefore necessary to characterise a second area that has similar physical, chemical, geological, radiological, and biological characteristics as the survey unit being evaluated, e.g., rock and soil compositions to the site under investigation, and to evaluate any depth-dependent changes in the background activity of naturally occurring and fallout-derived radionuclides. These background reference areas are normally selected from non-impacted areas, but are not limited to natural areas undisturbed by human activities.

Typically, this would involve collecting samples from an area sufficiently close to the site that its natural radioactivity characteristics are similar to those of the site but sufficiently far away that site-derived radioactivity will not have significantly enhanced the background levels. In site investigations where data are collected across large areas, some of which may never have been used for operations that deal with radioactive materials, it may be possible to obtain on-site information on background levels of radioactivity. However, it is desirable to supplement this information with data from off-site areas. For heterogeneous sites, it may be possible to define different background levels for different soil types and at different depths; for example, to distinguish between made ground and different natural strata.

3.3.5.3 Site under investigation as reference area

Background reference areas are normally selected from non-impacted areas, but are not limited to natural areas undisturbed by human activities as may be the case in heavy industrialised or urban areas (e.g., harbours). In these areas it may be difficult to find a reference area within an industrial complex for comparison to a survey unit if the radio-nuclides of potential concern are naturally occurring. Background may vary greatly due to different construction activities that have occurred at the site. Examples of construction activities that change background include: levelling; excavating; adding fill dirt; importing rocks or gravel to stabilize soil or underlay asphalt; manufacturing asphalt with different matrix rock; using different pours of asphalt or concrete in a single survey unit; layering asphalt over concrete; layering different thicknesses of asphalt, concrete, rock, or gravel; and covering or burying old features such as railroad beds or building footings. Background variability may also increase due to the concentration of fallout in low areas of parking lots where runoff water collects and evaporates. Variations in background of a factor of five or more can occur in the space of a few hectares.

It is unlikely that areas can be found that fulfil the (minimum) requirements of a reference area. In order to determine - assess - background levels of radioactivity at the site under investigation, it can be assumed that some parts of this site may never have been used for operations that deal with radioactive materials. Therefore, it may be possible to obtain on-site information on background levels. This on-site information can be obtained from a preliminary investigation combined with the information from a historical site assessment and adjusted with information gained from an exploratory investigation.

Example 3.2: Samples for background measurements

For example, background measurements may be taken from core samples of soil, pavement, or asphalt, a building or structure surface.

This option should be discussed with the responsible regulatory agency during survey planning. Generally, reference areas should not be part of the survey unit being evaluated.

There are a number of other possible actions to address these concerns. Reviewing and reassessing the selection of reference areas may be necessary. Selecting different reference areas to represent individual survey units is another possibility. More attention may also be needed in selecting survey units and their boundaries with respect to different areas of potential or actual background variability. More detailed scoping or characterization surveys may be needed to better understand background variability. Using radio-nuclide-specific measurement techniques instead of gross radioactivity measurement techniques may also be necessary. If a background reference area that satisfies the above recommendations is not available, consultation and negotiation with the responsible regulatory agency is recommended. Alternate approaches may include using published studies of radio-nuclide distributions.

3.3.5.4 Background chemical quality

For chemical contamination it is important to understand the background quality for soils and ground gases because, in some locations the natural background may contain elevated concentrations of a compound or element.

“Background” may also be elevated due to contamination from a neighbouring site and it is necessary to establish the concentrations to apportion liability. However, in both these media the risks from naturally elevated concentrations need to be assessed, and if necessary managed and controlled.

With groundwater, establishing the background quality is necessary, particularly where no quality objectives exist. Deriving background concentrations are integral to the decision-making process for both risk assessment and risk management purposes.

3.3.6 Establishing derived concentration guideline levels DCGLs

The information gained from laboratory analyses is essential in establishing and applying the DCGLs for a site. DCGLs provide the goal for essentially all aspects of designing, implementing, and evaluating the final status survey. The DCGLs discussed in this manual are limited to soil contamination (and structure surfaces); the user should consult the responsible regulatory agency(ies) if it is necessary to establish DCGLs for other environmental media (e.g., ground water, and other water pathways). This section contains information regarding the selection and application of DCGLs.

The development of DCGLs is often an iterative process, where the DCGLs selected or developed early in the Radiation Survey and Site Investigation (RSSI) Process are modified as additional site-specific information is obtained from subsequent surveys. One example of the iterative nature of DCGLs is the development of final clean-up levels, and soil screening levels[17] (SSLs) are selected or developed at a point early in the process, usually corresponding to the scoping survey in EURSSEM [75], [76]. A soil screening level can be further developed, based on site-specific information, to become a preliminary remediation goal, usually at a point corresponding to the characterization survey. If the preliminary remediation goal is found to be acceptable during the characterization survey, it is documented as the final clean-up level in the record of decision (ROD) for the site. The record of decision is typically in place prior to any remedial action, because the remedy is also documented in the record of decision.

3.3.6.1 Direct application of DCGLs

In the simplest case, the DCGLs may be applied directly to survey data to demonstrate compliance. This involves assessing the surface activity levels and volumetric concentrations of radio-nuclides and comparing measured values to the appropriate DCGL.

Example 3.3: Direct application of a DCGL

Consider a site that used only one radionuclide, such as ^{90}Sr throughout its operational lifetime. The default DCGL for ^{90}Sr in soil and on building surfaces may be obtained from the responsible agency. Survey measurements and samples are then compared to the volume activity and the surface concentration DCGLs for ^{90}Sr directly to demonstrate compliance. While seemingly straightforward, this approach is not always possible (e.g., when more than one radionuclide is present).

3.3.6.2 DCGLs and key-nuclides to assess the radioactivity of difficult to measure nuclides

For sites with multiple contaminants, it may be possible to measure just one of the contaminants and still demonstrate compliance for all of the contaminants present through the use of key-nuclide measurements. Both time and resources can be saved if the analysis of one radionuclide is simpler than the analysis of the other.

Example 3.4: Application of a DCGL in the case of a key-nuclide

Using measured ^{137}Cs (= key-nuclide) concentration as a surrogate for ^{90}Sr (= difficult to measure nuclide) reduces the analytical costs because wet chemistry separations do not have to be performed for ^{90}Sr on every sample

In using one key-radionuclide to measure the presence of others, a sufficient number of measurements, spatially separated throughout the survey unit, should be made to establish a "consistent" ratio. The number of measurements needed to determine the ratio is selected using the data quality objectives (DQO) process and based on the chemical, physical, and radiological characteristics of the nuclides and the site. If consistent radio-nuclide ratios cannot be determined during the historical site assessment (HSA) based on existing information, EURSSEM recommends that one of the objectives of scoping or characterization be a determination of the ratios rather than attempting to determine ratios based on the final status survey. If the ratios are determined using final status survey data, EURSSEM recommends that at least 10% of the measurements (both direct measurements and samples) include analyses for all radio-nuclides of concern.

In the use of key-nuclides, it is often difficult to establish a "consistent" ratio between two or more radio-nuclides. Rather than follow prescriptive guidance on acceptable levels of variability for the "key-nuclide – difficult to measure nuclide" ratio, a more reasonable approach may be to review the data collected to establish the ratio and to use the DQO process to select an appropriate ratio from that data.

17 Soil Screening Levels are currently available for chemical contaminants and are not designed for use at sites with radioactive contamination.

Example 3.5: Illustration of the application of key-nuclide measurements

Ten soil samples within the survey unit were collected and analyzed for ^{137}Cs (= key-nuclide) and ^{90}Sr (= difficult to measure nuclide) to establish a ratio.

The ratios of ^{90}Sr to ^{137}Cs were as follows: 6.6, 5.7, 4.2, 7.9, 3.0, 3.8, 4.1, 4.6, 2.4, and 3.3. An assessment of this example data set results in an average ^{90}Sr to ^{137}Cs ratio of 4.6, with a standard deviation of 1.7. There are various approaches that may be used to develop a ratio from this data - but each must consider the variability and level of uncertainty in the data. One may consider the variability in the ratio by selecting the 95% upper bound of the ratio (to yield a conservative value of ^{90}Sr from the measured ^{137}Cs), which is 8.0 in this case. Similarly, one may select the most conservative value from the data set (7.9).

The DQO process should be used to assess the use of key-nuclides. The benefit of using this approach is the reduced cost of not having to perform costly wet chemistry analyses on each sample. This benefit should be considered relative to the difficulty in establishing the surrogate ratio, as well as the potential consequence of unnecessary investigations that result from the error in using a "conservative" "key-nuclide – difficult to measure nuclide" ratio. Selecting a conservative "key-nuclide – difficult to measure nuclide" ratio ensures that potential exposures from individual radio-nuclides are not underestimated. The nuclide method can only be used with confidence when dealing with the same media in the same surroundings - for example, soil samples with similar physical and geological characteristics. The EURSSEM user will need to consult with the responsible regulatory agency for concurrence on the approach used to determine the surrogate ratio.

Once an appropriate "key-nuclide – difficult to measure nuclide" ratio is determined, one needs to consider how compliance will be demonstrated using key-nuclide measurements. That is, the user must modify the DCGL of the measured radionuclide to account for the inferred radionuclide. Continuing with the above example, the modified DCGL for ^{137}Cs must be reduced according to the following equation:

$$DCGL_{Cs,mod} = DCGL_{Cs} \times \frac{DCGL_{Sr}}{[(C_{Sr}/C_{Cs}) \times DCGL_{Cs}] + DCGL_{Sr}} \qquad (3\text{-}1)$$

where C^{Sr}/C^{Cs} is the surrogate ratio of ^{90}Sr to ^{137}Cs.

Assuming that the $DCGL^{Sr}$ is 15 Bq/kg, the $DCGL^{Cs}$ is 10 Bq/kg, and the surrogate ratio is 8 (as derived previously), the modified DCGL for ^{137}Cs ($DCGL^{Cs, mod}$) can be calculated using Equation 3-1:

$$DCGL_{Cs,mod} = 10 \times \frac{15}{[8 \times 10] + 15} = 1.6 \text{ Bq/kg}$$

This modified DCGL is then used for survey design purposes.

The potential for shifts or variations in the radionuclide ratios means that the key-nuclide method should be used with caution. Physical or chemical differences between the radio-nuclides may produce different migration rates, causing the radio-nuclides to separate and changing the radio-nuclide ratios. Remediation activities have a reasonable potential to alter the "key-nuclide – difficult to measure nuclide" ratio established prior to remediation. EURSSEM recommends that when the ratio is established prior to remediation, additional post-remediation samples should be collected to ensure that the data used to establish the ratio are still appropriate and representative of the existing site condition. If these additional post-remediation samples are not consistent with the pre-remediation data, surrogate ratios should be re-established.

Compliance with surface activity DCGLs for radio-nuclides of a decay series (*e.g.*, thorium and uranium) that emit both alpha and beta radiation may be demonstrated by assessing alpha, beta, or both radiations. However, relying on the use of alpha surface contamination measurements often proves problematic due to the highly variable level of alpha attenuation by rough, porous, and dusty surfaces. Beta measurements typically provide a more accurate assessment of thorium and uranium contamination on most building surfaces because surface conditions cause significantly less attenuation of beta particles than alpha particles. Beta measurements, therefore, may provide a more accurate determination of surface activity than alpha measurements.

The relationship of beta and alpha emissions from decay chains or various enrichments of uranium should be considered when determining the surface activity for comparison with the $DCGL_W$ values. When the initial member of a decay chain has a long half-life, the radioactivity associated with the subsequent members of the series will increase at a rate determined by the individual half-lives until all members of the decay chain are present at activity levels equal to the activity of the parent. This condition is known as secular equilibrium.

<u>*Example 3.6: Calculation of the surface activity*</u>

Consider that the average surface activity $DCGL_W$ for natural thorium is 1,000 Bq/m^2 (600 dpm/100 cm^2), and all of the progeny are in secular equilibrium - that is, for each disintegration of ^{232}Th there are six alpha and four beta particles emitted in the thorium decay series. Note that in this example, the surface activity $DCGL_W$ of 1,000 Bq/m^2 is assumed to apply to the total activity from all members of the decay chain. In this situation, the corresponding alpha activity $DCGL_W$ should be adjusted to 600 Bq/m^2 (360 dpm/100 cm^2), and the corresponding beta activity $DCGL_W$ to 400 Bq/m^2 (240 dpm/100 cm^2), in order to be equivalent to 1,000 Bq/m^2 of natural thorium surface activity. For a surface activity $DCGL_W$ of 1,000 Bq/m^2, the beta activity $DCGL_W$ is calculated as follows:

$$\frac{(1{,}000 \text{ Bq of chain})/m^2 \times 4\,\beta\,/(\text{dis of Th-232})}{(10 \text{ Bq of chain})\,/\,(1 \text{ Bq of Th-232})} = 400\,\beta\ \text{Bq}/m^2 \qquad (3\text{-}2)$$

To demonstrate compliance with the beta activity $DCGL_W$ for this example, beta measurements (in cpm) must be converted to activity using a weighted beta efficiency that accounts for the energy and yield of each beta particle. For decay chains that have not achieved secular equilibrium, the relative activities between the different members of the decay chain can be determined as previously discussed for “key-nuclide – difficult to measure nuclide” ratios.

Another example for the use of key-nuclides involves the measurement of exposure rates, rather than surface or volume activity concentrations, for radio-nuclides that deliver the majority of their dose through the direct radiation pathway. That is, instead of demonstrating compliance with soil or surface contamination DCGLs derived from the direct radiation pathway, compliance is demonstrated by direct measurement of exposure rates. To implement this key-nuclide method, historical site assessment (HSA) documentation should provide reasonable assurance that no radioactive materials are buried at the site and that radioactive materials have not seeped into the soil or groundwater. This key-nuclide approach may still be possible for sites that contain radio-nuclides that *do not* deliver the majority of their dose through the direct radiation pathway. This requires that a consistent relative ratio for the radio-nuclides that *do* deliver the majority of their dose through the direct radiation pathway can be established. The appropriate exposure rate limit in this case accounts for the radio-nuclide(s) that *do not* deliver the majority of their dose to the direct radiation pathway. This is accomplished by determining the fraction of the total activity represented by radio-nuclide(s) that *do* deliver the majority of their dose through the direct radiation pathway, and weighting the exposure rate limit by this fraction.

Note that the considerations for establishing consistent relative ratios discussed above apply to this key-nuclide approach as well. The responsible regulatory agency should be consulted prior to implementing this “key-nuclide – difficult to measure nuclide” approach.

3.3.6.3 Use of DCGLs for sites with multiple radio-nuclides

Typically, each radionuclide DCGL corresponds to the release criterion (*e.g.*, regulatory limit in terms of dose or risk). However, in the presence of multiple radio-nuclides, the total of the DCGLs for all radio-nuclides would exceed the release criterion. In this case, the individual DCGLs need to be adjusted to account for the presence of multiple radio-nuclides contributing to the total dose. One method for adjusting the DCGLs is to modify the assumptions made during exposure pathway modelling to account for multiple radio-nuclides. The key-nuclide measurements discussed in the previous section describe another method for adjusting the DCGL to account for multiple radio-nuclides. Other methods include the use of the unity rule and development of a gross activity DCGL for surface activity to adjust the individual radionuclide DCGLs.

The unity rule, represented in the expression below, is satisfied when radio-nuclide mixtures yield a combined fractional concentration limit that is less than or equal to one:

$$C_1/DCGL_1 + C_2/DCGL_2 + \ldots + C_n/DCGL_n < 1 \quad (3\text{-}3)$$

where:

C = concentration

DCGL = guideline value for each individual radionuclide (1, 2, ..., n)

For sites that have a number of significant radio-nuclides, a higher sensitivity will be needed in the measurement methods as the values of C become smaller. Also, this is likely to affect statistical testing considerations - specifically by increasing the numbers of data points necessary for statistical tests.

3.3.6.4 Integrated surface and soil contamination DCGLs

Surface contamination DCGLs apply to the total of fixed plus removable surface activity. For cases where the surface contamination is due entirely to one radionuclide, the DCGL for that radionuclide is used for comparison to measurement data (Section 3.3.6.1).

For situations where multiple radionuclides with their own DCGLs are present, a gross activity DCGL can be developed. This approach enables field measurement of gross activity, rather than determination of individual radio-nuclide activity, for comparison to the DCGL. The gross activity DCGL for surfaces with multiple radio-nuclides is calculated as follows:

- Determine the relative fraction (f) of the total activity contributed by the radionuclide.
- Obtain the DCGL for each radionuclide present.
- Substitute the values of f and DCGL in the following equation:

$$Gross\ Activity\ DCGL = 1 / (f_1/DCGL_1 + f_2/DCGL_2 + \ldots + f_n/DCGL_n) \quad (3\text{-}4)$$

Example 3.7: Calculation of an integrated surface and soil contamination DCGL

Assume that 40% of the total surface activity was contributed by a radionuclide with a DCGL of 8,300 Bq/m^2 (5,000 dpm/100 cm^2); 40% by a radionuclide with a DCGL of 1,700 Bq/m^2 (1,000 dpm/100 cm^2); and 20% by a radionuclide with a DCGL of 830 Bq/m^2 (500 dpm/100 cm^2). Using Equation 4-4:

$$Gross\ Activity\ DCGL = 1 / (0.40/8{,}300 + 0.40/1{,}700 + 0.20/830)$$

$$= 1{,}900\ Bq/m^2$$

Note that Equation 3-4 may not work for sites exhibiting surface contamination from multiple radio-nuclides having unknown or highly variable concentrations of radionuclides throughout the site. In these situations, the best approach may be to select the most conservative surface contamination DCGL from the mixture of radionuclides present. If the mixture contains radionuclides that cannot be measured using field survey equipment, laboratory analyses of surface materials may be necessary.

Because gross surface activity measurements are not nuclide-specific, they should be evaluated by the two-sample non-parametric tests described in Section 3.10 to determine if residual contamination meets the release criterion. Therefore, gross surface activity measurements should be performed for both the survey units being evaluated and for background reference areas. The background reference areas for surface activity typically involve building surfaces and construction materials that are considered free of residual radioactivity (see Section 3.3.5). The total surface activity due to residual contamination should not exceed the gross activity DCGL calculated above.

For soil contamination, it is likely that specific radio-nuclides, rather than gross activity, will be measured for demonstrating compliance. For radio-nuclides that are present in natural background, the two-sample non-parametric test described in Section 3.10.3 should be used to determine if residual soil contamination exceeds the release criterion. The soil contamination due to residual activity should not exceed the DCGL. To account for multiple background radio-nuclides, the DCGL should be adjusted in a manner similar to the gross activity DCGL described above. For a known mixture of these radio-nuclides, each having a fixed relative fraction of the total activity, the site-specific DCGLs for each radio-nuclide may be calculated by first determining the gross activity DCGL and then multiplying that gross DCGL by the respective fractional contribution of each radio-nuclide.

Example 3.8: Calculation of the DCGL for a known mixture of radio-nuclides

If ^{238}U, ^{226}Ra, and ^{232}Th have DCGLs of 190 Bq/kg (5.0 pCi/g), 93 Bq/kg (2.5 pCi/g), and 37 Bq/kg (1.0 pCi/g) and activity ratios of 40%, 40%, and 20%, respectively, Equation 4-4 can be used to calculate the gross activity DCGL.

$$\text{Gross Activity DCGL} = 1 / (0.40/190 + 0.40/93 + 0.20/37)$$
$$= 85\ Bq/m^2$$

The adjusted DCGLs for each of the contributory radio-nuclides, when present in the given activity ratios, are then 34 Bq/kg (0.40 × 85) for ^{238}U, 34 Bq/kg (0.40 × 85) for ^{226}Ra, and 17 Bq/kg (0.20 × 85) for ^{232}Th. Determining gross activity DCGLs to demonstrate compliance enables an evaluation of site conditions based on analysis for only one of the contributory contaminants (surrogate approach), provided the relative ratios of the contaminants do not change.

For situations where the background radio-nuclides occurring in background have unknown or variable relative concentrations throughout the site, it may be necessary to perform the two-sample non-parametric tests separately for each radio-nuclide present. The unity rule should be used to determine that the sum of each radio-nuclide concentration divided by its DCGL is less than or equal to one.

Therefore, at each measurement location calculate the quantity:

$$C_1/DCGL_1 + C_2/DCGL_2 + \ldots + C_n/DCGL_n \quad (3\text{-}5)$$

Where:

C is the radio-nuclide concentration.

The values of C are the data to be used in the statistical tests to determine if the average over the survey unit exceeds one.

The same approach applies for radio-nuclides that are not present in background, with the exception that the one-sample nonparametric statistical test described in Section 8.3 is used in place of the two-sample non-parametric test (see Section 3.5.1.1). Again, for multiple radio-nuclides either the surrogate approach or the unity rule should be used to demonstrate compliance, if relative ratios are expected to change.

3.3.7 Criteria for the selection of direct measurement, scanning and sample collection methods

The presence of radioactive and hazardous chemical wastes (mixed wastes) at a site can influence the survey design [37]. The external exposure rates or radioactivity concentration of a specific sample may limit the time that workers will be permitted to remain in intimate contact with the samples, or may dictate that smaller samples be taken and special holding areas be provided for collected samples prior to shipment. These special handling considerations may conflict with the size specifications for the analytical method, normal sampling procedures, or equipment. There is a potential for biasing sampling programs by selecting samples that can be safely handled or legally shipped to support laboratories. Because final status surveys are performed to demonstrate that a site can be safely released, issues associated with high levels of radioactivity are not expected to be a concern.

There are three methods for collecting radiation data while performing a survey:

- *Direct measurement*. A direct measurement is obtained by placing the detector near or against the surface or in the media being surveyed and reading the radioactivity level directly.
- *Scanning*. An evaluation technique performed by moving a portable radiation detection instrument at a constant speed and distance above the surface to semi-quantitatively detect elevated areas of radiation.
- *Sampling*. The process of collecting a portion of an environmental medium as representative of the locally remaining medium. The collected portion of the medium is then analyzed to determine the radionuclide concentration.

In practice, there has to be obtained a proper balance among the use of various measurement techniques. In general, there is an inverse correlation between the cost of a specific measurement technique and the detection levels being sought. Depending on the survey objectives, important considerations include survey costs and choosing the optimum instrumentation and measurement mix.

A certain minimum number of direct measurements or samples will be needed to demonstrate compliance with the release criterion based on the non-parametric statistical tests (see Section 3.3.10). In addition, the potential for areas of elevated contamination will have to be considered for designing scanning surveys. Areas of elevated activity may also affect the number of measurements; however, scanning with survey instruments should generally be sufficient to ensure that no areas with unusually high levels of radioactivity are left in place. Some measurements may also provide information of a qualitative nature to supplement other measurements. An example of such an application is in-situ gamma spectrometry to demonstrate the absence (or presence) of specific contaminants.

Table 3.12 presents a list of common contaminants along with recommended survey methods that have proven to be effective based on past survey experience in the decommissioning industry. This table provides a general indication of the detection capability of commercially-available instruments. In the next section more detailed information can be found on *detection sensitivity.*

Table 3.12 may be used to provide an initial evaluation of instrument capabilities for some common radio-nuclides at the example DCGLs listed in the table. For example, consider the contamination of a surface with ^{241}Am.

Table 3.12 indicates that ^{241}Am is detectable at the example DCGLs, and that viable direct measurement instruments include gas-flow proportional (α-mode) and alpha scintillation detectors. Table 3.12 should not be interpreted as providing specific values for an instrument’s detection sensitivity, which is discussed in Section3.3.7. In addition, NRC draft report [42], [77] provides further information on factors that may affect survey instrumentation selection.

Table 3.12 Selection of direct measurement techniques based on experience

	Structure surfaces		**Land areas**		**Direct Measurement Instruments**[2]		
Nuclide	**Example DCGL**[1] **(Bq/m^{2})**	**Detectable**	**Example DCGL**[1] **(Bq/m^{2})**	**Detectable**	**Surface activity**	**Soil activity**	**Exposure rate**
^{3}H	1.6x10^{6}	No	1.5x10^{4}	No	ND[6]	ND	ND
^{14}C	4.7x10^{5}	Yes	1.4x10^{3}	No	GPβ	ND	ND
^{54}Mn	1.3x10^{4}	Yes	450	Yes	GPβ[7], GM	γS, ISγ	PIC, γS, ISγ
^{55}Fe	1.8x10^{6}	No	4.1x10^{5}	No[5]	ND	ND (ISγ)	ND (ISγ)
^{60}Co	3.1x10^{3}	Yes	110	Yes	GPβ,GM	γS, ISγ	PIC, γS, ISγ
^{63}Ni	1.5x10^{6}	Yes	2.8x10^{5}	No	GPβ	ND	ND
^{90}Sr	6.0x10^{3}	Yes	420	No[5]	GPβ, GM	ND (GM, GPβ)	ND
^{99}Tc	6.4x10^{5}	Yes	1.9x10^{3}	No	GPβ, GM	ND	ND
^{137}Cs	8.2x10^{3}	Yes	400	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
^{152}Eu	6.6x10^{3}	Yes	240	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
^{226}Ra (C)[3]	970	Yes	210	Yes	GPα, αS	γS, ISγ	PIC, γS, ISγ
^{232}Th (C)[3]	340	Yes	320	Yes	GPα, αS, GPβ	γS, ISγ	PIC, γS, ISγ
U[4]	560	Yes	710	Yes	GPα, αS, GPβ, ISγ	γS, ISγ, GPβ	PIC, γS, ISγ
^{239}Pu ^{240}Pu ^{241}Pu	120	Yes	70	No[5]	GPα, αS	ND (ISγ)	ND
^{241}Am	110	Yes	70	Yes	GPα, αS	γS, ISγ	PIC, γS, ISγ

1 Example DCGLs based on values given in NRC draft report [78].
2 GPα = Gas-flow proportional counter (α-mode).
GM = Geiger-Mueller survey meter.
GPβ = Gas-flow proportional counter (β-mode).
PIC = Pressurized ionization chamber.
αS = Alpha scintillation survey meter.
γS = Gamma scintillation (gross).
ISγ = In-situ gamma spectrometry.
3 For decay chains having two or more radio-nuclides of significant half-life that reach secular equilibrium. The notation "(c)" indicates the direct measurement techniques assume the presence of progeny in the chain.
4 Depleted, natural, and enriched.
5 Possibly detectable at limits for areas of elevated activity.
6 Not detectable.
7 Bold indicates the preferred method where alternative methods are available.

Sample characteristics such as sample depth, volume, area, moisture level, and composition, as well as sample preparation techniques which may alter the sample, are important planning considerations for Data Quality Objectives. Sample preparation may include, but is not limited to, removing extraneous material, homogenizing, splitting, drying, compositing, and final preparation of samples. As is the case for determining survey unit characteristics, the physical sample characteristics and sampling method should be consistent with the dose or risk pathway modelling that is used to determine radio-nuclide DCGL's. If a direct measurement method is used, it should also be consistent with the pathway modelling.

For example, a sample depth of 15 cm (6 in.) for soil samples might be specified during the DQO process for a final status survey because this corresponds to the soil mixing or plow depth in several environmental pathway models. If contamination exists at a depth less than this, a number of models uniformly mix it throughout this depth to simulate the soil mixing associated with plowing. Similarly, models may be based on dry weight, which may necessitate either drying samples or data transformation to account for dry weight.

The DQOs and subsequent direction to the laboratory for analysis might include removal of material not relevant for characterizing the sample, such as pieces of glass, twigs, or leaves. Table 3.13 provides examples of how a particular field soil composition of fine-, medium-, and coarse-grained materials might determine laboratory analysis DQOs for particular radionuclides. Fine materials consist of clay (less than 0.002 mm) and silt (0.002 to 0.062 mm). Medium materials consist of sand, which can be further divided into very fine, fine, medium, coarse, and very coarse sand. Coarse materials consist of gravel, which is composed of pebbles (2 to 64 mm), cobbles (64 to 256 mm), and boulders (greater than 256 mm).

Table 3.13 Example of DQO planning considerations

Separate out and evaluate fine-grain material because re-suspension is associated with the fine grain fraction for the air pathway.
If contamination resides on sand, pebbles, and cobbles, analyze these materials for direct exposure pathway and analyze the fine-grain fraction for the air pathway.
Separation and homogenization are not necessary for analyses because direct exposure pathway depends upon the average concentration and presence of cobbles will usually not impact laboratory analysis.
Determine if pathway modelling considered the presence of cobbles.
Separate, homogenize, and evaluate fine-grain material because plant root uptake is associated with the fine-grain fraction for the plant ingestion pathway.
Separate, homogenize, and evaluate fine-grain materials because of their relevance for the contaminant source term for contaminant migration to the sub-surface for the water pathway.

3.3.7.1 Detection sensitivity

The detection sensitivity of a measurement system refers to a radiation level or quantity of radioactive material that can be measured or detected with some known or estimated level of confidence. This quantity is a factor of both the instrumentation and the technique or procedure being used.

The primary parameters that affect the detection capability of a radiation detector are the background count rate, the detection efficiency of the detector and the counting time interval. It is important to use actual background count rate values and detection efficiencies when determining counting and scanning parameters, particularly during final status and verification surveys.

When making field measurements, the detection sensitivity will usually be less than what can be achieved in a laboratory due to increased background and, often times, a significantly lower detection efficiency. It is often impossible to guarantee that pure alpha emitters can be detected *in-situ* since the weathering of aged surfaces will often completely absorb the alpha emissions. The report [79] contains data on many of the parameters that affect detection efficiencies *in-situ*, such as absorption, surface smoothness, and particulate radiation energy.

3.3.7.2 Direct measurement sensitivity

Prior to performing field measurements, an investigator must evaluate the detection sensitivity of the equipment proposed for use to ensure that levels below the DCGL can be detected. After a direct measurement has been made, it is then necessary to determine whether or not the result can be distinguished from the instrument background response of the measurement system. The terms that are used in this manual to define detection sensitivity for fixed point counts and sample analyses are:

- Critical level (L_C);
- Detection limit (L_D);
- Minimum detectable concentration (MDC).

The critical level (L_C) is the level, in counts, at which there is a statistical probability (with a pre-determined confidence) of incorrectly identifying a measurement system background value as "greater than background." Any response above this level is considered to be greater than background. The detection limit (L_D) is an *a priori* estimate of the detection capability of a measurement system, and is also reported in units of counts. The minimum detectable concentration (MDC) is the detection limit (counts) multiplied by an appropriate conversion factor to give units consistent with a site guideline, such as Bq/kg.

The following discussion provides an overview of the derivation contained in the well known publication by Currie [80] followed by a description of how the resulting formulae should be used. Publications by Currie [80], NRC [81] and Altshuler and Pasternak [82] provide details of the derivations involved.

The two parameters of interest for a detector system with a background response greater than zero are:

- L_C the net response level, in counts, at which the detector output can be considered "above background";
- L_D the net response level, in counts, that can be expected to be seen with a detector with a fixed level of certainty.

Assuming that a system has a background response and that random uncertainties and systematic uncertainties are accounted for separately, these parameters can be calculated using Poisson statistics. For these calculations, two types of decision errors should be considered. A Type I error (or "false positive") occurs when a detector response is considered to be above background when, in fact, only background radiation is present. A Type II error (or "false negative") occurs when a detector response is considered to be background when in fact radiation is present at levels above background. The probability of a Type I error is referred to as α (alpha) and is associated with L_C; the probability of a Type II error is referred to as β (beta) and is associated with L_D. Figure 3.3 graphically illustrates the relationship of these terms with respect to each other and to a normal background distribution.

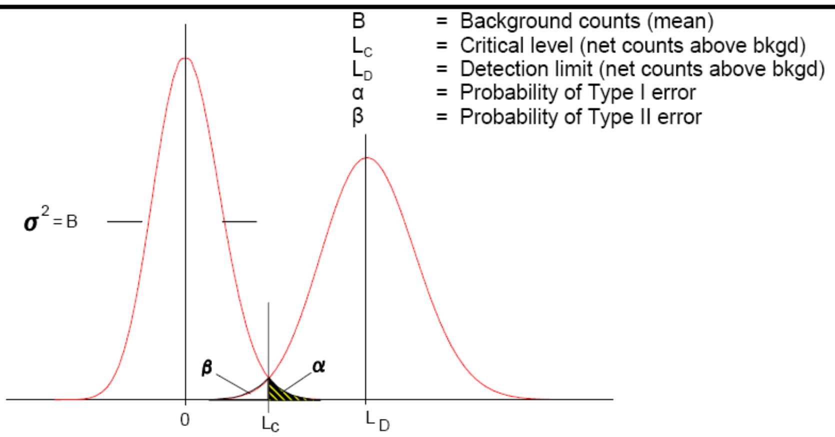


Figure 3.3 Graphically represented probabilities for Type I and Type II errors in detection sensitivity for instrumentation with a background response

If α and β are assumed to be equal, the variance (σ^2) of all measurement values is assumed to be equal to the values themselves. If the background of the detection system is not well known, then the critical detection level and the detection limit can be calculated by using the following formulae:

$$L_C = k\sqrt{(2B)}$$

$$L_D = k^2 + 2k\sqrt{(2B)} \qquad (3\text{-}6)$$

where:

L_C = critical level (counts);

L_D = detection limit (counts);

K = Poisson probability sum for α and β (assuming α and β are equal);

B= number of background counts that are expected to occur while performing an actual measurement.

The curve to the left in the diagram is the background distribution minus the mean of the background distribution. The result is a Poisson distribution with a mean equal to zero and a variance, σ^2, equal to B. Note that the distribution accounts only for the expected statistical variation due to the stochastic nature of radioactive decay. Currie assumed "paired blanks" when deriving the above stated relationships [80] which is interpreted to mean that the sample and background count times are the same.

If values of 0.05 for both α and β are selected as acceptable, then k = 1.645 (from 0, Table D.12 or Table 3.34) and Equation 3-6 can be written as:

$$L_C = 2.33\sqrt{(2B)}$$

$$L_D = 3 + 4.65\sqrt{(2B)} \quad (3\text{-}7)$$

Note: In Currie's derivation, the constant factor of 3 in the L_D formula was stated as being 2.71, but since that time it has been shown [83] and generally accepted that a constant factor of 3 is more appropriate. If the sample count times and background count times are different, a slightly different formulation is used.

For an integrated measurement over a preset time, the MDC can be obtained from Equation 3-7 by multiplying by the factor, C. This factor is used to convert from counts to concentration as shown in Equation 3-8:

$$MDC = C \times (3 + 4.65\sqrt{(B)}) \quad (3\text{-}8)$$

The total detection efficiency and other constants or factors represented by the variable C are usually not truly constants as shown in Equation 3-8. It is likely that at least one of these factors will have a certain amount of variability associated with it which may or may not be significant. These varying factors are gathered together into the single constant, C, by which the net count result will be multiplied when converting the final data. If C varies significantly between measurements, then it might be best to select a value, C', from the observed distribution of C values that represents a conservative estimate. For example, a value of C might be selected to ensure that at least 95% of the possible values of C are less than the chosen value, C'. The MDC calculated in this way helps assure that the survey results will meet the Data Quality Objectives. This approach for including uncertainties into the MDC calculation is recommended in both [81], [84]. Underestimating an MDC can have adverse consequences, especially if activity is later detected at a level above the stated MDC.

Summary of direct measurement sensitivity terms:

- The MDC is the *a priori* net activity level above the critical level that an instrument can be expected to detect 95% of the time. This value should be used when stating the detection capability of an instrument. The MDC is the detection limit, L_D, multiplied by an appropriate conversion factor to give units of activity. Again, this value is used before any measurements are made and is used to estimate the level of activity that can be detected using a given protocol.
- The critical level, L_C, is the lower bound on the 95% detection interval defined for L_D and is the level at which there is a 5% chance of calling a background value "greater than background." This value should be used when actually counting samples or making direct radiation measurements. Any response above this level should be considered as above background (*i.e.*, a net positive result). This will ensure 95% detection capability for L_D.

- From a conservative point of view, it is better to overestimate the MDC for a measurement method. Therefore, when calculating MDC and L_C values, a measurement system background value should be selected that represents the high end of what is expected for a particular measurement method. For direct measurements, probes will be moved from point to point and, as a result, it is expected that the background will most likely vary significantly due to variations in background, source materials, and changes in geometry and shielding. Ideally, the MDC values should be calculated for each type of area, but it may be more economical to simply select a background value from the highest distribution expected and use this for all calculations. For the same reasons, realistic values of detection efficiencies and other process parameters should be used when possible and should be reflective of the actual conditions. To a great degree, the selection of these parameters will be based on judgment and will require evaluation of site-specific conditions.
- MDC values for other counting conditions may be derived from Equation 3-8 depending on the detector and contaminants of concern. For example, it may be required to determine what level of contamination, distributed over 100 cm², can be detected with a 500 cm² probe or what contamination level can be detected with any probe when the contamination area is smaller than the probe active area. Table 3.14 lists several common field survey detectors with estimates of MDC values for ^{238}U on a smooth, flat plane. As such, these represent minimum MDC values and may not be applicable at all sites. Appropriate site-specific MDC values should be determined using the DQO Process.

Table 3.14 Examples of estimated detection sensitivities for alpha and beta survey instrumentation. (Static one minute counts for ^{238}U calculated using Equations 3-7 and 3-8)

Detector	Probe area (cm²)	Background (cpm)	Efficiency (cpm/dpm)	Approximate Sensitivity		
				L_C (counts)	L_D (counts)	MDC (Bq/m²)[a]
Alpha proportional	50	1	0.15	2	7	150
Alpha proportional	100	1	0.15	2	7	83
Alpha proportional	600	5	0.15	5	13	25
Alpha scintillation	50	1	0.15	2	7	150
Beta proportional	100	300	0.20	40	83	700
Beta proportional	600	1500	0.20	90	183	250
Beta GM pancake	15	40	0.20	15	32	1800

[a] Assumes that the size of the contamination area is at least as large as the probe area.

Example 3.9: Calculation of the MDC in Bq/m² of an instrument with a 15 cm² probe area

Sample Calculation 1:

The following example illustrates the calculation of an MDC in Bq/m² for an instrument with a 15 cm² probe area when the measurement and background counting times are each one minute:

$B = 40$ *counts*

$C = (5 \text{ dpm/count})(\text{Bq}/60 \text{ dpm})(1/15 \text{ cm}^2 \text{ probe area})(10{,}000 \text{ cm}^2/\text{m}^2)$

$= 55.6 \text{ Bq/m}^2\text{-counts}$

The MDC is calculated using Equation 3-8:

$$MDC = 55.6 \times (3 + 4.65\sqrt{(40)}) = 1{,}800 \text{ Bq/m}^2 \ (1{,}100 \text{ dpm}/100 \text{ cm}^2)$$

The critical level, L_C, for this example is calculated from Equation 3.7:

$L_C = 2.33\sqrt{(B)} = 15$ counts

Given the above scenario, if a person asked what level of contamination could be detected 95% of the time using this method, the answer would be 1,800 Bq/m² (1,100 dpm/100 cm²). When actually performing measurements using this method, any count yielding greater than 55 total counts, or greater than 15 net counts (55-40=15) during a period of one minute, would be regarded as greater than background.

3.3.7.3 Scanning sensitivity

The ability to identify a small area of elevated radioactivity during surface scanning is dependent upon the surveyor's skill in recognizing an increase in the audible or display output of an instrument. For notation purposes, the term "scanning sensitivity" is used throughout this section to describe the ability of a surveyor to detect a pre-determined level of contamination with a detector. The greater the sensitivity, the lower the level of contamination that can be detected.

Many of the radiological instruments and monitoring techniques typically used for occupational health physics activities may not provide the detection sensitivities necessary to demonstrate compliance with the DCGLs. The detection sensitivity for a given application can be improved (*i.e.*, lower the MDC) by:

- Selecting an instrument with a higher detection efficiency;
- Selecting an instrument with a lower background;
- Decreasing the scanning speed,
- Increasing the size of the effective probe area without significantly increasing the background response.

Scanning is usually performed during radiological surveys in support of decommissioning to identify the presence of any areas of elevated activity. The probability of detecting residual contamination in the field depends not only on the sensitivity of the survey instrumentation when used in the scanning mode of operation, but is also affected by the surveyor's ability - *i.e.*, human factors. The surveyor must make a decision whether the signals represent only the background activity, or residual contamination in excess of background. The greater the sensitivity, the lower the level of contamination that may be detected by scanning. Accounting for these human factors represents a significant change from the traditionally accepted methods of estimating scanning sensitivities.

An empirical method for evaluating the detection sensitivity for contamination surveys is by actual experimentation or, since it is certainly feasible, by simulating an experimental set-up using computer software. The following steps provide a simple example of how one can perform this empirical evaluation:

- A desired nuclide contamination level is selected.
- The response of the detector to be used is determined for the selected nuclide contamination level.
- A test source is constructed which will give a detector count rate equivalent to what was determined in step 2. The count rate is equivalent to what would be expected from the detector when placed on an actual contamination area equal in value to that selected in step 1.
- The detector of choice is then moved over the source at different scan rates until an acceptable speed is determined.

The most useful aspect of this approach is that the source can then be used to show surveyors what level of contamination is expected to be targeted with the scan. They, in turn, can gain experience with what the expected response of the detector will be and how fast they can survey and still feel comfortable about detecting the target contamination level. The person responsible for the survey can then use this information when developing a fixed point measurement and sampling plan.

The remainder of this section is dedicated to providing the reader with information pertaining to the underlying processes involved when performing scanning surveys for alpha, beta, and gamma emitting radio-nuclides. The purpose is to provide relevant information that can be used for estimating realistic scanning sensitivities for survey activities.

3.3.7.4 Scanning sensitivity for beta and gamma emitting nuclides

The minimum detectable concentration of a scan survey (scan MDC) depends on the intrinsic characteristics of the detector (efficiency, physical probe area, *etc.*), the nature (type and energy of emissions) and relative distribution of the potential contamination (point versus distributed source and depth of contamination), scan rate, and other characteristics of the surveyor. Some factors that may affect the surveyor's performance include the costs associated with various outcomes - *e.g.*, fatigue, noise, level of training, experience - and the survey's *a priori* expectation of the likelihood of contamination present. For example, if the surveyor believes that the potential for contamination is very low, as in a Class 3 area, a relatively large signal may be required for the surveyor to conclude that contamination is present. NRC draft report [85] provides a complete discussion of the human factors as they relate to the performance of scan surveys.

Signal detection theory

Personnel conducting radiological surveys for residual contamination at decommissioning sites must interpret the audible output of a portable survey instrument to determine when the signal ("clicks") exceeds the background level by a margin sufficient to conclude that contamination is present. It is difficult to detect low levels of contamination because both the signal and the background vary widely. Signal detection theory provides a framework for the task of deciding whether the audible output of the survey meter during scanning is due to background or signal plus background levels. An index of sensitivity (*d'*) that represents the distance between the means of the background and background plus signal (see Figure 3.3 for determining L_D), in units of their common standard deviation, can be calculated for various decision errors (correct detection and false positive rate).

As an example for a correct detection rate of 95% (complement of a false negative rate of 5%) and a false positive rate of 5%, *d'* is 3.29 (similar to the static MDC for the same decision error rates).

The index of sensitivity is independent of human factors, and therefore, the ability of an ideal observer (theoretical construct), may be used to determine the minimum *d'* that can be achieved for particular decision errors. The ideal observer makes optimal use of the available information to maximize the percent correct responses, providing an effective upper bound against which to compare actual surveyors. Table 3.15 lists selected values of *d'*.

The two stages of scanning

The framework for determining the scan MDC is based on the premise that there are two stages of scanning. That is, surveyors do not make decisions on the basis of a single indication. Rather, upon noting an increased number of counts, they pause briefly and then decide whether to move on or take further measurements. Thus, scanning consists of two components:

- Continuous monitoring;
- Stationary sampling.

In the first component, characterized by continuous movement of the probe, the surveyor has only a brief "look" at potential sources, determined by the scan speed. The surveyor's willingness to decide that a signal is present at this stage is likely to be liberal, in that the surveyor should respond positively on scant evidence, since the only "cost" of a false positive is a little time.

The second component occurs only after a positive response was made at the first stage. This response is marked by the surveyor interrupting his scanning and holding the probe stationary for a period of time, while comparing the instrument output signal during that time to the background counting rate. Owing to the longer observation interval, sensitivity is relatively high. For this decision, the criterion should be more strict, since the cost of a "yes" decision is to spend considerably more time taking a static measurement or a sample.

Table 3.15 Values of *d′* for selected true positive and false positive proportions

False positive	True positive proportion							
proportion	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95
0.05	1.90	2.02	2.16	2.32	2.48	2.68	2.92	3.28
0.10	1.54	1.66	1.80	1.96	2.12	2.32	2.56	2.92
0.15	1.30	1.42	1.56	1.72	1.88	2.08	1.32	2.68
0.20	1.10	1.22	1.36	1.52	1.68	1.88	2.12	2.48
0.25	0.93	1.06	1.20	1.35	1.52	1.72	1.96	2.32
0.30	0.78	0.91	1.05	1.20	1.36	1.56	1.80	2.16
0.35	0.64	0.77	0.91	1.06	1.22	1.42	1.66	2.02
0.40	0.51	0.64	0.78	0.93	1.10	1.30	1.54	1.90
0.45	0.38	0.52	0.66	0.80	0.97	1.17	1.41	1.77
0.50	0.26	0.38	0.52	0.68	0.84	1.04	1.28	1.64
0.55	0.12	0.26	0.40	0.54	0.71	0.91	1.15	1.51
0.60	0.00	0.13	0.27	0.42	0.58	0.82	1.02	1.38

Since scanning can be divided into two stages, it is necessary to consider the survey's scan sensitivity for each of the stages. Typically, the minimum detectable count rate (MDCR) associated with the first scanning stage will be greater due to the brief observation intervals of continuous monitoring - provided that the length of the pause during the second stage is significantly longer. Typically, observation intervals during the first stage are on the order of 1 or 2 seconds, while the second stage pause may be several seconds long. The greater value of MDCR from each of the scan stages is used to determine the scan sensitivity for the surveyor.

<u>Determination of the minimum detectable count rate (MDCR) and use of surveyor efficiency</u>

The minimum detectable number of net source counts in the interval is given by s_i. Therefore, for an ideal observer, the number of source counts required for a specified level of performance can be arrived at by multiplying the square root of the number of background counts by the detectability value associated with the desired performance (as reflected in *d'*) as shown in Equation 3-9:

$$s_i = d' \sqrt{(b_i)} \qquad (3\text{-}9)$$

where the value of *d'* is selected from Table 3.14 based on the required true positive and false positive rates and b_i is the number of background counts in the interval.

<u>Example 3.10: Determination of the minimum detectable count rate (MDCR) for scanning surveys</u>

Suppose that one wished to estimate the minimum count rate that is detectable by scanning in an area with a background of 1,500 cpm. Note that the minimum detectable count rate *must be considered for both scan stages - and the more conservative value is selected as the minimum count rate that is detectable. It will be assumed that a typical source remains under the probe for 1 second during the first stage, therefore, the average number of background counts in the observation interval is 25 (b_i = 1500 × (1/60)). Furthermore, as explained earlier, it can be assumed that at the first scanning stage a high rate (e.g., 95%) of correct detections is required, and that a correspondingly high rate of false positives (e.g., 60%) will be tolerated. From Table 3.15, the value of d', representing this performance goal, is 1.38. The net source counts needed to support the specified level of performance (assuming an ideal observer) will be estimated by multiplying 5 (the square root of 25) by 1.38. Thus, the net source counts per interval, s_i, needed to yield better than 95% detections with about 60% false positives is 6.9. The minimum detectable source count rate, in cpm, may be calculated by:*

$$MDCR = s_i \times (60/i) \tag{3-10}$$

For this example, MDCR is equivalent to 414 cpm (1,914 cpm gross). Table 3.16 provides the scan sensitivity for the ideal observer (MDCR) at the first scanning stage for various background levels, based on an index of sensitivity (d') of 1.38 and a 2-second observation interval.

Table 3.16 Scanning sensitivity (MDCR) of the ideal observer for various background levels*

Background (cpm)	MDCR (net cpm)	Scan Sensitivity (gross cpm)
45	50	95
60	60	120
260	120	380
300	130	430
350	140	490
400	150	550
1,000	240	1,240
3,000	410	3,410
4,000	480	4,480

* The sensitivity of the ideal observer during the first scanning stage is based on an index of sensitivity (d') of 1.38 and a 2-second observation interval.

The minimum number of source counts required to support a given level of performance for the final detection decision (second scan stage) can be estimated using the same method. As explained earlier, the performance goal at this stage will be more demanding. The required rate of true positives remains high (*e.g.*, 95%), but fewer false positives (*e.g.*, 20%) can be tolerated, such that *d'* (from Table 3.15) is now 2.48. One will assume that the surveyor typically stops the probe over a suspect location for about 4 seconds before making a decision, so that the average number of background counts in an observation interval is 100 (b_i = 1,500 × (4/60)). Therefore, the minimum detectable number of net source counts, s_i, needed will be estimated by multiplying 10 (the square root of 100) by 2.48 (the *d'* value); so s_i equals 24.8. The MDCR is calculated by 2.48 × (60/4) and equals 372 cpm. The value associated with the first scanning stage (this example, 414 cpm) will typically be greater, owing to the relatively brief intervals assumed.

Laboratory studies using simulated sources and backgrounds were performed to assess the abilities of surveyors under controlled conditions. The methodology and analysis of results for these studies are described in [79], [85]. The surveyor's actual performance as compared with that which is ideally possible (using the ideal observer construct) provided an indication of the efficiency of the surveyors. Based on the results of the confidence rating experiment, this surveyor efficiency (p) was estimated to be between **0.5** and **0.75**.

EURSSEM recommends assuming an efficiency value at the lower end of the observed range (*i.e.*, 0.5) when making MDC estimates. Thus, the required number of net source counts for the surveyor, $MDCR_{surveyor}$, is determined by dividing the MDCR by the square root of p. Continuing with this example, the surveyor MDCR is calculated by 414 cpm/0.707, or 585 cpm (2,085 cpm gross).

3.3.7.5 Determination of scan MDCs for land areas and structure surfaces

The survey design for determining the number of data points for areas of elevated activity (see Section 3.5.1.1) depends on the scan MDC for the selected instrumentation. In general, alpha or beta scans are performed on structure surfaces to satisfy the elevated activity measurements survey design, while gamma scans are performed for land areas. Because of low background levels for alpha emitters, the approach described here is not generally applied to determining scan MDCs for alpha contaminants - rather, the reader is referred to Section 3.3.7.6 for an appropriate method for determining alpha scan MDCs for building surfaces. In any case, the data requirements for assessing potential elevated areas of direct radiation depend on the scan MDC of the survey instrument (*e.g.*, floor monitor, GM detector, NaI scintillation detector).

Determination of scan MDCs for land areas

In addition to the MDCR and detector characteristics, the scan MDC (in pCi/g) for land areas is based on the area of elevated activity, depth of contamination, and the radionuclide (*i.e.*, energy and yield of gamma emissions). If one assumes constant parameters for each of the above variables, with the exception of the specific radionuclide in question, the scan MDC may be reduced to a function of the radionuclide alone. NaI(Tl) scintillation detectors are generally used for scanning land areas.

An overview of the approach used to determine scan MDCs for land areas follows. The NaI(Tl) scintillation detector background level and scan rate (observation interval) are postulated, and the MDCR for the ideal observer, for a given level of performance, is obtained. After a surveyor efficiency is selected, the relationship between the surveyor MDCR ($MDCR_{surveyor}$) and the radio-nuclide concentration in soil (in Bq/kg or pCi/g) is determined. This correlation requires two steps - first, the relationship between the detector's net count rate to net exposure rate (cpm per μR/h) is established, and second, the relationship between the radio-nuclide contamination and exposure rate is determined.

For a particular gamma energy, the relationship of NaI(Tl) scintillation detector count rate and exposure rate may be determined analytically (in cpm per μR/h). The approach used to determine the gamma fluence rate necessary to yield a fixed exposure rate (1 μR/h) - as a function of gamma energy - is provided in [79]). The NaI(Tl) scintillation detector response (cpm) is related to the fluence rate at specific energies, considering the detector's efficiency (probability of interaction) at each energy. From this, the NaI(Tl) scintillation detector versus exposure rates for varying gamma energies are determined. Once the relationship between the NaI(Tl) scintillation detector response (cpm) and the exposure rate is established, the $MDCR_{surveyor}$ (in cpm) of the NaI(Tl) scintillation detector can be related to the minimum detectable net exposure rate. The minimum detectable exposure rate is used to determine the minimum detectable radionuclide concentration (*i.e.*, the scan MDC) by modelling a specified small area of elevated activity.

Modelling (using Microshield^{TM}) of the small area of elevated activity (soil concentration) is used to determine the net exposure rate produced by a radionuclide concentration at a distance 10 cm above the source. This position is selected because it relates to the average height of the NaI(Tl) scintillation detector above the ground during scanning.

The factors considered in the modelling include:

- Radio-nuclide of interest (considering all gamma emitters for decay chains);
- Expected concentration of the radio-nuclide of interest;

- Areal dimensions of the area of elevated activity;
- Depth of the area of elevated activity;
- Location of dose point (NaI(Tl) scintillation detector height above the surface);
- Density of soil.

Modelling analyses are conducted by selecting a radionuclide (or radioactive material decay series) and then varying the concentration of the contamination. The other factors are held constant - the areal dimension of a cylindrical area of elevated activity is 0.25 m^2 (radius of 28 cm), the depth of the area of elevated activity is 15 cm, the dose point is 10 cm above the surface, and the density of soil is 1.6 g/cm^3. The objective is to determine the radio-nuclide concentration that is correlated to the minimum detectable net exposure rate.

Example 3.11: Calculation of scan MDC for a NaI(Tl) scintillation detector for a land area

The scan MDC for ^{137}Cs using a 1.5 in. by 1.25 in. NaI(Tl) scintillation detector is considered in detail. Assume that the background level is 4,000 cpm and that the desired level of performance, 95% correct detections and 60% false positive rate, results in a d' of 1.38. The scan rate of 0.5 m/s provides an observation interval of 1 second (based on a diameter of about 56 cm for the area of elevated activity). The $MDCR_{surveyor}$ may be calculated assuming a surveyor efficiency (p) of 0.5 as follows:

$$b_i = (4{,}000\ cpm) \times (1\ sec) \times (1\ min/60\ sec) = 66.7\ counts$$

$$MDCR = (1.38) \times (\sqrt{(66.7)}) \times (60\ sec/1\ min)\ ) = 680\ cpm$$

$$MDCR_{surveyor} = 680/\sqrt{(0.5)} = 960\ cpm$$

The corresponding minimum detectable exposure rate is determined for this detector and radionuclide. The manufacturer of this particular 1.5 in. by 1.25 in. NaI(Tl) scintillation detector quotes a count rate to exposure rate ratio for ^{137}Cs of 350 cpm per µR/h. The minimum detectable exposure rate is calculated by dividing the count rate (960 cpm) by the count rate to exposure rate ratio for the radio-nuclide of interest (350 cpm per µR/h). The minimum detectable exposure rate for this example is 2.73 µR/h.

Both ^{137}Cs and its short-lived progeny, ^{137m}Ba, were chosen from the Microshield™ library. The source activity and other modelling parameters were entered into the modelling code. The source activity was selected based on an arbitrary concentration of 5 pCi/g. The modeling code performed the appropriate calculations and determined an exposure rate of 1.307 µR/h (which accounts for build-up). Finally, the radio-nuclide concentrations of ^{137}Cs and ^{137}mBa (scan MDC) necessary to yield the minimum detectable exposure rate (2.73 µR/h) may be calculated using the following formula:

$$scan\ MDC = (5\ pCi/g)\ x\ (2.73\ \mu R/h) / 1.307\ \mu R/h = 10.4\ pCi/g \qquad (3\text{-}11)$$

It must be emphasized that while a single scan MDC value can be calculated for a given radionuclide - other scan MDC values may be equally justifiable depending on the values chosen for the various factors, including the MDCR (background level, acceptable performance criteria, observation interval), surveyor efficiency, detector parameters and the modelling conditions of the contamination. It should also be noted that determination of the scan MDC for radioactive materials - like uranium and thorium - must consider the gamma radiation emitted from the entire decay series. The document [79] provides a detailed example of how the scan MDC can be determined for enriched uranium.

Table 3.17 provides a number of scan MDCs for common radio-nuclides and radioactive materials in soil. It is important to note that the variables used in the above examples to determine the scan MDCs for the 1.25 in. by 1.5 in. NaI(Tl) scintillation detector - *i.e.*, the $MDCR_{surveyor}$ detector parameters (*e.g.*, cpm per µR/h), and the characteristics of the area of elevated activity - have all been held constant to facilitate the calculation of scan MDCs provided in Table 3.17. The benefit of this approach is that generally applicable scan MDCs are provided for different radioactive contaminants. Additionally, the relative detectability of different contaminants is evident because the only variable in Table 3.17 is the nature of the contaminant.

Table 3.17 NaI(Tl) scintillation detector scan MDCs for common radiological contaminants[a]

Radionuclide/Radioactive	1.25 in. by 1.5 in. NaI Detector		2 in. by 2 in. NaI Detector	
Material	Scan MDC (Bq/kg)	Weighted cpm/µR/h	Scan MDC (Bq/kg)	Weighted cpm/µR/h
^{241}Am	1,650	5,830	1,170	13,000
^{60}Co	215	160	126	430
^{137}Cs	385	350	237	900
230Th	111,000	4,300	78,400	9,580
^{226}Ra (in equilibrium with progeny)	167	300	104	760
^{232}Th decay series (Sum of all radio-nuclides in the thorium decay series)	1,050	340	677	830
^{232}Th (In equilibrium with progeny in decay series)	104	340	66.6	830
Depleted Uranium[b] (0.34% ^{235}U)	2,980	1,680	2,070	3,790
Natural Uranium[b]	4,260	1,770	2,960	3,990
3% Enriched Uranium[b]	5,070	2,010	3,540	4,520
20% Enriched Uranium[b]	5,620	2,210	3,960	4,940
50% Enriched Uranium[b]	6,220	2,240	4,370	5,010
75% Enriched Uranium[b]	6,960	2,250	4,880	5,030

a Refer to text for complete explanation of factors used to calculate scan MDCs. For example, the background level for the 1.25 in. by 1.5 in. NaI detector was assumed to be 4,000 cpm, and 10,000 cpm for the 2 in. by 2 in. NaI detector. The observation interval was 1 sec and the level of performance was selected to yield *d'* of 1.38.

b Scan MDC for uranium includes sum of ^{238}U, ^{235}U, and ^{234}U.

As noted above, the scan MDCs calculated using the approach in this section are dependent on several factors. One way to validate the appropriateness of the scan MDC is by tracking the residual radioactivity (both surface activity and soil concentrations) levels identified during investigations performed as a result of scanning surveys. The measurements performed during these investigations may provide an *a posteriori* estimate of the scan MDC that can be used to validate the *a priori* scan MDC used to design the survey.

Determination of scan MDCs for building/structure surfaces

The scan MDC is determined from the minimum detectable count rate (MDCR) by applying conversion factors that account for detector and surface characteristics and surveyor efficiency. As discussed above, the MDCR accounts for the background level, performance criteria (*d'*), and observation interval. The observation interval during scanning is the actual time that the detector can respond to the contamination source - this interval depends on the scan speed, detector size in the direction of the scan, and area of elevated activity. Because the actual dimensions of potential areas of elevated activity in the field cannot be known *a priori*, EURSSEM recommends postulating a certain area (*e.g.*, perhaps 50 to 200 cm²), and then selecting a scan rate that provides a reasonable observation interval.

$$Scan\ MDC = \frac{MDCR}{\sqrt{p}\ \varepsilon_i\ \varepsilon_s\ (probe\ area/100\ cm^2)} \qquad (3.12)$$

where:

MDCR = minimum detectable count rate;

ε_i = instrument efficiency;

ε_s = surface efficiency;

p = surveyor efficiency.

Example 3.12: Determination of a scan MDC for building/structure surfaces

The scan MDC (in dpm/100 cm²) for ^{99}Tc on a concrete surface may be determined for a background level of 300 cpm and a 2-second observation interval using a hand-held gas proportional detector (126 cm² probe area). For a specified level of performance at the first scanning stage of 95% true positive rate and 60% false positive rate (and assuming the second stage pause is sufficiently long to ensure that the first stage is more limiting), d' equals 1.38 (see Table 3.15) and the MDCR is 130 cpm (see Table 3.16). Using a surveyor efficiency of 0.5, and assuming instrument and surface efficiencies of 0.36 and 0.54, respectively, the scan MDC is calculated using Equation 3-12:

$$Scan\ MDC = \frac{130}{\sqrt{0.5}\ (0.36)\ (0.54)\ (1.26)} = 750\ dpm/100\ cm^2$$

Additional examples for calculating the scan MDC may be found in [79].

3.3.7.6 Determing a scan MDC for alpha emitters

Scanning for alpha emitters differs significantly from scanning for beta and gamma emitters in that the expected background response of most alpha detectors is very close to zero. The following discussion covers scanning for alpha emitters and assumes that the surface being surveyed is similar in nature to the material on which the detector was calibrated. In this respect, the approach is purely theoretical. Surveying surfaces that are dirty, non-planar, or weathered can significantly affect the detection efficiency and therefore bias the expected MDC for the scan. The use of reasonable detection efficiency values instead of optimistic values is highly recommended. 0 contains a complete derivation of the alpha scanning equations used in this section.

Since the time a contaminated area is under the probe varies and the background count rate of some alpha instruments is less than 1 cpm, it is not practical to determine a fixed MDC for scanning. Instead, it is more useful to determine the probability of detecting an area of contamination at a predetermined DCGL for given scan rates.

For alpha survey instrumentation with backgrounds ranging from < 1 to 3 cpm, a single count provides a surveyor sufficient cause to stop and investigate further. Assuming this to be true, the probability of detecting given levels of alpha surface contamination can be calculated by use of Poisson summation statistics.

Given a known scan rate and a surface contamination DCGL, the probability of detecting a single count while passing over the contaminated area is:

$$P(n \geq 1) = 1 - e^{-G\,E\,d\,/\,60\,v} \qquad (3\text{-}13)$$

where:

$P(n \geq 1)$ = probability of observing a single count;

G = contamination activity (dpm);

E	=	detector efficiency (4π);
d	=	width of detector in direction of scan (m);
v	=	scan speed (m/s);

See 0 for a complete derivation of these formulas.

Once a count is recorded and the guideline level of contamination is present the surveyor should stop and wait until the probability of getting another count is at least 90%. This time interval can be calculated by:

$$t = 13{,}800 / (C\ A\ E) \qquad (3\text{-}14)$$

where:

t	=	time period for static count (s);
C	=	contamination guideline (dpm/100 cm^2);
A	=	physical probe area (cm^2);
E	=	detector efficiency ($4\ \pi$).

Many portable proportional counters have background count rates on the order of 5 to 10 cpm, and a single count should not cause a surveyor to investigate further. A counting period long enough to establish that a single count indicates an elevated contamination level would be prohibitively inefficient. For these types of instruments, the surveyor usually will need to get at least 2 counts while passing over the source area before stopping for further investigation.

Assuming this to be a valid assumption, the probability of getting two or more counts can be calculated by:

$$\begin{aligned} P(n \geq 2) &= 1 - P(n = 0) - P(n = 1) \\ &= 1 - (1 + (G \times E + B) \times t / 60)\ (e^{-(G \times E+B) \times t / 60}) \end{aligned} \qquad (3\text{-}15)$$

Where:

$P(n \geq 2)$	=	probability of getting 2 or more counts during the time interval t;
$P(n = 0)$	=	probability of not getting any counts during the time interval t;
$P(n = 1)$	=	probability of getting 1 count during the time interval t;
B	=	background count rate (cpm).

All other variables are the same as for Equation 3-13.

0 provides a complete derivation of Equations 3-13 through 3-15 and a detailed discussion of the probability of detecting alpha surface contamination for several different variables. Several probability charts are included at the end of 0 for common detector sizes. Table 3.18 provides estimates of the probability of detecting 300 dpm/100 cm^2 for some commonly used alpha detectors.

Table 3.18 Probability of detecting 300 dpm/100 cm2 of alpha activity while scanning with alpha detectors using an audible output (calculated using Equation 3-13)

Detector type	Detection efficiency (cpm/dpm)	Probe dimension in direction of scan (cm)	Scan rate (cm/s)	Probability of detecting 300 dpm/100 cm²
Proportional	0.20	5	3	80 %
Proportional	0.15	15	5	90 %
Scintillation	0.15	5	3	70 %
Scintillation	0.15	10	3	90 %

3.3.7.7 Sensitivity of mobile systems with integrated positioning systems

In recent years, the advent of new technologies has introduced mobile sensor systems for acquiring data that include fully-integrated positioning systems. Portable and vehicle-based versions of these systems record survey data while moving over surfaces to be surveyed and simultaneously recording the location data from either a roving DGPS receiver or local microwave/sonar receiver. All measurement data are automatically stored and processed with the measurement location for later posting (see Section 3.10.8.5 for a discussion of posting plots) or for mapping the results. These systems are designed with a variety of detectors for different applications. For example, alpha or beta detectors have been mounted on a robot a fixed distance over a smooth surface. The robot moves at a predetermined speed over the surface to provide scanning results, and also records individual direct measurements at predetermined intervals. This type of system not only provides the necessary measurement data, but also reduces the uncertainty associated with human factors. Other systems are equipped with several types of radiation detectors, magnetometers, electromagnetic sensors, or various combinations of multiple sensors. The limitations of each system should be evaluated on a site-specific basis to determine if the positioning system, the detector, the transport system, or some combination based on site-specific characteristics will represent the limits of the system.

3.3.8 Additional investigations to support a radiological site characterisation

For a more detailed understanding of the behaviour of radioactive contamination in the nature, it is necessary to have good knowledge of the various environmental conditions influencing the fate of radionuclides in the biosphere, as well as of processes governing the radionuclide transport in the environment. In addition, information on human population as a potential receptor of radioactive contamination should also be known.

3.3.8.1 Geomorphology/topography

The geomorphologic investigation is conducted to develop an understanding of surficial features which influence the terrain stability and consequentially the integrity of the contaminated site itself. Namely, a series of slope processes like erosion (including landsliding, colluvial, and proluvial processes) may seriously threaten the contaminated site and promote the spread of contamination from the site into the environment. Most of the data will be included in the site description. Information on the natural topography and man-made changes can be useful in this context.

3.3.8.2 Climatology/meteorology

Both the climate at a site and the particular weather conditions at the time of a release of radioactivity can be important determinants for the movement of radioactivity.

Meteorological parameters may determine air concentrations and deposition of airborne contamination on the ground and influence the soil-water balance. Statistical data on the climate will give information on likelihood of flooding, resuspension by wind erosion, risk of fire, and probability of relocation of contamination by melting snow.

In the case of airborne contamination, exact information, or even informed estimates about wind directions and speeds, at various heights at the time can assist greatly in finding the resulting contamination plumes. Depending on the settling time of the material released, the weather patterns on a local, regional or global scale may be important. Precipitation can greatly alter the pattern of deposition of airborne contamination. Other meteorological parameters, such as the presence of temperature inversions or turbulence, can affect the vertical mixing of the radioactive dispersion or cloud.

The longer term climate of a contaminated area will influence the movement of radioactivity into and across the ground. Maximum wind speeds will determine re-suspension of dusts and will therefore affect off-site migration and become a factor in dose assessment. The prevailing wind direction will affect which populations are exposed. The rainfall patterns will affect likely future land use and influence off-site migration. Extreme weather conditions may also affect their choice of characterisation techniques that can be used.

The climate can influence the choice of measuring instruments (water tightness requirements; exposure to low or high temperatures; etc.), and the humidity and air pressure may influence some measurements. Parameters generally included are: temperature, precipitation, wind speed and direction, atmospheric stability, humidity conditions, and air (atmospheric) pressure.

3.3.8.3 Geology/geophysics

The geologic investigation is conducted to develop an understanding of the subsurface environment in which the radionuclides may be present. The geology may strongly control the behaviour of the radionuclides, and hence risk assessment and remediation design. Information generally to be collected during a geologic investigation is sought from the following areas, such as stratigraphy, lithology, mineralogy, geotechnics and geochemistry, and tectonics and seismicity.

Near surface sediments and features can be further characterised through the utilization of intrusive and non-intrusive geophysical techniques. The acquisition of geophysical data can help to build up a stratigraphic and structural picture of the underlying strata, and therefore tie in information between known geological control points.

Because geophysical techniques are often able to access difficult terrain and can produce data values relatively quickly, such techniques provide a relatively inexpensive way of acquiring data.

Geophysical surveys need to be very carefully planned, with the correct technique and associated methodology selected for the very specific problems of a given site. It will often be important to combine a number of techniques in order to build up an accurate picture of the underlying problem or feature. Examples of the effectiveness of multiple approaches are demonstrated [33].

A detailed discussion of the various geophysical techniques is beyond the scope of this document, but examples of their application and limitation are highlighted in Table 3.19.

Table 3.19 Summary of common geophysical techniques

Technique	Application	Limitations
Seismic	Geological structure, lateral and vertical extend of landfills and trenches	Unconsolidated ground
Resistivity	Contaminant plumes geological features	Bad contact of electrodes
Ground penetrating radar (GPR)	Buried objects, geological structure	Build up areas, microwaves
Electric logging	Sedimentological and stratigraphic boundaries	
Cone penetrometer tests (CPT)	Sedimentological boundaries and contaminants	Will not penetrate coarse sediments
Magnetics	Buried metallic objects, like drums and tanks	Background clutter
Electromagnetics	Buried objects, extent of landfills and trenches	Background clutter

3.3.8.4 Hydrogeology

Hydrogeological data are important because they describe conditions above (the vadose zone) and below the water table (the saturated zone). They can also be used to predict future concentrations and movement of the contaminants. Long-term monitoring of the contamination profile and groundwater conditions may be needed for a full understanding of the hydrogeological regime and its likely relevance to, and influence on, any remediation strategy. Parameters which may collected during such an investigation encompass: hydraulic head, flow direction and velocity, recharge/discharge points, hydraulic conductivity, hydrostratigraphy (aquifers/aquitards), and aquifer age and water properties (e.g., pH, conductivity, temperature).

Measurements of these parameters could prove to be expensive tasks. This is because there will often be requirements for involving drilling, placement of piezometers, pumping tests, and tracer tests. However, such studies may be necessary to understand local transport pathways. Long-term monitoring of groundwater flow and contaminant transport and model development are useful for providing a sound understanding of the groundwater regimes and in the cases of risk assessment would be necessary.

3.3.8.5 Hydrology

The hydrologic investigation addresses the physical characteristics of surface water bodies that represent potential pathways. Surface water bodies may be natural (i.e., rivers and lakes) or may be man made (i.e., irrigation, dam reservoirs, waste ponds) [38]. Parameters and descriptions which may be collected or developed during such an investigation include water flow rates, water volumes, circulation patterns (in lake), sediment descriptions, artificial sources, variability's over time, etc. (e.g., seasonal variations), and flooding history.

It could be beneficial to sample water which is upstream of contaminated areas in order to acquire data about background values. Water samples could be sampled at outset or during a monitoring programme continuously to create time series data. Fine grained sediments situated at the localities of highest depositional rates are generally preferred for sample collection.

3.3.8.6 Pedology

Pedologic investigation gives information to understand the properties of the soil layer supporting the contaminated site. Any spread of contamination from the site will penetrate it. Pedologic investigation can identify characteristics of soil as natural barrier for radionuclide transport. These include the physical properties (grain size, drainage class, lithological sequence, permeability, porosity, density, water content); and geochemical properties (leachability, leachate quality, elemental composition of the soil, pH, distribution coefficient K_d).

3.3.9 Quality control

Site surveys should be performed in a manner that ensures results are accurate and sources of uncertainty are identified and controlled. This is especially the case for final status surveys that are vital to demonstrating a facility satisfies pre-established release criteria. Quality control (QC) and quality assurance (QA) are initiated at the start of a project and integrated into all surveys as data quality objectives (DQOs) are developed. This carries over to the writing of a Quality Assurance Project Plan (QAPP), which applies to each aspect of a survey (see Section 2.13). Data quality is routinely a concern throughout the environmental remediation process, and one should recognize that QA/QC procedures will change as data are collected and analyzed, and as DQOs become more rigorous for the different types of surveys that lead up to a final status survey.

In general, surveys should be performed by trained individuals and should be conducted with approved written procedures and properly calibrated instruments that are sensitive to the suspected contaminant(s) present. However, even the best approaches for properly performing measurements and acquiring accurate data need to consider quality control activities. QC activities are necessary to obtain additional quantitative information to demonstrate that measurement results have the required precision and are sufficiently free of errors to accurately represent the site being investigated. The following two questions are the main focus of the rationale for the assessment of errors in environmental data collection activities:

- How many and what type of measurements are required to assess the quality of data from an environmental survey?
- How can the information from the quality assessment measurements be used to identify and control sources of error and uncertainties in the measurement process?

These questions are introduced as part of guidance that also includes an example to illustrate the planning process for determining a reasonable number of quality control (QC) measurements. This guidance also demonstrates how the information from the process may be used to document the quality of the measurement data. This process was developed in terms of soil samples collected in the field and then sent to a laboratory for analysis. For EURSSEM, these questions may be asked in relation to measurements of surface soils and building surfaces both of which include sampling, scanning, and direct measurements.

Quality control may be thought of in three parts:

- Determining the type of QC samples needed to detect precision or bias;
- Determining the number of samples as part of the survey design; and
- Scheduling sample collections throughout the survey process to identify and control sources of error and uncertainties.

Overall, survey activities associated with EURSSEM include obtaining the additional information related to QA of both field and laboratory activities.

The following factors should be considered when evaluating sources of bias, error, and uncertainty. Cross contamination is an added factor to consider for each of the following items:

- Sample collection methods;
- Handling and preparation of samples;
- Homogenization and aliquots of laboratory samples;
- Field methods for sampling, scanning, or direct measurements;
- Laboratory analytical process;
- Total bias contributed by all sources.

Systematic investigations of field or laboratory processes can be initiated to assess and identify the extent of errors, bias, and data variability and to determine if the data quality objectives (DQOs) are achieved. An important aspect of each QC determination is the representative nature of a sample or measurement (see Section 3.3.9.5 for a description of representativeness). If additional samples or measurements are not taken according to the appropriate method, the resulting QC information will be invalid or unusable. For example, if an inadequate amount of sample is collected, the laboratory analytical procedure may not yield a proper result. The QC sample must represent the sample population being studied. Misrepresentation itself creates a bias that, if undetected, leads to inaccurate conclusions concerning an analysis. At the very least, misrepresentation leads to a need for additional QA investigation.

3.3.9.1 Data quality indicators

The assessment of data quality indicators presented in this section is significant to determine data usability. The principal data quality indicators are precision, bias, representativeness, comparability, and completeness. Other data quality indicators affecting the RSSI process include the selection and classification of survey units, Type I and Type II decision error rates, the variability in the radionuclide concentration measured within the survey unit, and the lower bound of the gray region (see 0).

In some instances, the data quality indicator requirements will help in the selection of a measurement system. In other cases, the requirements of the measurement system will assist in the selection of appropriate levels for the data quality indicators.

Of the six principal data quality indicators:

- Precision and bias are quantitative measures.
- Representativeness and comparability are qualitative.
- Completeness is a combination of both qualitative and quantitative measures.
- Accuracy is a combination of precision and bias.
- The selection and classification of survey units is qualitative.
- Decision error rates, variability, and the lower bound of the gray region are quantitative measures.

Determining the usability of analytical results begins with the review of QC measurements (see Section 3.4.2.13) and qualifiers to assess the measurement result and the performance of the analytical method. If an error in the data is discovered, it is more important to evaluate the effect of the error on the data than to determine the source of the error. The documentation described in Section 3.11 is reviewed as a whole for some criteria. Data are reviewed at the measurement level for other criteria.

Factors affecting the accuracy of identification and the precision and bias of quantisation of individual radio-nuclides, such as calibration and recoveries, should be examined radionuclide by radionuclide. Table 3.20 presents a summary of QC measurements and the data use implications.

Table 3.20 Use of quality control data

Quality control criterion	**Effect on identification when criterion is not met**	**Quantitative bias**	**Use**
Spikes (Higher than expected result)	Potential for incorrectly deciding a survey unit does not meet the release criterion (Type II decision error)	High	Use data as upper limit
Spikes (Lower than expected result)	Potential for incorrectly deciding a survey unit does meet the release criterion[a] (Type I decision error)	Low	Use data as lower limit
Replicates (Inconsistent)	None, unless analyse found in one duplicate and not the other - then either Type I or Type II decision error	High or Low[b]	Use data as estimate - poor precision
Blanks (Contaminated)	Potential for incorrectly deciding a survey unit does not meet the release criterion (Type II decision error)	High	Check for gross contamination or instrument malfunction
Calibration (Bias)	Potential for Type I or Type II decision errors	High or Low[b]	Use data as estimate unless problem is extreme

[a] Only likely if recovery is near zero.
[b] Effect on bias determined by examination of data for each radio-nuclide.

3.3.9.2 Precision

Precision is a measure of agreement among replicate measurements of the same property under prescribed similar conditions. This agreement is calculated as either the range or the standard deviation. It may also be expressed as a percentage of the mean of the measurements such as relative range (for duplicates) or coefficient of variation.

For scanning and direct measurements, precision may be specified for a single person performing the measurement or as a comparison between people performing the same measurement. For laboratory analyses, precision may be specified as either intra-laboratory (within a laboratory) or inter-laboratory (between laboratories).

Precision estimates based on a single surveyor or laboratory represent the agreement expected when the same person or laboratory uses the same method to perform multiple measurements of the same location. Precision estimates based on two or more surveyors or laboratories refer to the agreement expected when different people or laboratories perform the same measurement using the same method.

Determining precision by replicating measurements with results at or near the detection limit of the measurement system is not recommended because the measurement uncertainty is usually greater than the desired level of precision. The types of replicate measurements applied to scanning and direct measurements are limited by the relatively uncomplicated measurement system (*i.e.*, the uncertainties associated with sample collection and preparation are eliminated). However, the uncertainties associated with applying a single calibration factor to a wide variety of site conditions mean these measurements are very useful for assessing data quality.

There are several types of replicate analyses available to determine the level of precision, and these replicates are typically distinguished by the point in the sample collection and analysis process where the sample is divided. Determining precision by replicating measurements with results at or near the detection limit of the measurement system is not recommended because the measurement uncertainty is usually greater than the desired level of precision.

- *Collocated Samples*. Collocated samples are samples collected adjacent to the routine field sample to determine local variability of the radionuclide concentration. Typically, collocated samples are collected about one-half to three feet away from the selected sample location. Analytical results from collocated samples can be used to assess site variation, but only in the immediate sampling area. Collocated samples should not be used to assess variability across a site and are not recommended for assessing error. Collocated samples can be non-blind, single-blind, or double-blind.
- *Field Replicates*. Field replicates are samples obtained from one location, homogenized, divided into separate containers and treated as separate samples throughout the remaining sample handling and analytical processes. These samples are used to assess error associated with sample heterogeneity, sample methodology and analytical procedures. Field replicates are used when determining total error for critical samples with contamination concentrations near the action level. For statistical analysis to be valid in such a case, a minimum of eight replicate samples would be required [86]). Field replicates (or field split samples) can be non-blind, single-blind, or double-blind and are recommended for determining the level of precision for a radiation survey or site investigation.
- *Replicates to Measure Operator Precision*. For scanning and direct measurements, replicates to measure operator precision provide an estimate of precision for the operator and the Standard Operating Procedure (SOP) or protocol used to perform the measurement. Replicates to measure operator precision are measurements performed using the same instrument at the same location, but with a different operator. Replicates to measure operator precision are usually non-blind or single-blind measurements.

- *Replicates to Measure Instrument Precision*. For scanning and direct measurements, replicates to measure instrument precision provide an estimate of precision for the type of instrument, the calibration, and the SOP or protocol used to perform the measurement. Replicates to measure instrument precision are measurements performed by the same operator at the same location, but with a different instrument. Replicates to measure instrument precision are usually non-blind or single-blind measurements.
- *Analytical Laboratory Replicate*. An analytical laboratory replicate is a sub-sample of a routine sample that is homogenized, divided into separate containers, and analyzed using the same analytical method. It is used to determine method precision, but because it is a non-blind sample, or known to the analyst, it can only be used by the analyst as an internal control tool and not as an unbiased estimate of analytical precision [87].
- *Laboratory Instrument Replicate*. A laboratory instrument replicate is the repeated measurement of a sample that has been prepared for counting (*i.e.*, laboratory sample preparation and radiochemical procedures have been completed). It is used to determine precision for the instrument (repeated measurements using same instrument) and the instrument calibration (repeated measurements using different instruments, such as two different germanium detectors with multi-channel analyzers). A laboratory instrument replicate is generally performed as part of the laboratory QC program and is a non-blind sample. It is typically used as an internal control tool and not as an unbiased estimate of analytical precision.

For many surveys a combination of sample, operator and laboratory replicates are used to provide an estimate of overall precision for both scanning and direct measurements. Replicates of direct measurements can be compared with one another similar to the analytical results for samples. Results for scanning replicates may be obtained by stopping and recording instrument readings at specific intervals during the scanning survey (effectively performing direct measurements at specified locations). An alternative method for estimating the precision of scanning is to evaluate the effectiveness of the scanning survey for identifying areas of elevated activity. The results of scanning are usually locations that are identified for further investigation. A comparison of the areas identified by the replicate scanning surveys can be performed either quantitatively (using statistical methods) or qualitatively (using professional judgment). Because there is a necessity to evaluate whether the same number of locations was identified by both replicates as well as if the identified locations are the same, there is difficulty in developing precision as a DQO that can be evaluated.

The two basic activities performed in the assessment of precision are estimating the radionuclide concentration variability from the measurement locations and estimating the measurement error attributable to the data collection process. The level for each of these performance measures should be specified during development of DQOs. If the statistical performance objectives are not met, additional measurements should be taken or one (or more) of the performance parameters changed.

Measurement error is estimated using the results of replicate measurements, as discussed in Section 3.9.2.9; for field measurements and for laboratory measurements. When collocated measurements are performed (in the field or in the laboratory) an estimate of total precision is obtained. When collocated samples are not available for laboratory analysis, a sample subdivided in the field and preserved separately can be used to assess the variability of sample handling, preservation, and storage along with the variability in the analytical process, but variability in sample acquisition is not included. When only variability in the analytical process is desired, a sample can be subdivided in the laboratory prior to analysis.

Summary statistics such as sample mean and sample variance can provide as assessment of the precision of a measurement system or component thereof for a project. These statistics may be used to estimate precision at discrete concentration levels, average estimated precision over applicable concentration ranges, or provide the basis for a continual assessment of precision for future measurements. Methods for calculating and reporting precision are provided in EPA guidance for quality assurance project plans.

Table 3.21 presents the minimum considerations, impacts if the considerations are not met, and corrective actions for precision.

Table 3.21 Minimum considerqtions for precision, impact if not met and corrective actions

Minimum considerations for precision	Impact when minimum considerations are not met	Corrective action
Confidence level as specified in DQOs. Power as specified in DQOs. Minimum detectable relative differences specified in the survey design and modified after analysis of background measurements if necessary. One set of field duplicates or more as specified in the survey design. Analytical duplicates and splits as specified in the survey design. Measurement error specified.	Errors in decisions to act or not to act based on analytical data. Unacceptable level of uncertainty. Increased variability of quantitative results. Potential for incorrectly deciding a survey unit does meet the release criterion for measurements near the detection limits (Type I decision error).	For surveying and sampling: - Add survey or sample locations based on information from available data that are known to be representative. - Adjust performance objectives. For analysis: - Analysis of new duplicate samples. - Review laboratory protocols to ensure comparability. - Use precision measurements to determine confidence limits for the effects on the data. The investigator can use the maximum measurement results to set an upper bound on the uncertainty if there is too much variability in the analyses.

3.3.9.3 Bias

Bias is the systematic or persistent distortion of a measurement process and result from faults in sampling designs and procedures, analytical procedures, sample contamination, losses, interactions with containers, deterioration, inaccurate instrument calibration, and other sources. Bias causes the mean value of the sample data to be consistently higher or lower than the true mean value.

Bias assessments for radio-analytical measurements

Bias assessments for radio-analytical measurements should be made using personnel, equipment, and spiking materials or reference materials as independent as possible from those used in the calibration of the measurement system. QC samples used to determine bias should be included as early in the analytical process as possible.

- *Reference Material*. A reference material or substance one or more of whose property values are sufficiently homogeneous and well established to be used for the calibration of an apparatus, the assessment of a measurement method, or for assigning values to materials [88]. A certified reference material is reference material for which each certified property value is accompanied by an uncertainty at a stated level of confidence. Radioactive reference materials may be available for certain radio-nuclides in soil (*e.g.*, uranium in soil), but reference building materials may not be available. Because reference materials are prepared and homogenized as part of the certification process, they are rarely available as double-blind samples. When appropriate reference materials are available (*i.e.*, proper matrix, proper radionuclide, proper concentration range), they are recommended for use in determining the overall bias for a measurement system.
- *Performance Evaluation Samples*. Performance evaluation sample are samples that evaluate the overall bias of the analytical laboratory and detect any error in the analytical method used. These samples are usually prepared by a third party, using a

quantity of analyte(s) which is known to the preparer but unknown to the laboratory, and always undergo certification analysis. The analyte(s) used to prepare the performance evaluation sample is the same as the analyte(s) of interest. Laboratory procedural error is evaluated by the percentage of analyte identified in the performance evaluation sample. Performance evaluation samples are recommended for use in determining overall bias for a measurement system when appropriate reference materials are not available. Performance evaluation samples are equivalent to matrix spikes prepared by a third party that undergo certification analysis and can be non-blind, single-blind, or double-blind.

- *Matrix Spike Samples*. Matrix spike samples are environmental samples that are spiked in the laboratory with a known concentration of a target analyte(s) to verify percent recoveries. They are used primarily to check sample matrix interferences but can also be used to monitor laboratory performance. However, a data set of at least three or more results is necessary to distinguish between laboratory performance and matrix interference. Matrix spike samples are often replicated to monitor method performance and evaluate error due to laboratory bias and precision (when four or more pairs are analyzed). These replicates are often collectively referred to as a matrix spike/matrix spike duplicate.

There are several additional terms applied to samples prepared by adding a known amount of the radionuclide of interest to the sample. The majority of these samples are designed to isolate individual sources of bias within a measurement system by preparing pre- and post-operation spikes. For example, the bias from the digestion phase of the measurement system can be determined by comparing the result from a pre-digest spike to the result from a post-digest spike.

When possible, bias assessments should be based on certified reference materials rather than matrix spikes or water spikes so that the effect of the matrix and the chemical composition of the contamination is incorporated into the assessment. While matrix spikes include matrix effects, the addition of a small amount of liquid spike does not always reflect the chemical composition of the contamination in the sample matrix. Water spikes do not account for either matrix effects or chemical composition of the contamination. When spikes are used to assess bias, a documented spiking protocol and consistency in following that protocol are important to obtaining meaningful data quality estimates.

Activity levels for bias assessment measurements should cover the range of expected contaminant concentrations, although the minimum activity is usually at least five times the MDC. For many final status surveys, the expected contaminant concentration is zero or background, so the highest activity will be associated with the bias assessment measurements. The minimum and maximum concentrations allowable in bias assessment samples should be agreed on during survey planning activities to prevent accidental contamination of the environment or an environmental level radio-analytical laboratory.

Scanning and direct measurements

Field work using scanning or direct measurements eliminates some sources of error because samples are not removed, containerized, nor transported to another location for analysis. The operator's technique or field instrument becomes the source of bias. In this case, detecting bias might incorporate field replicates (see Section 3.3.9.2) by having a second operator to revisit measurement locations and following the same procedure with the same instrument as was used by the first operator. This is an approach used to assess precision of measurements. A field instrument's calibration can also be checked by one or more operators during the course of a survey and recorded on a control chart. Differences in set up or handling of instruments by different operators may reveal a significant source of bias that is quite different from sources of bias associated with laboratory work.

For scanning and direct measurements there are a limited number of options available for performing bias assessment measurements. Perhaps the best estimate of bias for scanning and direct measurements is to collect samples from locations where scans or direct measurements were performed, analyze the samples in a laboratory, and compare the results. Problems associated with this method include the time required to obtain the results and the difficulty in obtaining samples that are representative of the field measurement to provide comparable results. A simple method of demonstrating that analytical bias is not a significant problem for scanning or direct measurements is to use the instrument performance checks to demonstrate the lack of analytical bias. A control chart can be used to determine the variability of a specific instrument and track the instrument performance throughout the course of the survey. Field background measurements can also be plotted on a control chart to estimate bias caused by contamination of the instrument.

There are also several types of samples used to estimate bias caused by contamination:

- *Background Sample*. A background sample is a sample collected up-gradient of the area of potential contamination (either on-site or off-site) where there is little or no chance of migration of the contaminants of concern. Background samples are collected from the background reference area, determine the natural composition and variability of the soil (especially important in areas with high concentrations of naturally occurring radio-nuclides), and are considered "clean" samples. They provide a basis for comparison of contaminant concentration levels with samples collected from the survey unit when the statistical tests described in Section 3.9.2.9 are performed.
- *Field Blanks*. Field blanks are samples prepared in the field using certified clean sand or soil and then submitted to the laboratory for analysis. A field blank is used to evaluate contamination error associated with sampling methodology and laboratory procedures. It also provides information about contaminants that may be introduced during sample collection, storage, and transport. Field blanks are recommended for determining bias resulting from contamination for a radiation survey or site investigation.
- *Method Blank*. A method blank is an analytical control sample used to demonstrate that reported analytical results are not the result of laboratory contamination. It contains distilled or deionised water and reagents, and is carried through the entire analytical procedure (laboratory sample preparation, digestion, and analysis). The method blank is also referred to as a reagent blank. The method blank is generally used as an internal control tool by the laboratory because it is a non-blind sample.

Table 3.22 presents the minimum considerations, impacts if the considerations are not met, and corrective actions for bias.

Table 3.22 Minimum considerations for bias, impact if not met and corrective actions

Minimum considerations for bias	Impact when minimum considerations are not met	Corrective action
Matrix spikes to assess bias of non-detects and positive sample results if specified in the survey design. Analytical spikes as specified in the survey design. Use analytical methods (routine methods whenever possible) that specify expected or required recovery ranges using spikes or other QC measures. No radio-nuclides of potential concern detected in the blanks.	Potential for incorrectly deciding a survey unit does meet the release criterion (Type I decision error): if spike recovery is low, it is probable that the method or analysis is biased low for that radionuclide and values of all related samples may underestimate the actual concentration. Potential for incorrectly deciding a survey unit does not meet the release criterion (Type II decision error): if spike recovery exceeds 100%, interferences may be present, and it is probable that the method or analysis is biased high. Analytical results overestimate the true concentration of the spiked radio-nuclide.	Consider re-sampling at affected locations. If recoveries are extremely low or extremely high, the investigator should consult with a radio-chemist or health physicist to identify a more appropriate method for reanalysis of the samples.

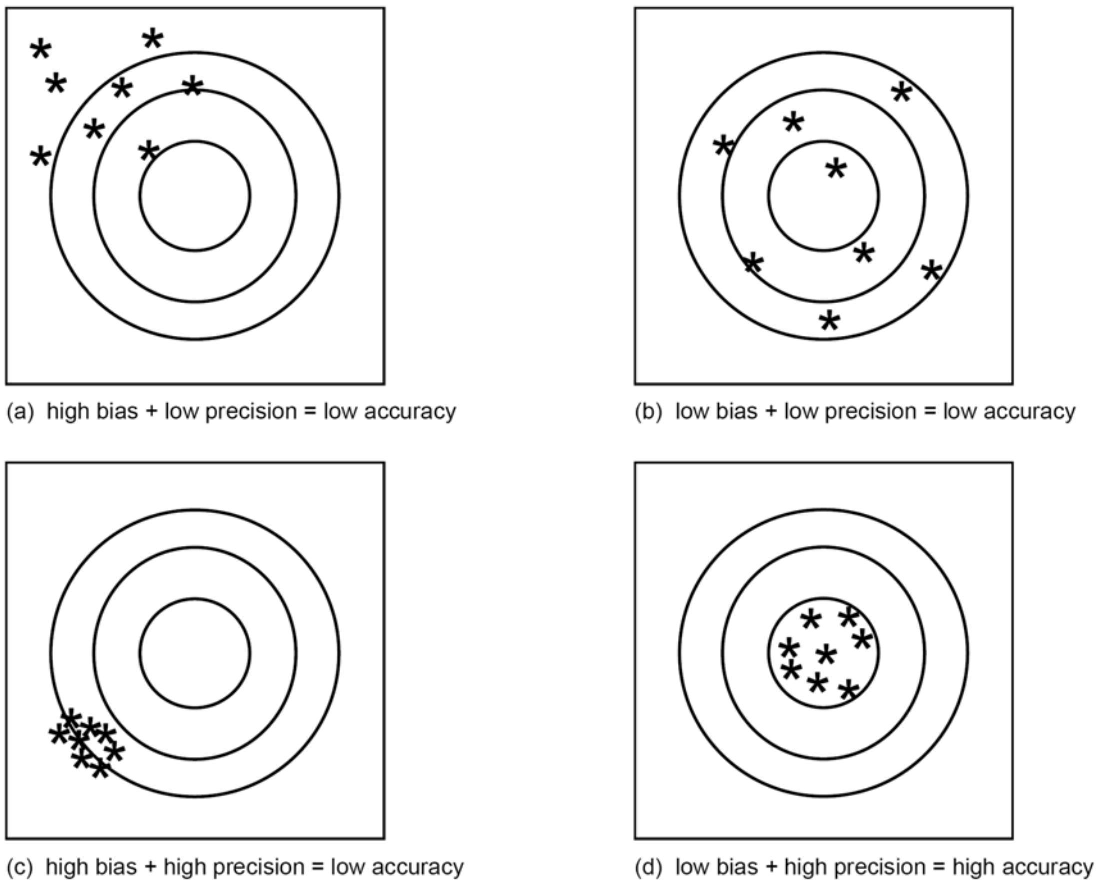
3.3.9.4 Accuracy

Accuracy is a measure of the closeness of an individual measurement or the average of a number of measurements to the true value. Accuracy includes a combination of random error (precision) and systematic error (bias) components that result from performing measurements. Systematic and random uncertainties (or errors) are discussed in more detail in Section 3.9.2.9.

Accuracy is determined by analyzing a reference material of known contaminant concentration or by reanalyzing material to which a known concentration of contaminant has been added. To be accurate, data must be both precise and unbiased. Using the analogy of archery, to be accurate one's arrows must land close together and, on average, at the spot where they are aimed. That is, the arrows must all land near the bull's eye (see Figure 3.4).

Accuracy is usually expressed either as a percent recovery or as a percent bias. Determination of accuracy always includes the effects of variability (precision); therefore, accuracy is used as a combination of bias and precision. The combination is known statistically as mean square error. Mean square error is the quantitative term for overall quality of individual measurements or estimators.

Mean square error is the sum of the variance plus the square of the bias. (The bias is squared to eliminate concern over whether the bias is positive or negative.) Frequently it is impossible to quantify all of the components of the mean square error - especially the biases - but it is important to attempt to quantify the magnitude of such potential biases, often by comparison with auxiliary data.



(a) high bias + low precision = low accuracy

(b) low bias + low precision = low accuracy

(c) high bias + high precision = low accuracy

(d) low bias + high precision = high accuracy

Figure 3.4 Measurement bias and random measurement uncertainties

3.3.9.5 Representativeness

Representativeness is a measure of the degree to which data accurately and precisely represent a characteristic of a population parameter at a sampling point or for a process condition or environmental condition. Representativeness is a qualitative term that should be evaluated to determine whether in-situ and other measurements are made and physical samples collected in such a manner that the resulting data appropriately reflect the media and contamination measured or studied.

Representativeness of data is critical to data usability assessments. The results of the environmental radiological survey will be biased to the degree that the data do not reflect the radio-nuclides and concentrations present at the site. Non-representative radionuclide identification may result in false negatives. Non-representative estimates of concentrations may be higher or lower than the true concentration. With few exceptions, non-representative measurements are only resolved by additional measurements. Sample collection and analysis is typically less representative of true radionuclide concentrations at a specific measurement location than performing a direct measurement. This is caused by the additional steps required in collecting and analyzing samples, such as sample collection, field sample preparation, laboratory sample preparation, and radiochemical analysis. However, direct measurement techniques with acceptable detection limits are not always available. When sampling is required as part of a survey design, it is critical that the sample collection procedures consider representativeness.

Representativeness is primarily a planning concern. The solution to enhancing representativeness is in the design of the survey plan. Representativeness is determined by examining the survey plan. Analytical data quality affects representativeness since data of low quality may be rejected for use.

Table 3.23 presents the minimum considerations, impacts if the considerations are not met, and corrective actions for representativeness.

Table 3.23 Minimum considerations for representativeness, impact if not met and corrective actions

Minimum considerations for representativeness	Impact when minimum considerations are not met	Corrective action
Survey data representative of survey unit. Documented sample preparation procedures. Filtering, compositing, and sample preservation may affect representativeness. Documented analytical data as specified in the survey design.	Bias high or low in estimate of extent and quantity of contaminated material. Potential for incorrectly deciding a survey unit does meet the release criterion (Type I decision error). Inaccurate identification or estimate of concentration of a radio-nuclide. Remaining data may no longer sufficiently represent the site if a large portion of the data are rejected, or if all data from measurements at a specific location are rejected.	Additional surveying or sampling. Examination of effects of sample preparation procedures. Re-analysis of samples, or re-surveying or re-sampling of the affected site areas. If the re-surveying, re-sampling, or re-analyses cannot be performed, document in the site environmental radiological survey report what areas of the site are not represented due to poor quality of analytical data.

3.3.9.6 Comparability

Comparability is the qualitative term that expresses the confidence that two data sets can contribute to a common analysis and interpolation. Comparability should be carefully evaluated to establish whether two data sets can be considered equivalent in regard to the measurement of a specific variable or groups of variables.

Comparability is not compromised provided that the survey design is unbiased, and the survey design or analytical methods are not changed over time. Comparability is a very important qualitative data indicator for analytical assessment and is a critical parameter when considering the combination of data sets from different analyses for the same radio-nuclides.

The assessment of data quality indicators determines if analytical results being reported are equivalent to data obtained from similar analyses. Only comparable data sets can be readily combined.

The use of routine methods (e.g., sampling, sample preparation and preservation, see Section 3.4) simplifies the determination of comparability because all laboratories use the same standardized procedures and reporting parameters. In other cases, the decision maker may have to consult with a health physicist and/or radio-chemist to evaluate whether different methods are sufficiently comparable to combine data sets.

There are a number of issues that can make two data sets comparable, and the presence of each of the following items enhances their comparability:

- Two data sets should contain the same set of variables of interest.
- Units in which these variables were measured should be convertible to a common metric.
- Similar analytic procedures and quality assurance should be used to collect data for both data sets.
- Time of measurements of certain characteristics (variables) should be similar for both data sets.
- Measuring devices used for both data sets should have approximately similar detection levels.
- Rules for excluding certain types of observations from both samples should be similar.
- Samples within data sets should be selected in a similar manner.
- Sampling frames from which the samples were selected should be similar.
- Number of observations in both data sets should be of the same order of magnitude.

These characteristics vary in importance depending on the final use of the data. The closer two data sets are with regard to these characteristics, the more appropriate it will be to compare them. Large differences between characteristics may be of only minor importance depending on the decision that is to be made from the data.

Table 3.24 presents the minimum considerations, impacts if they are not met, and corrective actions for comparability.

Table 3.24 Minimum considerations for comparability, impact if not met and corrective actions

Minimum considerations for comparability	**Impact when minimum considerations are not met**	**Corrective action**
Unbiased survey design or documented reasons for selecting another survey design. The analytical methods used should have common analytical parameters. Same units of measure used in reporting. Similar detection limits. Equivalent sample preparation techniques. Analytical equipment with similar efficiencies or the efficiencies should be factored into the results.	Non-additivity of survey results. Reduced confidence, power, and ability to detect differences, given the number of measurements available. Increased overall error.	For surveying and sampling: - Statistical analysis of effects of bias. For analytical data: - Preferentially use those data that provide the most definitive identification and quantitation of the radio-nuclides of potential concern. For quantitation, examine the precision and accuracy data along with the reported detection limits. Reanalysis using comparable methods.

3.3.9.7 Completeness

Completeness is a measure of the amount of valid data obtained from the measurement system, expressed as a percentage of the number of valid measurements that should have been collected (i.e., measurements that were planned to be collected).

Completeness for measurements is calculated by the following formula:

$$\%\ \text{Completeness} = \frac{(\text{Number of valid measurements}) \times 100}{\text{Total number of measurements planned}}$$

Completeness is not intended to be a measure of representativeness; that is, it does not describe how closely the measured results reflect the actual concentration or distribution of the contaminant in the media being measured. A project could produce 100% data completeness (*i.e.*, all planned measurements were actually performed and found valid), but the results may not be representative of the actual contaminant concentration.

Alternatively, there could be only 70% data completeness (30 lost or found invalid), but, due to the nature of the survey design, the results could still be representative of the target population and yield valid estimates. The degree to which lack of completeness affects the outcome of the survey is a function of many variables ranging from deficiencies in the number of measurements to failure to analyze as many replications as deemed necessary by the QAPP and DQOs. The intensity of effect due to incompleteness of data is sometimes best expressed as a qualitative measure and not just as a quantitative percentage.

Completeness can have an effect on the DQO parameters. Lack of completeness may require reconsideration of the limits for decision error rates because insufficient completeness will decrease the power of the statistical tests described in Section 3.9.2.9.

For most final status surveys, the issue of completeness only arises when the survey unit demonstrates compliance with the release criterion and less than 100% of the measurements are determined to be acceptable. The question now becomes whether the number of measurements is sufficient to support the decision to release the survey unit. This question can be answered by constructing a power curve as described in 0 and evaluating the results. An alternative method is to consider that the number of measurements estimated to demonstrate compliance in Section 3.5.1.1 was increased by 20% to account for lost or rejected data and uncertainty in the calculation of the number of measurements. This means a survey with 80% completeness may still have sufficient power to support a decision to release the survey unit.

Completeness is of greater concern for laboratory analyses than for direct measurements because the consequences of incomplete data often require the collection of additional samples. Direct measurements can usually be repeated fairly easily. The collection of additional samples generally requires a remobilization of sample collection personnel which can be expensive. Conditions at the site may have changed making it difficult or impossible to collect representative and comparable samples without repeating the entire survey.

On the other hand, if it is simply an analytical problem and sufficient sample was originally collected, the analysis can be repeated using archived sample material. Samples collected on a grid to locate areas of elevated activity are also a concern for completeness. If one sample analysis is not valid, the entire survey design for locating areas of elevated activity may be invalidated.

Table 3.25 presents the minimum considerations, impacts if the considerations are not met, and corrective actions for completeness.

Table 3.25 Minimum considerations for completeness, impact if not met and corrective actions

Minimum considerations for completeness	Impact when minimum considerations are not met	Corrective action
Percentage of measurement completeness determined during planning to meet specified performance measures.	Higher potential for incorrectly deciding a survey unit does not meet the release criterion (Type II decision error). Reduction in power. A reduction in the number of measurements reduces site coverage and may affect representativeness. Reduced ability to differentiate site levels from background. Impact of incompleteness generally decreases as the number of measurements increases.	Resurveying, re-sampling, or reanalysis to fill data gaps. Additional analysis of samples already in laboratory. Determine whether the missing data are crucial to the survey.

3.3.9.8 Other sources of uncertainty

Counting errors are often not the limiting factor in the repeatability or accuracy of results. Whenever samples are taken from a heterogenous medium such as soil, there will usually be a large sample to sample variation. In general, the larger the sample size taken, the more statistically valid will be the result. Where gamma spectrometry is being undertaken, the use of a Marinelli beaker which surrounds the sensitive volume of the detector will give an optimum geometry in terms of sensitivity and in terms of maximizing the sample size. If this approach is taken, care should be taken that:

- True coincidence summing does not adversely affect the results at a significant level.
- The range of gamma rays in the sample medium is not much less than the thickness of the sample (otherwise, the detector will be sensitive to a much smaller volume of sample than might have been believed).

The latter effect will be compensated adequately if:

- The calibration standard used is similar in density to the sample density or
- To apply a detector efficiency program to calculate the effect.

3.3.9.9 Uncertainty introduced by the applied statistical method(s)

EURSSEM encourages the use of statistics to provide a quantitative estimate of the probability that the release criterion is not exceeded at a site. While it is unlikely that any site will be able to demonstrate compliance with a dose- or risk-based regulation without at least considering the use of statistics, EURSSEM recognizes that the use of statistical tests may not always provide the most effective method for demonstrating compliance.

For example, EURSSEM recommends a simple comparison to an investigation level to evaluate the presence of small areas of elevated activity in place of complicated statistical tests. At some sites a simple comparison of each measurement result to the derived concentration guideline level ($DCGL_W$), to demonstrate that all the measurement results are below the release criterion, may be more effective than statistical tests for the overall demonstration of compliance with the regulation provided an adequate number of measurements are performed.

EURSSEM recommends the use of *non-parametric statistical tests* for evaluating environmental data.

There are two reasons for this recommendation:

- Environmental data is usually not normally distributed.

- There are often a significant number of qualitative survey results (e.g., less than Minimum Detectable Concentration - MDC).

Either one of these conditions means, that parametric statistical tests may not be appropriate. If one can demonstrate that the data are distributed according to a certain parametric statistical test and that there are a sufficient number of results to support this decision concerning a survey unit, parametric tests will generally provide higher power (or require fewer measurements to support a decision concerning the survey unit). The tests to demonstrate that the data are distributed according to a certain parametric statistical test generally require more measurements than the non-parametric tests.

The parameter of interest is the mean concentration in the survey unit. The non-parametric tests recommended in this manual, in their most general form, are tests of the median. If one assumes that the data are from a symmetric distribution - where the median and the mean are effectively equal - these are also tests of the mean.

If the assumption of symmetry is violated, then non-parametric tests of the median approximately test the mean. That is, the correct decision will be made about whether or not the mean concentration exceeds the derived concentration guideline level (DCGL), even when the data come from a skewed distribution. In this regard, the nonparametric tests are found to be correct more often than the commonly used Student's t-test. The robust performance of the Sign and Wilcoxon Rank Sum (WRS) tests over a wide range of conditions is the reason that they are recommended in this manual.

There are a wide variety of statistical tests designed for use in specific situations. These tests may be preferable to the generic non-parametric statistical tests recommended in EURSSEM when the underlying assumptions for these tests can be verified.

When a given set of assumptions is true, a parametric test designed for exactly that set of conditions will have the highest power. For example, if the data are from a normal distribution, the Student's t-test will have higher power than the non-parametric tests. It should be noted that for large enough sample sizes (e.g., large number of measurements), the Student's t-test is not a great deal more powerful than the non-parametric tests. On the other hand, when the assumption of normality is violated, the non-parametric tests can be very much more powerful than the Student's t-test. Therefore, any statistical test may be used provided that the data are consistent with the assumptions underlying their use. When these assumptions are violated, the prudent approach is to use the non-parametric tests which generally involve fewer assumptions than their parametric equivalents.

Table 3.26 lists several examples of statistical tests that may be considered for use at individual sites or survey units. A brief description of the tests and references for obtaining additional information on these tests are also listed in the table. Applying these tests may require consultation with a statistician.

Table 3.26 Examples of alternate statistical tests

Alternate Tests	**Probability Model Assumed**	**Type of Test**	**Advantages**	**Disadvantages**
Alternate 1 – Sample Tests (no reference area measurements)				
Student's t Test [89]	Normal	Parametric test for H_o: Mean < L	Appropriate if data appears to be normally distributed and symmetric.	Relies on a non-robust estimator for μ and σ. Sensitive to outliers and departures from normality.
t Test Applied to Logarithms [89]	Lognormal	Parametric test for H_o: Mean < L	This is a well-known and easy-to-apply test. Useful for a quick summary of the situation if the data is skewed to right.	Relies on a non-robust estimator for σ. Sensitive to outliers and departures from lognormality.
Minimum Variance Unbiased Estimator For Lognormal Mean [90]	Lognormal	Parametric estimates for mean and variance of lognormal distribution	A good parametric test to use if the data is lognormal.	Inappropriate if the data is not lognormal.

Alternate Tests	Probability Model Assumed	Type of Test	Advantages	Disadvantages
Chen Test [91]	Skewed to right, including Lognormal	Parametric test for H_o: Mean > 0	A good parametric test to use if the data is lognormal.	Applicability only for testing H_o: "survey unit is clean". Survey unit must be significantly greater than 0 to fail. Inappropriate if the data is not skewed to the right.
Bayesian Approaches [92]	Varies, but a family of probability distributions must be selected.	Parametric test for H_o: Mean < L	Permits use of subjective "expert judgment" in interpretation of data.	Decisions based on expert judgment may be difficult to explain and defend.
Bootstrap [93]	No restriction	Nonparametric. Uses re-sampling methods to estimate sampling variance.	Avoids assumptions concerning the type of distribution.	Computer intensive analysis required. Accuracy of the results can be difficult to assess.
Lognormal Confidence Intervals using Bootstrap [94]	Lognormal	Uses re-sampling methods to estimate one-sided confidence interval for lognormal mean.	Nonparametric method applied within a parametric lognormal model.	Computer intensive analysis required. Accuracy of the results can be difficult to assess.
Alternate 2 – Sample Tests (reference area measurements are required)				
Student's t Test [89]	Symmetric, normal	Parametric test for difference in means H_o: $\mu_x < \mu_y$	Easy to apply. Performance for non-normal data is acceptable.	Relies on a non-robust estimator for σ, therefore test results are sensitive to outliers.
Mann-Whitney Test [95]	No restrictions	Nonparametric test difference in location H_o: $\mu_x < \mu_y$	Equivalent to the WRS test, but used less often. Similar to re-sampling, because test is based on set of all possible differences between the two data sets.	Assumes that the only difference between the test and reference areas is a shift in location.
Kolmogorov-Smirnov [95]	No restrictions	Nonparametric test for any difference between the 2 distributions	A robust test for equality of two sample distributions against all alternatives.	May reject because variance is high, although mean is in compliance.
Bayesian Approaches [96]	Varies, but a family of probability distributions must be selected	Parametric tests for difference in means or difference in variance.	Permits use of "expert judgment" in the interpretation of data.	Decisions based on expert judgment may be difficult to explain and defend.
2-Sample Quantile Test [97]	No restrictions	Nonparametric test for difference in shape and location	Will detect if survey unit distribution exceeds reference distribution in the upper quantiles.	Applicable only for testing H_o: "survey unit is clean". Survey unit must be significantly greater than 0 to fail.
Simultaneous WRS and Quantile Test [97]	No restrictions	Nonparametric test for difference in shape and location	Additional level of protection provided by using two tests. Has advantages of both tests.	Cannot be combined with the WRS test that uses H_o: "survey unit is not clean". Should only be combined with WRS test for H_o: "survey unit is clean".
Bootstrap and other Re-sampling Methods [93]	No restrictions	Nonparametric. Uses re-sampling methods to estimate sampling variance.	Avoids assumptions concerning the type of distribution. Generates informative re-sampling distributions for graphing.	Computer intensive analysis required.
Alternate to Statistical Tests				
Decision Theory[98]	No restrictions	Incorporates loss function in the decision theory approach.	Combines elements of cost-benefit analysis and risk assessment into the planning process.	Limited experience in applying the method to compliance demonstration and decommissioning. Computer intensive analysis required.

3.3.9.10 Uncertainty in data interpretation

It should be recognised that there will always be an element of uncertainty in the interpretation of site characterisation data. This needs to be acknowledged in the reporting and quantified where possible. The significance of the uncertainty and methods of reducing it should also be explained to stakeholders. There are three aspects to site characterisation data uncertainty:

- *Conceptual model uncertainty*. The initial conceptual model of the site will have formed the basis for identification of potential pollutant linkages and for the design of the survey. The site characterisation will have focused on reducing those uncertainties in the preliminary conceptual model that are of greatest significance to possible adverse impacts on receptors. Nevertheless, some residual uncertainty will remain at the end of the site characterisation process. For example, there may be uncertainty regarding the presence of preferential flowpaths at the site (perhaps associated with sub-surface services or made ground). Areas of remaining uncertainty should be identified for phased investigation or other potential uncertainty reducing measures such as increased numbers of samples, real-time data collection to identify target areas or use of the Triad approach. The greater the natural or inherent variation in residual radioactivity, the greater the uncertainty associated with a decision based on the survey results.
- *Data uncertainty*. Only a very small fraction of the site will have been directly sampled. It is important to evaluate the extent to which data obtained are representative of the site. Key issues to consider for the acquired data are set out in Table 3.34. The unanswered question is: “How well do the survey results represent the true level of residual radioactivity in the survey unit?”
- *Measurement errors*. These create uncertainty by masking the true level of residual radioactivity and may be classified as random or systematic errors. Random errors affect the precision of the measurement system, and show up as variations among repeated measurements. Systematic errors show up as measurements that are biased to give results that are consistently higher or lower than the true value.

Table 3.27 Key issues in data uncertainty

Area of uncertainty	Potential solutions
Sample heterogeneity (sub-sampling errors: see Section 3.4).	Ensure representative sample mixing, splitting etc.
Spatial variability of the parameter being measured.	Optimised contaminated land investigation approach (design).
Systematic measurement biases (gross alpha/beta analysis of soil: see Section 3.4 and 0).	Use laboratory practices to reduce uncertainty.

3.3.9.11 Number of quality control measurements

The number of QC measurements is determined by the available resources and the degree to which one needs assurance that a measurement process is adequately controlled. The process is simplified, for example, when the scope of a survey is narrowed to a single method, one sampling crew, and a single laboratory to analyze field samples. Increasing the number of samples and scheduling sample collections and analyses over time or at different laboratories increases the level of difficulty and necessitates increasing the number of QC measurements. The number of QC measurements may also be driven upward as the action level approaches a given instrument’s detection limit. This number is determined on a case-by-case basis, where the specific contaminant and instruments are assessed for detecting a particular radionuclide.

A widely used standard practice is to collect a set percentage, such as 5%, of samples for QA purposes [99]. However, this practice has disadvantages. For example, it provides no real assessment of the uncertainties for a relatively small sample size. For surveys where the required number of measurements increases, there may be a point beyond which there is little added value in performing additional QC measurements. Aside from cost, determining the appropriate number of QC measurements essentially depends on site-specific factors. For example, soil may present a complex and variable matrix requiring many more QC measurements for surface soils than for building surfaces.

A performance based alternative to a set percentage or rule of thumb can be implemented [87]. First, potential sources of error or uncertainty, the likelihood of occurrence, and the consequences in the context of the DQOs should be determined. Then, the appropriate type and number of QC measurements based on the potential error or uncertainty are determined. For example, field replicate samples (*i.e.*, a single sample that is collected, homogenized, and split into equivalent fractions in the field) are used to estimate the combined contribution of several sources of variation. Hence, the number of field replicate samples to be obtained in the study should be dictated by how precise the estimate of the total measurement should be.

Factors influencing this estimate include:

- The number of measurements;
- The number and experience of personnel involved;
- The current and historical performance of sampling and analytical procedures used;
- The variability of survey unit and background reference area radioactivity measurement systems used;
- The number of laboratories used;
- The level of radioactivity in the survey unit (which for a final status survey should be low);
- How close an action level (*e.g.*, DCGL) is to a detection limit (which may represent a greater concern after reducing or removing radionuclide concentrations by remediation).

Table 3.28 Upper confidence limits for the true variance as a function of the number of QC measurements used to determine the estimated variance [87]

Degrees of Freedom*	**Level of Confidence (%)**			
	90	**95**	**97.5**	**99**
2	9.49	19.49	39.21	99.50
5	3.10	4.34	6.02	9.02
10	2.05	2.54	3.08	3.91
15	1.76	2.07	2.40	2.87
20	1.61	1.84	2.08	2.42
25	1.52	1.71	1.91	2.17
30	1.46	1.62	1.78	2.01
40	1.38	1.51	1.64	1.80
50	1.33	1.44	1.61	1.68
100	1.21	1.28	1.35	1.43

* To obtain the necessary number of quality control measurements, add one to the degrees of freedom.

The precision of an estimate of the "true" variance for precision or bias within a survey design depends on the number of degrees of freedom used to provide the estimate. Table

3.28 provides the one-sided upper confidence limits for selected degrees of freedom assuming the results of the measurements are normally distributed. Confidence limits are provided for 90, 95, 97.5, and 99 percent confidence levels. At the stated level of confidence, the “true” variance of the estimate of precision or bias for a specified number of QC measurements will be between zero and the multiple of the estimated variance listed in Table 3.28. For example, for five degrees of freedom one would be 90% confident that the true variance for precision falls between zero and 3.10 times the estimated variance. The number of QC measurements is equal to one greater than the degrees of freedom.

When planning surveys, the number of each type of QC measurement can be obtained from Table 3.28. For example, if the survey objective is to estimate the variance in the bias for a specific measurement system between zero and two times the estimated variance at a 95% confidence level, 15 degrees of freedom or 16 measurements of a material with known concentration (*e.g.*, performance evaluation samples) would be indicated. EURSSEM recommends that the survey objective be set such that the true variance falls between zero and two times the estimated variance. The level of confidence is then determined on a site-specific basis to adjust the number of each type of QC measurement to the appropriate level (*i.e.*, 11, 16, 21 or 31 measurements). The results of the QC measurements are evaluated during the assessment phase of the data life cycle (see Section 3.10.8 and Section 2.13).

Example 3.13: A contaminated site with ^{60}Co and consisting of four Class 1 interior survey units

A site is contaminated with ^{60}Co and consists of four Class 1 interior survey units, nine Class 2 interior survey units, two Class 3 interior survey units, and one Class 3 exterior survey unit. Three different measurement systems are specified in the survey design for performing scanning surveys, one measurement system is specified for performing direct measurements for interior survey units, and one measurement system is specified for measuring samples collected from the exterior survey unit.

Repeated measurements are used to estimate precision. For scan surveys there is not a specified number of measurements. 10% of the scans in each Class 1 survey unit were repeated as replicates to measure operator precision (see Section 3.3.9.2) within 24 hours of the original scan survey. 5% of each Class 2 and Class 3 survey unit were similarly repeated as replicates to measure operator precision. The results of the repeated scans were evaluated based on professional judgment. For direct measurements and sample collection activities, a 95% confidence level was selected as consistent with the objectives of the survey. Using Table 3.28, it was determined that 16 repeated measurements were required for both the direct measurement technique and the sample collection and laboratory measurement technique. Because 72 direct measurements would be performed in Class 1 survey units, 99 in Class 2 survey units, and 20 in Class 3 survey units, it was anticipated that at least 16 direct measurements would have sufficient activity above background to perform repeated measurements and obtain usable results (see Section 3.5 for guidance on determining the number of measurements. The 16 direct measurement locations to be repeated would be selected based on the results of the direct measurements and would represent the entire usable range of activity found in the survey units rather than measuring the 16 locations with the highest activities. (The usable range of activity includes the highest measurement result in the survey unit and the lowest measurement result with an acceptable measurement uncertainty compared to the desired level of precision.) The repeated measurements would be performed by different operators using the same equipment, but they would not know the results of the original survey. To ensure that the measurements would be valid, the QC measurements to check for contamination would be performed at the same time. Because the laboratory’s QA program called for periodic checks on the precision of the laboratory instruments, the total survey design precision for laboratory measurements was measured. Because the only samples collected would come from a Class 3 area, the sample activities were expected to be close to or below the measurement system MDC. This meant that field replicate samples would not provide any usable information. Also, QC *samples for bias were repeated to obtain a usable estimate of precision for the survey design.*

Measurements of materials with known concentrations above background (e.g., performance evaluation samples) and known concentrations at or below background (e.g., field blanks) are used to estimate bias. For scan surveys, the repeated scanning performed to estimate precision would also serves as a check for contamination using blanks. Because there was no appropriate material of known concentration on which to perform bias measurements, the calibration checks were used to demonstrate that the instruments were reading properly during the surveys. A control chart was developed using the instrument response for an un-calibrated check source. Measurements were obtained using a specified source-detector alignment that could be easily repeated. Measurements were obtained at several times during the day over a period of several weeks prior to taking the instruments into the field. Calibration checks were performed before and after each survey period in the field and the results immediately plotted on the control chart to determine if the instrument was performing properly. This method was also adopted for the direct measurement system. 20 samples were required by the survey design for the Class 3 exterior survey unit. To ensure that the samples were truly blind for the laboratory, samples three times the requested volume were collected. These samples were sent to a second laboratory for preparation. Each sample was weighed, dried, and reweighed to determine the moisture content. Then each sample was ground to a uniform particle size of 1 mm (approximately 16 mesh) and divided into three separate aliquots (each aliquot was the same size). For each sample one aliquot was packaged for transport to the laboratory performing the analysis. After these samples were packaged, 16 of the samples had both of the remaining aliquots spiked with the same level of activity using a source solution traceable to the National Institute of Science and Technology (NIST). The 16 samples each had a different level of activity within a range that was accepted by the laboratory performing the analysis. These 32 samples were also packaged for transport to the laboratory. In addition, 16 samples of a soil similar to the soil at the site were prepared as blanks to check against contamination. The 20 samples, 32 spikes, and 16 blanks were transported to the laboratory performing the analyses in a single shipment so that all samples were indistinguishable from each other except by the sample identification.

3.3.9.12 Controlling sources of error

During the performance of a survey, it is important to identify sources of error and uncertainty early in the process so that problems can be resolved. The timing of the QC measurements within the survey design can be very important. In order to identify problems as early as possible, it may be necessary to perform a significant number of QC measurements early in the survey. This can be especially important for surveys utilizing an innovative or untested survey design. Survey designs that have been used previously and produced reliable results may be able to space the QC measurement evenly throughout the survey, or even wait to have samples analyzed at the end of the survey, as long as the objectives of the survey are achieved.

For example, a survey design requires a new scanning method to be used for several survey units when there are little performance data available for this technique. To ensure that the technique is working properly, the first few survey units are re-scanned to provide an initial estimate of the precision and bias. After the initial performance of the techniques has been verified, a small percentage of the remaining survey units is re-scanned to demonstrate that the technique is operating properly for the duration of the survey.

Identifying sources of error and uncertainty is only the first step. Once the sources of uncertainty have been identified, they should be minimized and controlled for the rest of the survey. Section 3.10.8 discusses the assessment of survey data and provides guidance on corrective actions that may be appropriate for controlling sources of error or uncertainty after they have been identified.

3.3.10 Radiological and additional surveys or investigations versus timeline

The level of effort associated with the design of the sampling and analysis plan to apply depends on the aim and scope, the complexity of the investigation and on applicable or selected intrusive and non-intrusive characterization methods. Large, complicated sites generally receive a significant amount of effort during the design phase, while smaller sites may not require as much planning. This graded approach defines data quality requirements according to the type of investigations/survey being designed, the risk of making a decision error based on the data collected, and the consequences of making such an error. This approach provides a more effective survey design combined with a basis for judging the usability of the data collected.

In Figure 3.5 the following types of investigations have been defined:

- Preliminary investigation.
- Exploratory investigation.
- Main investigation.
- Supplementary investigation.
- Final investigation.

It is evident that:

- A developed strategy can be applied during different investigations and
- Each investigation can have a different strategy.

In general the radiological and non-radiological characterisations can be divided in six stages of the site survey, remediation and restoration process (see Figure 3.5).

Preliminary investigation	Exploratory investigation	Supplementary investigation(s)	Main investigation	Supplementary investigation(s)	Final investigation

Time →

Figure 3.5 Site characterization and the land time management process timeline

3.3.10.1 Minimum information (results) required from an investigation

The minimum information (results) required from the DQO Process to proceed with the methods described in EURSSEM are:

- Classify and specify boundaries of survey units: this can be accomplished at any time, but must be finalized during final status survey planning (see Section 3.3.2).
- State the null hypothesis (H_0): the residual radioactivity in the survey unit exceeds the release criterion (see 0).
- Specify a gray region where the consequences of decision errors are relatively minor: the upper bound of the gray region is defined as the $DCGL_W$, and the lower bound of the gray region (LBGR) is a site-specific variable generally initially selected to equal one half the $DCGL_W$ and adjusted to provide an acceptable value for the relative shift (see Section 3.5.1.1 and 0).
- Define Type I and Type II decision errors and assign probability limits for the occurrence of these errors: the probability of making a Type I decision error (α) or a Type II decision error (β) are site-specific variables (see 0).

- Estimate the standard deviation of the measurements in the survey unit: the standard deviation (σ) is a site-specific variable, typically estimated from preliminary survey data (see Section 3.9.2.9 and 0).
- Specify the relative shift: the shift (Δ) is equal to the width of the gray region ($DCGL_W$ - LBGR), and the relative shift is defined as Δ/σ, which is generally designed to have a value between one and three (see Section.3.5.1.1 and 0).
- Specify the detection limit for all measurement techniques (scanning, direct measurement, and sample analysis) specified in the QAPP: the minimum detectable concentration (MDC) is unique for each measurement system.
- Calculate the estimated number of measurements (N) and specify the measurement locations required to demonstrate compliance: the number of measurements depends on the relative shift (Δ/σ), Type I and Type II decision error rates (α and β), the potential for small areas of elevated activity, and the selection and classification of survey units (see Section 3.3.2.2 and 0).
- Specify the documentation requirements for the survey, including survey planning documentation: documentation supporting the decision on whether or not the site complies with the release criterion is determined on a site-specific basis.

3.3.10.2 Preliminary investigation or scoping survey

The aim of the preliminary investigation is to compile and evaluate the available information on the potentially contaminated site and a preliminary hazard assessment. Preliminary investigations are conducted nowadays completed before the historical site assessment (HAS) in order to take into account the survey results in the historical site assessment (see Section 2.4).

From these data an initial site conceptual model (or models) may be constructed, which will subsequently be used to design the site investigation phases of work. The model(s) will also be the basis for a hazard assessment and aid development of historical site survey, waste management, quality management plans and communications plans.

A preliminary investigation comprises a desk study and site walk over to establish historical activities, current status, and the environmental setting and may include a limited amount of surface scanning, surface activity measurements, and sample collection (smears, soil, water, vegetation, paint, building materials, subsurface materials). From this information, an initial conceptual model of the site can be formed and potential hazards identified.

For evaluating survey results, the survey data should be converted to the same units as those in which DCGLs are expressed (see Section 3.10.1). Identification of potential radionuclide contaminants at the site is performed using direct measurements or laboratory analysis of samples. The data are compared to the appropriate regulatory DCGLs.

If the results of the survey and of the historical site assessment indicate that an area is Class 3 and no contamination is found, the area may be classified as Class 3 and a Class 3 final status survey is performed. If the scoping survey locates contamination, the area may be considered as Class 1 (or Class 2) for the final status survey and a characterisation survey is typically performed. Sufficient information should be collected to identify situations that require immediate radiological attention

For scoping surveys that potentially serve to release the site from further consideration, the survey design should consist of sampling based on the historical site assessment data and professional judgment. If residual radioactivity is *not* identified during judgment sampling, it may be appropriate to classify the area as Class 3 and perform a final status survey for Class 3 areas. Refer to Section 2.7 and Section 3.3.10.6 for a description of final status surveys. However, collecting additional information during subsequent surveys (*e.g.*, characterization surveys) may be necessary to make a final determination as to area classification.

3.3.10.3 Exploratory investigation

An exploratory investigation may be necessary, particularly where the preliminary investigation has found little or ambiguous information and there is a high degree of uncertainty. Non-intrusive investigation techniques, such as surface radiation surveys, are very useful at this stage. It is used to test areas of greatest uncertainty with respect to the conceptual model of contamination and site characteristics. The additional information provided aids to the design of the main investigation and enables historical site survey requirements to be specified. Sufficient information may be provided to update the risk assessment, for example, by eliminating a particular pollutant linkage because a pathway no longer exists. This phase is optional and is mostly seen as an opportunity to gather a limited amount of additional information in order to plan the main (detailed) investigation.

3.3.10.4 Main investigation or characterisation survey

Main investigation or characterization survey provides detailed information on the horizontal and vertical distribution of radioactive contamination, together with geological, geotechnical and hydro-geological information. Surface surveys may also be required to provide, for example, ecological and hydrological data. Supplementary investigations may be necessary to produce specific information on areas of uncertainty not resolved by the main phase, information required to clarify technical matters related to remedial and restoration options, or for validation studies.

For areas classified as Class 1 or Class 2, a characterization survey is warranted. The main investigation or characterization survey should be planned based on the historical site assessment, scoping and exploratory surveys.

The characterization survey is the most comprehensive of all the survey types and generates the most data. These characterisation objectives should include:

- Determining the nature and extent of radiological contamination.
- Evaluating remediation alternatives, e.g., unrestricted use, restricted use, on-site disposal, off-site disposal, etc.
- Input to pathway analysis/dose or risk assessment models for determining site-specific DCGLs (Bq/kg, Bq/m^2).
- Estimating the occupational and public health and safety impacts during remediation / decommissioning.
- Surveys of different media, e.g., surface soils, interior and exterior surfaces of buildings.
- Preparing a reference grid.
- Systematic as well as judgment measurements.
- Evaluating remediation technologies.
- Input to final status survey design.

The decision as to which media will be surveyed is a site-specific decision addressed throughout the Radiation Survey and Site Investigation Process.

In more detail, results of characterisation surveys should include:

- The identification and distribution of contaminants in surface and subsurface soils.
- The distribution and concentration of contaminants in surface water, groundwater, and sediments.
- The identification and distribution of contamination pavement, buildings, structures, and other site facilities.

- The distribution and concentration of contaminants in other impacted media such as vegetation or paint.
- The survey should also identify the portions of the site that have not been affected by these activities and where no remediation is anticipated.
- Sufficient information on the physical characteristics of the site, including surface features, meteorology and climatology, surface water hydrology, geology, demography and land use, and hydrogeology.
- When planning for the potential use of characterization survey data as part of the final status survey, the characterization data must be of sufficient quality and quantity for that use (see Section 3.3.9 and Section 3.5).
- This survey should also address environmental conditions that could affect the rate and direction of contaminant transport in the environment, depending on the extent of contamination identified above.

The design of the site characterization or investigation survey is based on the specific DQOs for the information to be collected, and is planned using the historical site assessment, scoping survey, expletory investigation results. The DQO process ensures that an adequate amount of data with sufficient quality is collected for the purpose of characterization. The site characterization process typically begins with a review of the historical site assessment, which includes available information on site description, operational history, and the type and extent of contamination (from the scoping survey, if performed). The site description, or conceptual site model as first developed in Section 2.4.9, consists of the general area, dimensions, and locations of contaminated areas on the site. A site map should show site boundaries, roads, hydro-geologic features, major structures, and other features that could affect decommissioning activities.

Note that because of site-specific characteristics of contamination, performing all types of measurements described here may not be relevant at every site. For example, detailed characterization data may not be needed for areas with contamination well above the DCGLs that clearly require remediation. Judgment should be used in determining the types of characterization information needed to provide an appropriate basis for decontamination decisions.

By conducting a survey, the selection of survey instrumentation and analytical techniques are typically based on a knowledge of the appropriate DCGLs, because remediation decisions are made based on the level of the residual contamination as compared to the DCGL. Exposure rate measurements may be needed to assess occupational and public health and safety. The location of underground utilities should be considered before conducting a survey to avoid compounding the problems at the site.

The applied measuring and sampling techniques should be commensurate with the intended use of the data, as characterization survey data may be used to supplement final status survey data, provided that the data meet the selected DQOs.

Characterization surveys for surface and subsurface soils and media involve employing techniques to determine the lateral and vertical extent and radionuclide concentrations in the soil. This may be performed using either sampling and laboratory analyses, or *in-situ* gamma spectrometry analyses, depending on the detection capabilities of each methodology for the expected contaminants and concentrations. Note that *in-situ* gamma spectrometry analyses or any direct surface measurement cannot easily be used to determine vertical distributions of radio-nuclides. Sample collection followed by laboratory analysis introduces several additional sources of uncertainty that need to be considered during survey design. In many cases, a combination of direct measurements and samples is required to meet the objectives of the survey.

Radio-nuclide concentrations in background soil samples should be determined for a sufficient number of soil samples that are representative of the soil in terms of soil type, soil depth, *etc*. It is important that the background samples be collected in non-impacted areas. Consideration should be given to spatial variations in the background radionuclide concentrations.

Surface water and sediment sampling may be necessary depending on the potential for these media to be contaminated. The contamination potential depends on several factors, including the proximity of surface water bodies to the site, size of the drainage area, total annual rainfall, and spatial and temporal variability in surface water flow rate and volume. Refer to Section 2.4.8.6 for further consideration of the necessity for surface water and sediment sampling.

For the evaluation of the characterisation survey data, these data should be converted to the same units as those in which DCGLs are expressed. Identification of potential radionuclide contaminants at the site is performed through laboratory and *in-situ* analyses. Appropriate regulatory DCGLs for the site are selected and the data are then compared to the DCGLs. For characterization data that are used to supplement final status survey data, the statistical methodology in Section 3.10 should be followed to determine if a survey unit satisfies the release criteria.

For characterization data that are used to help guide remediation efforts, the characterization survey data are used to identify locations and general extent of residual activity. The survey results are first compared with DCGLs. Surfaces and environmental media are then differentiated as exceeding DCGLs, not exceeding DCGLs, or not contaminated, depending on the measurement results relative to the DCGL value. Direct measurements indicating areas of elevated activity are further evaluated and the need for additional measurements is determined.

The documentation of a site characterization survey should provide a complete and unambiguous record of the radiological status of the site. In addition, sufficient information to characterize the extent of contamination, including all possible affected environmental media, should be provided in the report. This report should also provide sufficient information to support reasonable approaches or alternatives to site decontamination.

3.3.10.5 Supplementary investigation or remedial action support survey

Supplementary investigations or remedial action support surveys are optional and can be performed to support comparison of options and implementation of preferred remediation and restoration options.

The remedial action support survey typically relies on a simple radiological parameter, such as direct radiation near the surface, as an indicator of effectiveness. The investigation level (the level below which there is an acceptable level of assurance that the established DCGLs have been attained) is determined and used for immediate, in-field decisions (see Section 3.3.2.7). Such a remedial action survey is intended for expediency and cost effectiveness and does not provide thorough or accurate data describing the radiological status of the site. Note that this survey does not provide information that can be used to demonstrate compliance with the DCGLs and is an interim step in the compliance demonstration process. Areas that are determined to satisfy the DCGLs on the basis of the remedial action support survey will then be surveyed in detail by the final status survey. Alternatively, the remedial action support survey can be designed to meet the objectives of a final status survey as described in Section 2.7 and Section 3.3.10.6. DCGLs may be recalculated based on the results of the remediation process as the regulatory program allows or permits.

A remedial action support survey is performed while remediation is being conducted, and guides the clean-up in a real-time mode.

A remedial action support surveys are conducted:

- To support remediation activities.

- To serve to monitor the effectiveness of decontamination efforts that are intended to reduce residual radioactivity at or below the DCGL criteria.
- To guide the clean-up in a real-time mode.
- To determine when a site or survey unit is ready for the final status survey.
- To provide updated estimates of site-specific parameters used for planning the final status survey.

The determination that a survey unit is ready for a final status survey following remediation is an important step in the Radiation Survey and Site Investigation Process. In addition, remedial activities result in changes to the distribution of contamination within the survey unit. For most survey units, the site-specific parameters used during final status survey planning (*e.g.*, variability in the radionuclide concentration, probability of small areas of elevated activity) will need to be re-established following remediation. Obtaining updated values for these critical parameters should be considered when planning a remedial action support survey.

There will be radio-nuclides and media that cannot be evaluated at the $DCGL_W$ using field monitoring techniques. For these cases, it may be feasible to collect and analyze samples by methods that are quicker and less costly than radionuclide-specific laboratory procedures. Field laboratories and screening techniques may be acceptable alternatives to more expensive analyses. Reviewing remediation plans may be required to get an indication of the location and amount of remaining contamination following remediation.

Field survey instruments and procedures should be selected based on their detection capabilities for the expected contaminants and their quantities. Survey methods typically include scans of surfaces followed by direct measurements to identify residual radioactivity. The residual surface activity levels can be expected to be comparible to the DCGLs, and a determination should be made on the need for further decontamination efforts.

Survey activities for soil excavations include surface scans using field instrumentation that should be sensitive to beta and gamma activity. Because it is difficult to correlate scanning results to radionuclide concentrations in soil, and especially with a multi radionuclide contamination, judgment should be carefully exercised when using scan results to guide the clean-up efforts. Field laboratories and screening techniques may provide a better approach for determining whether or not further soil remediation is necessary.

If results of these survey activities indicate that remediation has been successful in meeting the DCGLs, decontamination efforts can be ceased and final status survey activities can be initiated. Further remediation may be needed if results indicate the presence of residual activity in excess of the DCGLs.

The remedial action support survey is intended to guide the clean-up and alert those performing remedial activities that additional remediation is needed or that the site may be ready to initiate a final survey. Data that indicate an area has been successfully remediated could be used to estimate the variance for the survey units in that area. Information identifying areas of elevated activity that existed prior to remediation may be useful for planning final status surveys.

3.3.10.6 Final investigation or final status survey

The final investigation or final status survey is used to demonstrate compliance with release criteria and regulations.

The primary objectives of the final status survey are:

- To select/verify survey unit classification.

- To demonstrate that the potential dose or risk from residual contamination is below the release criterion for the site and/or for each survey unit and meets the release criterion.
- To demonstrate that the potential dose or risk from small areas of elevated activity is below the release criterion for the site and/or for each survey unit and meets the release criterion.
- The final investigation or final status survey provides data to demonstrate that all radiological parameters satisfy the established guideline values and conditions.

Although the final status survey is discussed as if it were an activity performed at a single stage of the site investigation process, this does not have to be the case. Data from other surveys conducted during the Radiation Survey and Site Investigation Process - such as scoping, characterization, and remedial action support surveys - can provide valuable information for planning a final status survey provided they are of sufficient quality.

Professional judgment and biased sampling are important for locating contamination and characterizing the extent of contamination at a site.

The design process of a final status survey begins with the development of data quality objectives (DQOs) and the null and alternative hypotheses should be clearly stated. On the basis of these objectives, hypotheses and the known or anticipated radiological conditions at the site, the numbers and locations of measurement and sampling points used to demonstrate compliance with the release criterion are then determined. Note: the null hypothesis (H_o) tested is that residual contamination exceeds the release criterion; the alternative hypothesis (H_a) is that residual contamination meets the release criterion.

It is advised that by planning the final status survey early discussions are organised with the regulatory agency concerning logistics for confirmatory or verification surveys.

The final step of the DQO process includes selecting the optimal design that satisfies the DQOs. For some sites or survey units, the guidance provided in this section may result in a survey design that cannot be accomplished with the available resources. For these situations, the planning team will need to relax one or more of the constraints used to develop the survey design as described in Section 2.7.

At the data evaluation of final status surveys two statistical tests are used. For contaminants that are present in background, the Wilcoxon Rank Sum (WRS) test is advised. When contaminants are not present in background, the Sign test is advised.

To determine data needs for these tests, the acceptable probability of making Type I decision errors (α) and Type II decision errors (β) should be established (see Section 2.7 and 0, Section A.2). The acceptable decision error rates are a function of the amount of residual radioactivity and are determined during survey planning using the DQO Process. The evalution of survey results may cause that additional data and/or additional remediation and/or resurvey may be necessary. The scope of further actions should be agreed upon and developed as part of the data quality objective process before any action begins.

Documentation of the final status survey should provide a complete and unambiguous record of the radiological status of the survey unit, relative to the established DCGLs. In addition, sufficient data and information should be provided to enable an independent re-creation and evaluation at some future time. Much of the information in the final status report will be available from other decommissioning documents; however, to the extent practicable, this report should be a stand-alone document with minimum information incorporated by reference. The report should be independently reviewed (see Section 3.10.8) and should be approved by a designated person (or persons), who is capable of evaluating all aspects of the report prior to release, publication, or distribution.

3.3.10.7 Confirmatory or verification survey

A confirmatory survey (also known as an independent verification survey), may be performed by the responsible regulatory agency or by an independent third party (e.g., contracted by the regulatory agency) to provide data to substantiate results of the final status survey.

Another purpose of the confirmatory activities may be to identify any deficiencies in the final status survey documentation based on a thorough review of survey procedures and results. Independent confirmatory survey activities are usually limited in scope to spot-checking conditions at selected locations, comparing findings with those of the final status survey, and performing independent statistical evaluations of the data developed from the confirmatory survey and the final status survey.

3.3.10.8 Decisions based on investigation results

Compliance demonstration is simply a decision as to whether or not an investigation/survey unit meets the release criterion. For most sites this decision is based on the results of one or more surveys. When survey results are used to support a decision, the decision maker[18] needs to ensure that the data will support that decision with satisfactory confidence.

Usually a decision maker will make a correct decision after evaluating the data. However, since uncertainty in the survey results is unavoidable, the possibility of errors in decisions supported by survey results is unavoidable. For this reason, positive actions must be taken to manage the uncertainty in the survey results so that sound, defensible decisions may be made. These actions include proper survey planning to control known causes of uncertainty, proper application of quality control (QC) procedures during implementation of the survey plan to detect and control significant sources of error, and careful analysis of uncertainty before the data are used to support decision making.

Decisions are made, in coordination with the stakeholders, e.g., responsible regulatory agency, based on the conclusions drawn from the assessment process. The ultimate objective is to make technically defensible decisions with a specified level of confidence.

3.3.11 Site preparation prior to remediation actions

Site preparation involves obtaining consent for performing the survey, establishing the property boundaries, evaluating the physical characteristics of the site, accessing surfaces and land areas of interest, and establishing a reference coordinate system. Site preparation may also include removing equipment and materials that restrict access to surfaces. The presence of furnishings or equipment will restrict access to building surfaces and add additional items that the survey should address.

3.3.11.1 Consent for characterisation survey

When facilities or sites are not owned by the organization performing the surveys, consent from the site or equipment owner should be obtained before conducting the surveys. All appropriate local, state, and federal officials as well as the site owner and other affected parties should be notified of the survey schedule. Section 2.4.7 discusses consent for access of a site.

3.3.11.2 Property bondaries

Property boundaries may be determined from property survey maps furnished by the owners or from plat maps obtained from city or county tax maps. Large-area properties and

[18] The term decision maker is used throughout this section to describe the person, team, board, or committee responsible for the final decision regarding disposition of the survey unit.

properties with obscure boundaries or missing survey markers may require the services of a professional land surveyor.

If the radiological survey is only performed inside buildings, a tax map with the buildings accurately located will usually suffice for site/building location designation.

3.3.11.3 Physical characteristics

The physical characteristics of the site will have a significant impact on the complexity, schedule, and cost of a survey. These characteristics include the number and size of structures, type of building construction, wall and floor penetrations, pipes, building condition, total area, topography, soil type, and ground cover. In particular, the accessibility of structures and land areas (see Section 2.4.9 and Section 3.3.2.2) has a significant impact on the survey effort. In some cases survey techniques (e.g., in situ gamma spectrometry discussed in Sections 3.3.7, 3.4.2.4 and 3.6.2.3 can preclude or reduce the need to gain physical access or use intrusive techniques. This should be considered during survey planning.

Land areas

Depending upon site processes and operating history, the radiological survey may include varying portions of the land areas. Potentially contaminated open land or paved areas to be considered include storage areas (*e.g*., equipment, product, waste, and raw material), liquid waste collection lagoons and sumps, areas downwind (based on predominant wind directions on an average annual basis, if possible) of stack release points, and surface drainage pathways. Additionally, roadways and railways that may have been used for transport of radioactive or contaminated materials that may not have been adequately contained could also be potentially contaminated.

Buried piping, underground tanks, sewers, spill areas, and septic leach fields that may have received contaminated liquids are locations of possible contamination that may necessitate sampling of subsurface soil (see Section 3.4). Information regarding soil type (*e.g*., clay, sand) may provide insight into the retention or migration characteristics of specific radionuclides. The need for special sampling by coring or split-spoon equipment should be anticipated for characterization surveys.

If radioactive waste has been removed, surveys of excavated areas will be necessary before backfilling. If the waste is to be left in place, subsurface sampling around the burial site perimeter to assess the potential for future migration may be necessary.

Additionally, potentially contaminated rivers, harbours, shorelines, and other outdoor areas may require survey activities including environmental media (*e.g*., sediment, marine biota) associated with these areas.

Structures on site

Building design and condition will have a marked influence on the survey efforts. The time involved in conducting a survey of building interior surfaces is essentially directly proportional to the total surface area. For this reason the degree of survey coverage decreases as the potential for residual activity decreases. Judgment measurements and sampling, which are performed in addition to the measurements performed for the non-parametric tests, are recommended in areas likely to have accumulated deposits of residual activity. As discussed in Section 3.3.2.8, Section 3.3.10.4 and Section 3.10, judgment measurements and samples are compared directly to the appropriate DCGL.

The condition of surfaces after decontamination may affect the survey process. Removing contamination that has penetrated a surface usually involves removing the surface material. As a result, the floors and walls of decontaminated facilities are frequently badly scarred or broken up and are often very uneven. Such surfaces are more difficult to survey because it is not possible to maintain a fixed distance between the detector and the surface. In addition, scabbled or porous surfaces may significantly attenuate radiations - particularly alpha and low-energy beta particles. Use of monitoring equipment on wheels is precluded by rough surfaces, and such surfaces also pose an increased risk of damage to fragile detector probe faces. These factors should be considered during the calibration of survey instruments; NRC report NUREG-1507 provides additional information on how to address these surface conditions [79]. The condition of the building should also be considered from a safety and health standpoint before a survey is conducted. A structural assessment may be needed to determine whether the structure is safe to enter.

Expansion joints, stress cracks, and penetrations into floors and walls for piping, conduit, and anchor bolts, etc., are potential sites for accumulation of contamination and pathways for migration into sub-floor soil and hollow wall spaces. Drains, sewers, and septic systems can also become contaminated. Wall/floor interfaces are also likely locations for residual contamination. Coring, drilling, or other such methods may be necessary to gain access for survey. Intrusive surveying may require permitting by local regulatory authorities. Suspended ceilings may cover areas of potential contamination such as ventilation ducts and fixtures.

Exterior building surfaces will typically have a low potential for residual contamination. However, there are several locations that should be considered during survey planning. If there are roof exhausts, roof accesses that allow for radioactive material movement, or the facility is proximal to the air effluent discharge points, the possibility of roof contamination should be considered. Because roofs are periodically resurfaced, contaminants may be trapped in roofing material, and sampling this material may be necessary. Roof drainage points such as drip-lines along overhangs, downspouts, and gutters are also important survey locations. Wall penetrations for process equipment, piping, and exhaust ventilation are potential locations for exterior contamination. Window ledges and outside exits (doors, doorways, landings, stairways, *etc.*) are also building exterior surfaces that should be addressed.

3.3.11.4 Clearing to provide access

In addition to the physical characteristics of the site, a major consideration is how to address inaccessible areas that have a potential for residual radioactivity. Inaccessible areas may need significant effort and resources to adequately survey. This section provides a description of common inaccessible areas that may have to be considered. The level of effort expended to access these difficult-to-reach areas should be commensurate with the potential for residual activity. For example, the potential for the presence of residual activity behind walls should be established before significant effort is expended to remove drywall.

Land Areas

If ground cover needs to be removed or if there are other obstacles that limit access by survey personnel or necessary equipment, the time and expense of making land areas accessible should be considered. In addition, precautionary procedures need to be developed to prevent spreading surface contamination during ground cover removal or the use of heavy equipment.

Removal or relocation of equipment and materials that may entail special precautions to prevent damage or maintain inventory accountability should be performed by the property owner whenever possible. Clearing open land of brush and weeds will usually be performed by a professional land-clearing organization under subcontract arrangements. However, survey personnel may perform minor land-clearing activities as needed.

An important consideration prior to clearing is the possibility of bio-uptake and consequent radiological contamination of the material to be cleared. Special precautions to avoid exposure of personnel involved in clearing activities may be necessary. Initial radiological screening surveys should be performed to ensure that cleared material or equipment is not contaminated.

The extent of site clearing in specific areas depends primarily on the potential for radioactive contamination existing in those areas where: 1) the radiological history or results of previous surveys do not indicate potential contamination of an area (it may be sufficient to perform only minimum clearing to establish a reference coordinate system); 2) contamination is known to exist or a high potential for contamination necessitates completely clearing an area to provide access to all surfaces; and 3) new findings as the survey progresses may indicate that additional clearing be performed.

Open land areas may be cleared by heavy machinery (*e.g.*, bulldozers, bush-hogs, and hydro-axes). However, care should be exercised to prevent relocation of surface contamination or damage to site features such as drainage ditches, utilities, fences, and buildings. Minor land clearing may be performed using manually operated equipment such as brush-hooks, power saws, knives, and string trimmers. Brush and weeds should be cut to the minimum practical height necessary to facilitate measurement and sampling activities (approximately 15 cm). Care should be exercised to prevent unnecessary damage to or removal of mature trees or shrubs.

Potential ecological damage that might result from an extensive survey should be considered. If a survey is likely to result in significant or permanent damage to the environment, appropriate environmental analyses should be conducted prior to initiating the survey. In addition, environmental hazards such as poison ivy, ticks carrying Lyme disease, and poisonous snakes, spiders, or insects should be noted. These hazards can affect the safety and health of the workers as well as the schedule for performing the survey

Structures

Structures and indoor areas should be sufficiently cleared to permit completion of the survey. Clearing includes providing access to potentially contaminated interior surfaces (*e.g.*, drains, ducting, tanks, pits, ceiling areas, and equipment) by removing covers, disassembly, or other means of producing adequate openings.

Building features such as ceiling height, construction materials, ducts, pipes, etc., will determine the ease of accessibility of various surfaces. Scaffolding, cranes, lifts, or ladders may be necessary to reach some surfaces, and dismantling portions of the building may be required.

The presence of furnishings and equipment will restrict access to building surfaces and add additional items that the survey should address. Remaining equipment indirectly involved in the process may need to be dismantled in order to evaluate the radiological status, particularly of inaccessible parts of the equipment. Removing or relocating certain furnishings, such as lab benches and hoods, to obtain access to potentially contaminated floors and walls may also be necessary. The amount of effort and resources dedicated to such removal or relocation activities should be commensurate with the potential for contamination. Where the potential is low, a few spot-checks may be sufficient to provide confidence that covered areas are free of contamination. In other cases, complete removal may be warranted.

Piping, drains, sewers, sumps, tanks, and other components of liquid handling systems present special difficulties because of the inaccessibility of interior surfaces. Process information, operating history, and preliminary monitoring at available access points will assist in evaluating the extent of sampling and measurements included in the survey.

If the building is constructed of porous materials (*e.g.*, wood, concrete) and the surfaces were not sealed, contamination may be found in the walls, floors, and other surfaces. It may be necessary to obtain cores of these surfaces for laboratory analysis.

Another accessibility problem is the presence of contamination beneath tile or other floor coverings. This often occurs because the covering was placed over contaminated surfaces, or the joints in tile were not sealed to prevent penetration. The practice in some facilities has been to “fix” contamination (particularly alpha emitters) by painting over the surface of the contaminated area. Thus, actions to obtain access to potentially contaminated surfaces, such as removing wall and floor coverings (including paint, wax, or other sealer) and opening drains and ducts, may be necessary to enable representative measurements of the contaminant. If alpha radiation or very low energy beta radiation is to be measured, the surface should be free of overlying material, such as dust and water, which may significantly attenuate the radiations.

3.3.12 Regulatory confirmation and verification

The regulator responsible for the site often confirms whether the site is acceptable for release (see also Section 3.12). This confirmation may be accomplished by the agency or an impartial party. Although some actual measurements may be performed, much of the work required for confirmation and verification will involve evaluation and review of documentation and data from survey activities. The evaluation may include site visits to observe survey and measurement procedures or split-sample analyses by the regulatory agency's laboratory.

Therefore, accounting for confirmation and verification activities during the planning stages is important to each type of survey. In some cases, post-remedial sampling and analysis may be performed by an impartial party. The review of survey results should include verifying that the data quality objectives are met, reviewing the analytical data used to demonstrate compliance, and verifying that the statistical test results support the decision to release the site. Confirmation and verification are generally ongoing processes throughout the Radiation Survey and Site Investigation (RSSI) Process.

3.4 Site characterisation: Samples

3.4.1 Introduction

Consideration must be given to the different types of samples and their sampling requirements of the different media present on a site. Radioactive contamination may be restricted to the soil layer. It may also behave differently in the vadose and saturated layers. Rock or clay layers may be impenetrable to radioactivity or may bind radioactivity.

Measurements in "secondary" media, i.e., other than those containing the main contaminant, may give useful information on the distribution or presence of activity. Biota which concentrate activity may help in detecting the presence of radionuclides which are otherwise buried or at low concentrations. Emanation of gases (radon, tritium) from buried sources can help determine the presence of radioactivity. Most of these measurements should be regarded as qualitative rather than quantitative, but they prove valuable in early stages of characterization to identify areas for further investigation.

Guidance is given on radiological, biological, soil, liquid and gas sample collection, and the growing area of real-time data collection using sensing techniques.

In each case, it has to be considered for each sample or real-time data collection of samples what is its beneficial value/added information for the conceptual model(s), site characterisation and remediation objectives. This can be achieved by considering the conceptual model(s) and asking a question such as:

- For what principal pathways in the conceptual model(s) is this sample needed?

The analyses results of the sample(s) may also help to give an answer on other questions such as:

- For the principal mechanisms of contamination at the site, what are the typical sizes and spacing’s of the source areas?
- How mobile are the contaminants? For example, is it possible that a contaminant in the soil will also contaminate groundwater?

- How deep are the contaminants likely to penetrate into the sub-surface environment?
- What are the objectives of the site investigation, and what is the required level of confidence in the results?
- If remediation was required, what "averaging volume" would be used for waste characterisation? This issue is of greatest importance on sites where contamination is heterogeneously distributed (i.e., "hot spots" and "cold spots" are present).

Therefore, this section deals also with the concept of "radioactively contaminated sites" and give detail information about possible sources of contamination, radionuclides of concern and their behaviour in specific environments.

As investigations will be performed with different scopes (see Figure 3.4), requirements for samples will also differ. Therefore attention is given to key considerations for sampling of:

- Dose rates.
- Alpha and beta emitting radionuclides.
- Photon emitting radionuclides.
- Neutron emitting radionuclides.
- Biological samples.
- Soil and rock samples.
- Liquid samples.
- Gas samples.

The last topic to deal with in this section in the design process of a field-based site characterization is the selection of sampling locations, patterns and frequencies. The more general considerations are dealt with in a separated section while if they are only valid for a certain sample, this information is presented together with the other sample key considerations.

3.4.2 Samples

3.4.2.1 Introduction

This section provides guidance on developing appropriate sample collection procedures for surveys designed to demonstrate compliance with a dose- or risk-based regulation. Sample collection procedures are concerned mainly with ensuring that a sample is representative of the sample media, is large enough to provide sufficient material to achieve the desired detection limit, and is consistent with assumptions used to develop the conceptual site model and the from this model Derived Concentration Guideline Levels (DCGLs).

Proper sample preparation and preservation are essential parts of any radioactivity sampling program. The sampling objectives should be specified before sampling activities begin. Precise records of sample collection and handling are necessary to ensure that data obtained from different locations or time frames are correctly compared.

The appropriateness of sample preparation techniques is a function of the analysis to be performed. Field sample preparation procedures are a function of the specified analysis and the objectives of the survey. It is essential that these objectives be clearly established and agreed upon in the early stages of survey planning (see Section 3.3).

3.4.2.2 Dose rate

External dose can be assessed by using passive devices, which integrate the gamma radiation over the measurement period, such as thermoluminescence dosimeters (TLDs), the film badge and track etch. A device that possesses both active and passive qualities is the electronic dosimeter.

A typical TLD can detect radiation level approximately at 0.005 uGy/h but, at least one month exposure time is necessary. If all infrastructures for performing TLD measurements exist, it is an inexpensive methodology since the detector itself is of low cost (and re-useable). Its disadvantage is the long period of exposure required and special care is needed so as not to lose the TLD during the exposure time in an unguarded area. Film badges have similar properties but are more sensitive to the environment in which they are deployed (temperature, humidity) and require greater care and a larger facility for preparation and analysis.

3.4.2.3 Alpha and beta emitting radionuclides

Due to their properties, in-situ detection of alpha and beta emitters is very difficult and often only qualitative. In fact, very few portable detection systems exist for either of these types of emitters and they are often extremely radionuclide specific.

Laboratory sample preparation for alpha emitting radio-nuclides is similar to that for beta emitting radio-nuclides. Sample dissolution and purification tasks are also similar to those performed for beta emitting radionuclides.

Laboratory sample preparation is an important step in the analysis of surface soil and other solid samples for beta emitting radionuclides. The laboratory will typically have a sample preparation procedure that involves drying the sample and grinding the soil so that all of the particles are less than a specified size to provide a homogeneous sample. A small portion of the homogenized sample is usually all that is required for the individual analysis.

Once the sample has been prepared, a small portion is dissolved, fused, or leached to provide a clear solution containing the radionuclide of interest. The only way to ensure that the sample is solubilised is to completely dissolve the sample. However, this can be an expensive and time-consuming step in the analysis. In some cases, leaching with strong acids can consistently provide greater than 80% recovery of the radionuclide of interest and may be acceptable for certain applications. Gross beta measurements may be performed on material that has not been dissolved.

3.4.2.4 Photon emitting radionuclides

Energy specific measurements of gamma radiation are of use if identification of the isotopes present at a site is a requirement. It may help if measurements of a specific isotope are required against a background, possibly varying with time or position, of another radionuclide (such as naturally occurring radium or ^{40}K).

Although simple instruments may be valuable in locating or delineating areas of high activity, at levels near to the natural background they must be used with care if statistical counting effects or local variations in background are not to be misinterpreted as variation in contaminant. It may be the case that integration times of simple instruments have to be set sufficiently long that spectrometric methods could give a more accurate result in less time. It must be emphasized that background radiation levels can vary rapidly, not only spatially but also with time due to changes in solar radiation or due to radon releases from the ground changing with atmospheric pressure.

As an example, if there is a known area of contamination on a site, staff may be instructed not to survey in detail the area of most concentrated contamination, but to explore the outer limits of contamination so as to be able to delineate the extent of the contaminated area.

Figure 3.6 shows a typical in-situ gamma spectrometry measurement with the detector placed at 1 meter above the soil surface. At this height, 85-90% of the gamma radiation detected is originating from a circle with radius of 10 meter from the detector. The in-situ gamma spectrometer will depending on its design, at a height of 1 meter, effectively detect radionuclides to a depth of up to 15-50 cm. The effective area observed by this detector (> ~300 m^2) may, in fact, give a more representative picture of contamination than conventional sampling and analysis.

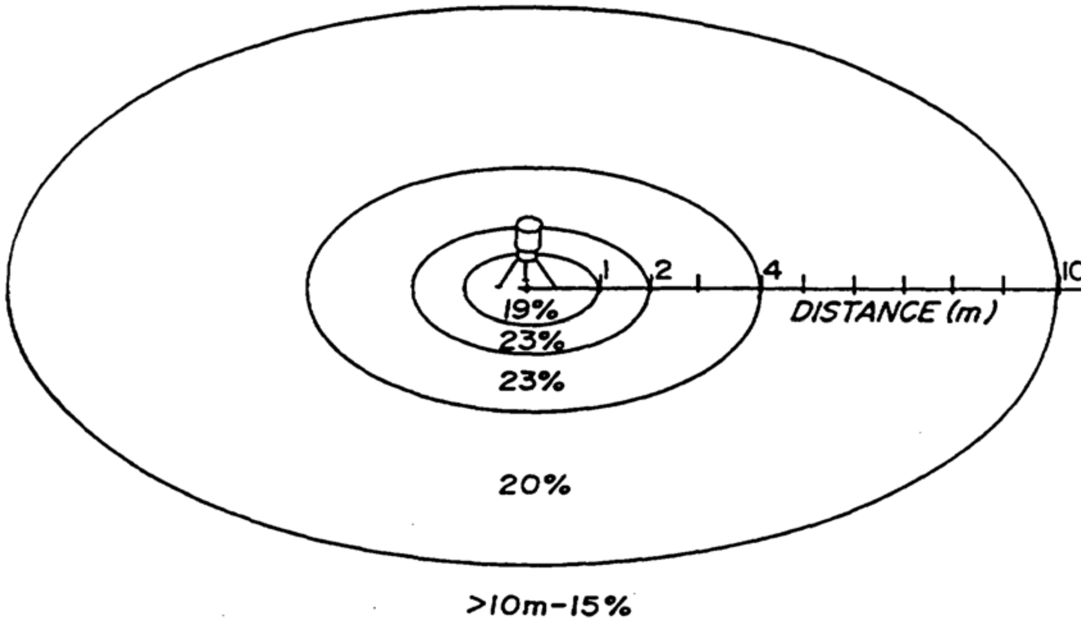


Figure 3.6 Area observed by an in-situ gamma ray spectrometer at 1 m above the ground. Depicted is the percent contribution to total 662 keV primary flux for a typical ^{137}Cs source distribution from past atmospheric weapons testing fall-out

It should be mentioned first that there are limitations in using in-situ spectrometry. Due to the nature of radionuclide transport through matter (soil and air) and to the attenuation of ionising radiation, in-situ spectrometry is, for the most part, limited to the measurement of gamma rays and some X-ray emitters.

The ideal site for collecting a gamma spectrum is a large (20 m diameter or more) fiat, open area with little or no natural or man-made obstruction. For standard measurements, the height of the detector above the ground is an important parameter. One meter is often chosen for reasons of convenience; the higher the detector the greater the area which contributes to the measurement (and the faster an area may be surveyed, although this is at the expense of lateral resolution).

For undisturbed soils, the actual depth profile of the radionuclide of interest is highly dependent on whether it is present as a naturally occurring gamma ray emitter or it was released into the environment from anthropogenic sources and, if so, the time of the release, the mobility of the radionuclide in that specific environment, and the position of release (deposited on the surface, released from a buried pipe, etc.). Usually, naturally occurring emitters (e.g., ^{40}K, ^{238}U, ^{232}Th) are distributed approximately uniformly throughout the soil. Those that are present as the result of nuclear weapons testing fall-out (e.g., ^{137}Cs) tend to be distributed with the activity decreasing exponentially with depth. In the case of a very recent accidental airborne release, the ^{137}Cs probably would be distributed only on the soil surface. In such a case ^{134}Cs will also be measured.

In some cases, in-situ spectrometry has been used to determine soil depth profiles directly using differential attenuation for those nuclides which emit two (or more) gamma rays, analysis of the scattered component of the radiation, or (with a lead shield) measurements of the angular incidence of the radiation. Demonstration of this technique was conducted at a former United States weapons production facility using a p-type germanium closed-end coaxial detector to determine the surface soil concentration of uranium. The depth profile of

^{238}U was obtained to a depth of 5-10 cm by observing the attenuation of 63 keV line with respect to the 93 keV line.

Multi-line isotopes such as ^{134}Cs can be used to determine an approximate depth profile by virtue of the differential attenuation of gamma rays of different energies. This approach is limited by the small number of radioisotopes having the suitable spectra and which also are commonly found on contaminated sites.

There is no special sample preparation required for counting samples using a germanium detector or a sodium iodide detector beyond placing the sample in a known geometry for which the detector has been calibrated. The samples can be measured as they arrive at the laboratory, or the sample can be dried, ground to a uniform particle size, and mixed to provide a more homogeneous sample if required by the standard operation procedures.

3.4.2.5 Neutron emitting radionuclides

Information available in literature about this topic will be included in a later edition of EURSSEM.

3.4.2.6 Biological samples

Some species of flora and fauna have the ability to concentrate naturally occurring or artificial radionuclides. Iodine, for example, is known to concentrate in certain algae and shellfish, while caesium can exhibit an enhanced uptake in plants like lichens, heather, fir and spruce, as well as mushrooms. It should be noted that in general, radionuclides have stable sister isotopes which are common in nature and are taken up to varying degrees by biota. Natural processes of plant or animal uptake have evolved which ought not to be affected by the nuclear properties of the element. This results in a broad and mainly still uninvestigated field of promising use as bio-indicators and, moreover, for bio-remediation.

Some bio-indicators have been identified, as shown in Table 3.29, which does not claim to be exhaustive.

Table 3.29 Example bio-indicators for some key radioelements

Bio-indicator	Radio-element
Algae, shellfish, peat deposits	Iodine
Heather	Caesium
Snail shell, fish bone	Strontium
Mushrooms, fir, spruce	Caesium
Mycorhiza plants	Caesium
Thyme	Caesium in Mediterranean regions
Lichen	Caesium in boreal ecosystems
Honey	Caesium
Milk	Caesium, strontium and iodine
Seaweed	Ruthenium, technicium
Sheep droppings	Caesium

Due to the fact that most risk- and dose-based regulations are concerned with potential future land use that may differ from the current land use, vegetation samples are unsuitable for demonstrating compliance with regulations. There is a relationship between radionuclide concentrations in plants and those in soil (the soil-to-plant transfer factor is used in many models to develop DCGLs) and the plant concentration could be used as a surrogate measurement of the soil concentration. In most cases, a measurement of the soil itself as the parameter of interest is more appropriate and introduces less uncertainty in the result.

In some situations the vegetative cover is not considered part of the surface soil sample and is removed in the field. For agricultural scenarios where external exposure is not the primary concern, soil particles greater than 2 mm (0.08 in.) are sometimes not considered as part of the sample. Foreign material (*e.g.*, plant roots, glass, metal, or concrete) is also then not considered part of the sample, but should be reviewed on a site-specific basis. It is important that the sample collection procedure clearly indicate what is and what is not considered part of the sample.

3.4.2.7 Soil and rock samples

Soil and rock samples, both above and below ground level, can provide essential information towards determining the accumulated amounts of contaminants which have been deposited on the ground. It is very important to ensure that the samples taken are seen to provide a realistic representation of both the perceived problem and the area (laterally and/or vertically) over which the contamination is anticipated to exist.

Soil and rock samples are of two main types: mechanically disturbed or undisturbed.

Mechanically disturbed samples are generally adequate for contamination surveys, whereas mechanically undisturbed samples are typically required for geotechnical surveys. There are three main methods of selecting soil and rock samples in the field:

- Sampling from predefined depth intervals.
- Sampling based on visual features (i.e., from different geological units or different layers of made ground).
- Sampling based on the results of radiological or chemical monitoring.

When excavating on a potentially contaminated site, radiation monitors may be used to identify the excavated material with the highest levels of radioactive contamination. This information can then be used to focus sampling, ensuring that at least some of the samples containing the highest levels of radioactive contamination are selected. Care should be taken to avoid over-estimating the volume of contaminated material present if only the most radioactive samples are selected for analysis.

In any survey, it is important that:

- Samples are representative of ground conditions.
- Sufficient material is collected to enable all required analyses to be undertaken (including sufficient material for repeat analysis, should this be necessary). The sample size can be significant when undertaking radiological measurements and, in general, large volumes of soil are more representative than small volumes of soil. For example, the time taken to analyse for gamma-emitting radionuclides to a specified detection limit by gamma spectrometry is approximately inversely proportional to the weight of sample analysed. In general, it is sufficient to collect approximately from 100 –1000 g of sample in an appropriate container for gamma spectrometry analysis.
- Samples have a constant volume, because the volume is related to comparability of the results while the sampling surface area is more closely related to the representativeness of the results.
- Maintaining a constant surface area and depth for samples collected for a particular survey can eliminate problems associated with different depth profiles. The actual surface area included as part of the sample may be important for estimating the probability of locating areas of elevated concentration.

Certain other analyses require additional field sample preparation. For example, analysis for tritium or volatile organic compounds typically require the soil or rock sample to be stored in a sealed septum vial immediately after collection, the aim being to prevent the loss of volatile compounds during transportation to the laboratory. The chemical or radiochemical analyst will provide advice on the volumes of samples required and on any field preparation required (for example, the addition of ultra-pure water).

In some cases, for example when remediation of the site is a probable outcome of the site characterisation and where a large averaging volume has been agreed with the appropriate regulator, it may be appropriate to homogenise samples from a large volume of material. For example, this approach has been used to determine the average contaminant concentrations in ~30 m^3-sized disposal pits.

Disturbed soil samples

Disturbed soil may be brought to ground surface using any of the intrusive investigation techniques listed in Section 3.7, Site characterisation: Intrusive methods. Disturbed samples are generally collected from the spoil produced by the excavation process, using a tool such as a stainless-steel trowel, and placed into the appropriate sample containers (as supplied or advised by the analytical testing laboratory).

It will often be necessary to characterise areas of made ground or coarse-grained soil (such as glacial till or rock fill). In this case, samples that are representative of the entirety of the ground cannot be collected because of the presence of coarse gravels, cobbles and boulders. It is neither practicable nor appropriate (given that any contamination will be concentrated within the finer-grained fraction) to analyse these coarse-grained components of the soil. In this case, the coarse-grained fraction should be discarded, and only the finer-grained fraction sent for chemical and radiochemical analysis. The approximate proportion of unsampled material should be recorded to enable the measured contaminant concentration in the finer-grained component to be corrected (i.e., diluted), if required, to account for the presence of the coarser fraction.

It is best practice to consider the extent of any bias introduced by analysing only the finer fractions of the soil samples. This can be achieved by grinding and homogenising soil samples (at least the sub-pebble-sized fraction), and analysing the resulting sample.

Undisturbed soil samples

Relatively mechanically undisturbed soil samples are generally collected by using one of the standard drilling techniques (such as cable percussive drilling or coring through the centre of a hollow stem auger). The samples are usually collected using an open tube sampler, such as a U100 tube or a plastic core liner. Rotary coring is typically used to obtain mechanically undisturbed rock samples.

Soil field sample preparation and preservation

Proper sample preparation and preservation are essential parts of any radioactivity sampling program. The sampling objectives should be specified before sampling activities begin. Precise records of sample collection and handling are necessary to ensure that data obtained from different locations or time frames are correctly compared.

The appropriateness of sample preparation techniques is a function of the analysis to be performed. Field sample preparation procedures are a function of the specified analysis and the objectives of the survey. It is essential that these objectives be clearly established and agreed upon in the early stages of survey planning (see Section 2).

Soil and sediment samples, in most protocols, require no field preparation and are not preserved. In some protocols, cooling of soil samples to 4°C is required during shipping and storage of soil samples. This is not a practice normally followed for the radiochemical analysis of soil samples.

When replicate samples are prepared in the field, it is necessary to homogenize the sample prior to separation into replicates. There are standard procedures for homogenizing soil in the laboratory, but the equipment required for these procedures may not be available in the field. Simple field techniques, such as cone and quarter, or using a riffle splitter to divide the sample may be appropriate if the sample can be dried. If the sample contains significant amounts of residual water (*e.g.*, forms clumps of soil) and there are no facilities for drying the sample, it is recommended that the homogenization and separation into replicates be performed in a laboratory. It is preferable to use non-blind replicates where the same laboratory prepares and analyzes the replicates rather than use poorly homogenized or heterogeneous samples to prepare replicate samples.

3.4.2.8 Liquid samples

Key considerations for a groundwater characterisation program

Characterizing surface or groundwater involves techniques that determine the extent and distribution of contaminants [41]. This may be performed by collecting grab samples of the surface or groundwater in a well-mixed zone. At certain sites, it may be necessary to collect stratified water samples to provide information on the vertical distribution of contamination. Sediment sampling should also be performed to assess the relationship between the composition of the suspended sediment and the bedload sediment fractions (*i.e.*, suspended sediments compared to deposited sediments). When judgment sampling is used to find radionuclides in sediments, contaminated sediments are more likely to be accumulated on fine-grained deposits found in low-energy environments (*e.g.*, deposited silt on inner curves of streams).

The key considerations for a groundwater characterisation programme are:

- By identifying of a groundwater contamination the responsible regulatory agency should be contacted, because:
  - Groundwater release criteria and DCGLs should be established by the appropriate regulatory.
  - The default DCGLs for soil may be inappropriate since they are usually based on initially uncontaminated groundwater.
- Groundwater contamination characterisation programmes should determine the extent and distribution of contaminants, rates and direction of groundwater migration, and the assessment of potential effects of groundwater withdrawal on the migration of groundwater contaminants.
- Boreholes should be located to provide information on water level and water quality:
  - Up-gradient of any potential sources.
  - In or close to potential source areas.
  - On the down-gradient boundary of the site.
  - As sentinel boreholes and at compliance point.
- If significant groundwater contamination is detected, further boreholes may be required to define the plume of contaminated water.
- Hydrogeological testing should be performed to determine the permeability of the rocks/soil and to establish the hydraulic gradients within and across the site.
- Boreholes should not be completed as long-term monitoring points until the geological and hydro-geological environment is fully understood. In particular:
  - Coordinates of the boreholes/sampling locations should be noted to grid coordinates.
  - The key horizons for contaminant transport should be identified and targeted.
  - Monitoring boreholes should be designed to minimise or prevent vertical flows (‘crossflows’) through the screen and open section.

- Construction specifications on the monitoring wells should also be provided, including elevation, internal and external dimensions, types of casings, type of screen and its location, borehole diameter, and other necessary information on the wells.
- The requirements for monitoring and sampling non-aqueous-phase liquids (NAPLs) should be considered.
- Well construction materials should be compatible with the types and concentrations of contaminants present.

- Targeted sampling of groundwater is appropriate where the groundwater pathway can be identified with reasonable confidence, i.e., where contaminant sources and groundwater flow directions are known. In this manner, the contaminant plume(s) can be delineated and groundwater quality leaving the site can be monitored.
- Non-targeted sampling may be appropriate to the earliest stage of an investigation, if there is no information on potential sources of contamination or on the hydro-geological environment.
- Groundwater background characterisation should be determined by sufficient sampling and analysis of groundwater samples collected from the same aquifer up-gradient of the site. The background samples should not be affected by site operations and should be representative of the quality of the groundwater that would exist if the site had not been contaminated. Consideration should be given to any spatial or temporal variations in the background radionuclide concentrations.

Following completion of the hydro-geological characterisation, long-term monitoring of groundwaters and/or surface waters may be required to:

- Evaluate environmental liabilities and their development with time.
- Ensure compliance with regulatory limits (e.g., requisite monitoring: see Section 2.2.2.4).
- Validate in situ remediation measures (including "natural attenuation").

In some instances, the requirement for long term monitoring will be established at the start of the site characterisation programme. In other instances, the requirement will only become evident after completion of the site works and evaluation of site data. Where the requirement for long term monitoring is established at the outset of the investigation, the survey design should take account of this.

If long term monitoring is to be undertaken, it is good practice to define and document clearly the objectives of the monitoring before the programme starts. Further, the data from the programme should be subject to regular quality checks and technical assessment, and there should be regular review of the need for continued monitoring. These procedures will ensure that inappropriate data are not collected and that the monitoring programme does not continue beyond the period when it was required.

Good practice procedures for the collection of representative groundwater samples are available and are discussed further in the next alineas. Water abstracted from the boreholes during development and sampling must be managed in accordance with the operating procedures of the site and with national legislation. It may be necessary to treat water prior to disposal onto the ground surface (for example, using activated carbon to remove organic contaminants) or to transport the waste water to a liquid effluent treatment plant (for example, to remove radioactive contamination). Finally, a borehole maintenance programme should be established to ensure that the groundwater sampling points remain fit for purpose.

Sampling locations of surface water and groundwater

It is possible that contamination of surface waters and groundwaters may have arisen as a result of operations and activities on the site (see Table 3.1). Consideration should therefore be given to sampling surface waters and groundwaters and to building understanding of the hydrological and hydro-geological environments. Therefore, the sampling of surface and groundwater should be performed in areas of run-off from active operations, at plant outfall locations, both upstream and downstream of the outfall, and any other areas likely to contain residual activity.

The locations of the surface water and groundwater sampling points should take account of factors affecting the temporal and spatial variation in water quality and flows, including:

- The locations and extents of known or suspected sources of contamination.
- Surface water and groundwater catchments.
- Tidal patterns.
- Seasonal or ephemeral variation in surface water flow.
- The local and regional groundwater flow pattern at the site (including identification of both horizontal and vertical hydraulic gradients).
- The hydro-geological properties of the rocks and soils (which, together with information on hydraulic gradients, enables groundwater flow directions and velocities to be estimated).
- Background water quality.

Sampling of groundwater

Groundwater sampling methodologies are described in detail in a number of other guidance documents [9], [36], [126]. An outline of the methodology is given below.

Groundwater samples are generally collected by one of two methods:

- Pump sampling.
- Bail sampling.

The method used will depend on the feature from which the groundwater sample is being obtained (completed borehole, temporary cased borehole or trial pit) and on issues such as the amount of suspended sediment present and the permeability of the surrounding material. Usual practice is for trial pits to be bail-sampled and for boreholes to be pump-sampled.

Pump sampling is the preferred method of sampling from a borehole because a large volume of water can be withdrawn prior to collecting the sample, ensuring that the sample is representative of the groundwater in the rock mass rather than that in the borehole. It is best practice to withdraw three borehole volumes of groundwater prior to collecting samples, or to carry out in-line monitoring (for electrical conductivity, pH etc) and to sample after measurements have stabilised.

When pump-sampling a borehole on a nuclear-licensed or defense site, adequate provision should be made for disposal of the waste-water generated.

Direct disposal of radioactively contaminated water to ground, or by a surface water body, will not be possible. Similarly, disposal of chemically contaminated water to ground or by a surface water body would require authorisation. Therefore pumping to bowser or to storage containers (drums or IBCs) for disposal via an approved route is recommended.

Use of low-flow pumps which are carefully located in well characterised and designed boreholes can limit the amount of liquid waste generated. These systems are designed not to pump out three borehole volumes, but to directly draw into the borehole, the aquifer water from a flowing horizon. The discharges of the pumps should be monitored for physico-chemical (temperature, conductivity and reduction potential), and samples should only be taken once these parameters have stabilised and indicate aquifer representative water is being taken. Therefore even these pumps will generate some liquid waste.

Radiological monitoring using standard field instruments will typically not detect contamination in water samples, because the radionuclides are typically present at much lower activity concentrations than in soil and may only emit “soft” beta or alpha radiation. Laboratory analysis of groundwater samples for radioactivity is generally required. For example, this is the case for tritium, a “soft” beta emitter, which is a common radioactive contaminant found, as tritiated water, in groundwater in the vicinity of some nuclear-licensed and defense sites, see Section 3.9.2.5. Tritiated water is highly mobile in soils and groundwater. Naturally occurring dissolved radon/radon daughters are also likely to be present.

The selection of suitable sample containers and preservation techniques (typically involving refrigeration or the addition of acid or alkali to prevent precipitation or degradation of the sample) is discussed in existing guidance [34], [35] and is not considered in detail here.

Exact requirements should be discussed with the analysts, and these may change depending on the method of analysis used and the limit of detection required. All groundwater samples should be filtered (typically to 0.45 µm) in the field prior to addition of the preservative. It is good practice (i) to refrigerate groundwater samples to approximately 4°C after collection and prior to analysis, (ii) to store samples in the dark and (iii) to minimise sample storage time. This is particularly important for analysis of organic compounds, which may otherwise degrade during storage. In practice, refrigeration of large samples (around 5 litres) for radionuclide analysis is impracticable and is not necessary. An illustrative groundwater sample storage and preservation scheme is shown in Table 3.30.

Table 3.30 Illustrative scheme for storage and preservation of water samples

Determinand	Container	Preservation
All radionuclides except tritium	5 litre HDPE	50 ml HNO_3
Tritium	0.5 litre glass	None
Metals	1 litre HDPE	Hardness, HNO_3
Cyanide	0.1 litre HDPE	NaOH
Major ions and anions	250 ml HDPE	None
Non-volatile and semi-volatile organics	1 litre amber glass bottle	None
Volatile organics	Glass serum vials (sealed with PTFE-faced rubber septum)	None

Sampling of non-aqueous-phase liquids

Non-aqueous-phase liquids (NAPL) divide into two types, light NAPL (LNAPL) or dense NAPL (DNAPL). These types are less dense and more dense than water respectively and hence will either sink through or float on the groundwater.

Sampling dense NAPL’s is extremely difficult, primarily because the probability of intersecting a pool of dense NAPL in the base of an aquifer, and having the dense NAPL flow into the borehole, is low. Dense NAPL is usually inferred to be present in an aquifer by, for example, high or increasing dissolved concentrations with depth, or from records of known disposals. The sampling of DNAPL will not be discussed further here. Further information on dense NAPL’s is provided elsewhere (for example, [30], [38], [116], [127]).

The sampling of LNAPL may be carried out in a number of ways, provided that the borehole is of suitable design (the screen section of the monitoring point should extend from just above to below the zone of water table fluctuation). The most common and simplest method of sampling is to bail a sample from the surface of the groundwater. The LNAPL sample should be collected before any groundwater purging, and should be carried out in such a way as not to emulsify the free product.

The thickness of LNAPL in the borehole can be determined using an interface probe, although it should be noted that this will probably not reflect the thickness in the aquifer, because of capillary pressure effects.

Installation of permanent liquid monitoring points

All of the borehole drilling methods (see Section 3.7.1.1) may be used for the installation of groundwater or gas monitoring points. The key issues to consider when selecting the drilling technique are:

- Achieving the project monitoring objectives.
- Confidence that the drilling technique can achieve the required depth of penetration at the required borehole diameter.
- Health and safety issues, such as the potential generation of airborne contamination during drilling (for example if air-flush rotary drilling is the selected technique).
- Any limitations on the use of a flushing medium (e.g., air, foam, water), which may compromise sample quality.
- Environmental issues, such as spreading of contamination in the ground and control of drilling returns.
- Speed and cost.

Trial pits may also be used for the installation of shallow monitoring points, by carefully backfilling around the monitoring equipment. However, it should be noted that a large volume of soil would be disturbed and this may affect the results obtained during monitoring.

Details of the design, construction, installation and commissioning of permanent groundwater and gas monitoring points are beyond the scope of this guidance document. Readers should refer to the extensive guidance already available on the subject [30], [33], [34], [36].

Sampling of sediments

Information available in literature about this topic will be included in a later edition of EURSSEM.

Liquid and sediment field sample preparation and preservation

Liquid samples may need filtering and acidification. Storage at reduced temperatures (*i.e.*, cooling or freezing) to reduce biological activity may be necessary for some samples. Addition of chemical preservatives for specific radionuclides or media may also be required.

Sediment samples, in most protocols, require no field preparation and are not preserved. In some protocols, cooling of soil samples to 4°C is required during shipping and storage of soil samples. This is not a practice normally followed for the radiochemical analysis of soil samples.

When replicate samples are prepared in the field, it is necessary to homogenize the sample prior to separation into replicates. There are standard procedures for homogenizing liquids in the laboratory, but the equipment required for these procedures may not be available in the field. It is preferable to use non-blind replicates where the same laboratory prepares and analyzes the replicates rather than use poorly homogenized or heterogeneous samples to prepare replicate samples.

Analyses of liquid samples

The analyses of radio-nuclide concentrations in liquids (e.g., surface and groundwater with or without organic or inorganic constituents, and non-aqueous-phase liquids (NAPL)), should include gross alpha and gross beta assessments, as well as any necessary radionuclide-specific analyses. Non-radiological parameters, such as specific conductance, pH, and total organic carbon may be used as surrogate indicators of potential contamination, provided that a specific relationship exists between the radio-nuclide concentration and the level of the indicator (*e.g.*, a linear relationship between pH and the radio-nuclide concentration in water is found to exist, then the pH may be measured such that the radionuclide concentration can be calculated based on the known relationship rather than performing an expensive nuclide-specific analysis).

3.4.2.9 Gas samples

Air

Air sampling may be necessary at some sites depending on the local geology and the radio-nuclides of potential concern. This may include collecting air samples or filtering the air to collect re-suspended particulates. Air sampling is often restricted to monitoring activities for occupational and public health and safety and is not required to demonstrate compliance with risk- or dose-based regulations. Section 2.4.8.8 describes examples of sites where air sampling may provide information useful to designing a final status survey. At some sites, radon measurements may be used to indicate the presence of radium, thorium, or uranium in the soil. Section 3.4.2.10 and 0 provide information on this type of sampling.

Ground gas surveying

Where spills or leaks of volatile organic compounds have occurred, ground gas surveying is recommended. Areas of waste disposal may be identified by ground gas surveying for landfill gas or for volatile compounds if these were known to be deposited. Extensive guidance on ground gas monitoring is available [30], [33].

Radium decays to radon, a short-lived radioactive gas. Detection of radon in ground gas may therefore provide information on the presence of buried radium-contaminated materials. Ground gas surveying for radon is already widely used in the mineral exploration industry to detect uranium ore bodies. Detection of radon in air may also be required to evaluate radiological dose arising from the inhalation of radon. An action level of 2’000Bq/m^3 was set by the former National Radiological Protection Board [100].

However, sole reliance on ground gas spike surveys is not recommended, and further investigation from permanent installations is recommended. Ground gas surveying from shallow permanent monitoring points, with confirmatory laboratory analyses, provides information on volatile or gaseous contaminants within the near-surface soils. Such monitoring techniques are used to identify the source of volatile or gaseous contaminants (or their parents, in the case of ^{222}Rn), such as those that may be associated with areas of contaminated land.

Although ground gas surveying appears to be straightforward, there may be significant uncertainties in interpreting the data, principally due to variations in the permeability and moisture content of the ground, which affect the ability of ground gas to migrate. In addition, results are commonly influenced by meteorological factors, such as the extent of recent rainfall, barometric pressure and windspeed.

Ground gas surveys may be used as an indicator of the presence of a number of contaminants, including:

- Tritium (possibly as water vapour).
- ^{14}C and other volatile organic compounds (VOCs) such as petroleum hydrocarbons or organic solvents [32].
- Radon (an indicator of the presence of radionuclides in the uranium and thorium decay chains). The presence of above background concentrations of radon in air directly indicates that there is a source nearby of radium or its parent isotopes.

- Organic compounds that are not VOCs, but that produce CO_2 gas during biological or chemical breakdown.
- Mercury [32].

The largest potential use of ground gas surveying on nuclear-licensed sites and defence sites will be the identification of sources of VOC contamination. Radon gas surveying may also have some potential use on these sites as the presence of radon indicates that radionuclides in the uranium or thorium decay chains are present.

Limitations of ground gas surveying are that migration of ground gas may be significantly affected by the near surface geological and man-made structures. Because of this the gas concentration may not be proportional to the concentration of contaminant in the source area. Interpretation of results may be difficult and a negative result does not necessarily indicate that there are no contaminants present.

Ground gas sampling from permanent monitoring points

The sampling of permanently installed gas monitoring points is generally used for monitoring methane production from landfilled putrescible wastes. It is unlikely that such monitoring will be required on nuclear-licensed sites or defense sites. Extensive guidance on the identification of landfill gas already exists [30], [34].

Installation of permanent gas monitoring points

See Section 3.4.2.8, alinea 'Installation of permanent liquid monitoring points'.

Airborne particulates

Information available in literature about this topic will be included in a later edition of EURSSEM.

3.4.2.10 Radon sampling

There are three radon isotopes in nature: ^{222}Rn (radon) in the ^{238}U decay chain, ^{220}Rn (thoron) in the ^{232}Th chain and ^{219}Rn (actinon) in the ^{235}U chain. ^{219}Rn is the least abundant of these three isotopes, and because of its short half-life of 4 seconds it has the least probability of emanating into the atmosphere before decaying. ^{220}Rn with a 55 second half-life is somewhat more mobile. ^{222}Rn with a 3.8 d half-life is capable of migrating through several decimetres of soil or building material and reaching the atmosphere. Therefore, in most situations, ^{222}Rn should be the predominant airborne radon isotope.

Radon concentrations within a fixed structure can vary significantly from one section of the building to another and can fluctuate over time. If a home has a basement, for instance, it is usually expected that a higher radon concentration will be found there. Likewise, a relatively small increase in the relative pressure between the soil and the inside of a structure can cause a significant increase in the radon emanation rate from the soil into the structure. Many factors play a role in these variations, but from a practical standpoint it is only necessary to recognize that fluctuations are expected and that they should be accounted for. Long term measurement periods are required to determine a true mean concentration inside a structure and to account for the fluctuations.

Integrating sampling methods for radon

With integrating sampling methods, measurements are made over a period of days, weeks, or months and the device is subsequently read by an appropriate device for the detector media used. The most common detectors used are activated charcoal adsorbers, electret ion chamber (EIC), and alpha track plastics. Short term fluctuations are averaged out, thus making the measurement representative of average concentration. Results in the form of an average value provide no way to determine the fluctuations of the radon concentration over the measurement interval. Successive short term measurements can be used in place of single long term measurements to gain better insight into the time dependence of the radon concentration.

Continuous sampling methods for radon

Devices that measure direct radon concentrations over successive time increments are generally called continuous radon monitors. These systems are more complex than integrating devices in that they measure the radon concentration and log the results to a data recording device on a real time basis. Continuous radon measurement devices normally allow the noble gas radon to pass through a filter into a detection chamber where the radon decays and the radon and/or the resulting progeny are measured. The most common detectors used for real time measurements are ion chambers, solid state surface barrier detectors, and ZnS(Ag) scintillation detectors.

Continuous methods offer the advantage of providing successive, short term results over long periods of time. This allows the investigator not only to determine the average radon concentration, but also to analyze the fluctuations in the values over time. More complicated systems are available that measure the relative humidity and temperature at the measurement location and log the values along with the radon concentrations to the data logging device. This allows the investigator to make adjustments, if necessary, to the resulting data prior to reporting the results.

Radon progeny measurements

Radon progeny measurements are performed by collecting charged aerosols onto filter paper and subsequently counting the filter for attached progeny. Some systems pump air through a filter and then automatically count the filter for alpha and/or beta emissions. An equivalent but more labour intensive method is to collect a sample using an air sampling pump and then count the filter in stand-alone alpha and/or beta counting systems. The measurement system may make use of any number of different techniques ranging from full alpha and beta spectrometric analysis of the filters to simply counting the filter for total alpha and or beta emissions.

When performing total (gross) counting analyses, the assumption is usually made that the only radioisotopes in the air are due to ^{222}Rn and its progeny. This uncertainty, which is usually very small, can be essentially eliminated when performing manual sampling and analysis by performing a follow up measurement of the filter after the radon progeny have decayed to a negligible level. This value can then be used as a background value for the air. Of course, such a simple approach is only applicable when ^{222}Rn is the isotope of concern. For ^{219}Rn or ^{220}Rn, other methods would have to be used.

Time is a significant element in radon progeny measurements. Given any initial equilibrium condition for the progeny isotopes, an investigator must be able to correlate the sampling and measurement technique back to the true concentration values. When collecting radon progeny, the build-up of total activity on the filter increases asymptotically until the activity on the filter becomes constant. At this point, the decay rate of the progeny atoms on the filter is equal to the collection rate of progeny atoms. This is an important parameter to consider when designing a radon sampling procedure.

Note that the number of charged aerosol particles in the air can affect the results for radon progeny measurements. If the number of particles is few, as is possible when humidity is low and a room is very clean, then most of the progeny will not be attached and can plate out on room surfaces prior to reaching the sample filter. This is not a problem if the same conditions always exist in the room. However, the calculated dose would underestimate the dose that would be received in a higher humidity or dust concentration state with the same radon progeny concentration.

Radon emanation measurements

Sometimes it is desirable to characterize the source of radon in terms of the rate at which radon is emanating from a surface - that is, soil, uranium mill tailings, or concrete. One method used for measuring radon emanation (flux) is briefly described here.

The measurement of radon emanation can be achieved by adsorption onto charcoal using a variety of methods such as a charcoal canister or a large area collector (*e.g.*, 25 cm PVC end cap). The collector is deployed by firmly twisting the end cap into the surface of the material to be measured. After 24 hours of exposure, the activated charcoal is removed and transferred to plastic containers. The amount of radon adsorbed on the activated charcoal is determined by gamma spectroscopy. Since the area of the surface is well defined and the deployment period is known, the radon flux (in units of Bq/m^2s or pCi/m^2s) can be calculated.

This method is reliable for measuring radon emanation in normal environmental situations. However, care should be taken if an extremely large source of radon is measured with this method. The collection time should be chosen carefully to avoid saturating the canister with radon. If saturation is approached, the charcoal loses its ability to absorb radon and the collection rate decreases. Even transporting and handling of a canister that is saturated with radon can be a problem due to the dose rate from the gamma rays being emitted. One would rarely encounter a source of radon that is so large that this would become a problem; however, it should be recognized as a potential problem. Charcoal can also become saturated with water, which will affect the absorption of radon. This can occur in areas with high humidity.

An alternative method for making passive radon emanation measurements has been developed recently using electret ionization chambers (EICs). EIC technology has been widely used for indoor radon measurements. The passive EIC procedure is similar to the procedures used with large area activated charcoal canisters. In order to provide the data for the background corrections, an additional passive monitor is located side by side on a radon impermeable membrane. These data are used to calculate the net radon emanation. The Florida State Bureau of Radiation Protection has compared the results from measurements of several phosphor-gypsum flux beds using the charcoal canisters and EICs and has shown that the two methods give comparable results. The passive method seems to have overcome some of the limitations encountered in the use of charcoal. The measurement periods can be extended from hours to several days in order to obtain a better average, if needed. EIC flux measurements are not affected by environmental conditions such as temperature, humidity, and air flow. The measured sensitivities are comparable to the charcoal method but, unlike charcoal, EICs do not become saturated by humidity. Intermediate readings can be made if needed. In view of the low cost of the EIC reading/analyzing equipment, the cost per measurement can be as much as 50% lower than the charcoal method with additional savings in time.

3.4.2.11 Geological

Geological logging

All boreholes and trial pits should be logged. In addition, the following information should be recorded:

- Depth and results of any in-situ radiological or chemical monitoring.
- Depths and depth ranges and type of any samples collected for chemical or radiochemical analysis.
- Depths of any man-made features.

Geotechnical tests

In some circumstances it may be possible to combine a contaminated land survey with a geotechnical survey. Samples retrieved from all types of subsurface investigations should be regarded as a potential resource for other projects. However, a number of points should be borne in mind:

- The quality of the contaminated land survey may be degraded if sampling locations are moved to provide the best location for geotechnical sampling (or vice versa).
- The appropriate intrusive method for the contaminated land survey may not be appropriate for the geotechnical survey (or vice versa).
- Samples must be tested for radioactive contamination prior to the geotechnical testing being carried out. This is required to establish any special health and safety measures that need to be undertaken.
- Consideration should be given to the appropriate storage of materials retrieved for tests for other projects, such as remediation pilot trials.

Geotechnical testing methods are described in detail in [101]. Some examples of common tests are given in Table 3.31.

Table 3.31 Common in-situ and ex-situ tests

In-situ tests	**Ex-situ tests**
Standard penetration tests	Liquid and plastic limit tests
In-situ California bearing ratio test	Moisture content
Hand shear vane test	Undrained triaxial compression tests
Perth penetrometer test	California bearing ratio test
	pH and sulphate testing

Note: Although pH and sulphate testing are chemical tests, they are included in the geotechnical suite as they are used to determine the potential for degradation of foundation to occur.

3.4.2.12 Real time collection of data (samples)

The collection of real-time data is a developing area, with improvements in instrumentation and miniaturisation of technologies. The fast gathering, interpreting, and sharing of data facilitates support for real-time decision making. The range of technologies supporting real-time measurements includes:

- Field analytical instrumentation.
- In-situ sensing systems.
- Geophysics.
- Computer systems that assist project planning, store, display, map, manipulate and share data.

For real-time radioactive data collections see also Section 3.6.2.

Geophysical acquisition of subsurface real-time data is discussed in Section 3.6.3, and cone penetrometer test geo-environmental probes are cited in Table 3.43, Techniques for intrusive sampling.

Real-time monitoring is suitable for other forms of physico-chemical parameters. The use of data loggers to record groundwater fluctuations is an established technology, but other parameters could be monitored, particularly for water quality, as the technologies develop, offering:

- High frequency data collection.
- Smart technology enabling conditional water sampling.
- In-situ calibration.

- Data retrieval via telemetry/mobile phone links.

Tests for chemical or radioactive contaminants can be carried out on-site, as opposed to sending samples to a laboratory for analysis. In general, field tests provide indicators of contaminant concentrations, rather than actual concentrations, and results need to be verified with a small population of laboratory analyses. Examples of commonly used field tests for soils are:

- Immuno-assay techniques (measures relative concentrations of selected organics, e.g., VOCs, PAH).
- Headspace analysis (FID or PID measurement of volatiles).
- Field chromatography.
- Biosensors (e.g., enzyme systems, antibodies, deoxyribonucleic acid or microorganism).
- Colourimetric test strip (wet chemistry, but not immuno-assay).
- Mobile XRF for metal analyses.
- Membrane interface probe.

Samples taken in the field may also be analysed in a mobile laboratory to obtain higher detection limits, but care should be taken to protect against high background, particularly for radioactivity analyses.

The real advantage with collection of real-time data is that it is quick and often relative cheap. It also provides an instant result and can be used to direct investigation immediately. However, the quality of real-time data should always be assessed against the quality criteria set for the project. Back-up off-site laboratory verification will be required for radioactive and non-radioactive contaminants, particularly where the data gathered is sent to the regulators.

3.4.2.13 Quality control samples

The use of the types of quality control (QC) samples (see Table 3.32) described below should be standard practice.

Table 3.32 Quality control samples

Quality control samples	Description
Blanks	- Materials that do not (or should not) contain the chemical or radionuclide being analysed for. Ideally, the blank should be of a similar material ('matrix') to the samples being tested. A variety of blanks may be used, to determine the potential for contamination of the samples at various stages of the sample collection and analysis procedure.
	- Field/method blank (typically applicable to water sampling). A radionuclide/chemical free sample that is taken to the field and then processed, transported and analysed in the same manner as the actual samples.
	- Analytical blank. A radionuclide/chemical free material used in analytical testing laboratory to evaluate background contamination and cross-contamination.
Duplicate samples	- Samples taken either to assess reproducibility of the field sampling procedure ('field duplicate') or to enable inter- or intra-laboratory comparison ('split samples'). Note: it is very difficult to collect duplicate soil samples as contaminant concentrations may vary over very small distances. However, duplicate samples of waters should yield the same result.
Standard samples	- Samples that contain known concentrations of the chemical or radionuclide being analysed for. These samples may be used by the analytical testing laboratory as a check on analytical results or may be submitted with the batch of samples for analysis. Typically, only standard solutions would be submitted in the latter case, because of the difficulty of preparing homogenous soil samples.
External quality control samples	- Samples of material spiked with a level of radioactivity known only to an external laboratory. These are tested alongside the field samples, to provide reassurance that the analyses are correct.

3.5 Site characterisation: Sampling frequencies, locations and patterns

As described in Table 3.2, the design of the site investigation must be clearly linked to the preliminary conceptual model of the site, and procedures must be in place to allow regular and systematic review of the strategy. A key aspect of the site investigation plan is the design of an appropriate sampling strategy, e.g., decision about sampling locations, patterns and frequencies to meet the objectives of the site investigation.

Where remediation is the probable outcome of the site characterisation, it is essential that the survey design is suitable to allow waste volumes to be predicted. In particular, in the case of radioactively contaminated land, disposal costs (per unit volume) for exempt wastes are considerably lower than for low-level radioactive wastes (LLW). Over-estimation of LLW based on poor data results in high and unrealistic project budgets. Conversely, under-estimation of LLW has the opposite effect.

A summary of the key guidance issues is given below, while extensive guidance is given in the next sections.

There are two approaches to soil sampling:

- Targeted or judgmental sampling, which focuses on known or suspected sources of contamination, such as storage tanks, disposal pits and pipelines. The results from non-intrusive surveys (such as geophysical surveys, radiological surveys and drains surveys: see Section 3.6.4) are used to support the design of the targeted sampling.
- Non-targeted sampling, which aims to characterise the contamination status of an area or volume of ground.

In the case of targeted sampling of a known area of significant contamination, for example where significant levels of radioactivity have been detected by a non-intrusive radiological survey, it may not be necessary to characterise the area in detail during the early stages of the investigation. Instead, it may be more valuable to characterise the surrounding area in order to define the "envelope" of contamination and to provide information on the area of land that may require remediation. More detailed characterisation of the most contaminated areas will be required to define a remediation and waste management strategy, and it may be appropriate to undertake this as a supplementary investigation.

Two approaches to designing non-targeted sampling grids are presented in the existing guidance.

- In BS10175:2001 for exploratory investigations[31]; Typical densities of sampling grids can vary from 50 m to 100 m centres and for main investigations from 20 m to 25 m centres. A greater density of sampling grid may be considered appropriate where heterogeneous contamination is indicated, for example, on a former gasworks site where in localized areas 10 m centres may be necessary. A high density sampling grid may also be necessary where a high level of confidence is required for the outcome of a risk assessment (for example for a housing development.
- In contrast MARSSIM presents a statistical approach in which the number of sampling points required to detect a certain size of "hot spot" with a certain level of confidence can be calculated [2]. Given this frequency of sampling, it is possible to state that, at the level of confidence specified:
  - A hot spot of specific size (if one exists) will not be missed.
  - If contamination is not found, a hot spot of at least the specified size does not exist.

The size of the hot spot can be considered in a number of ways. It may be the expected size of the contaminated area or the maximum size of contamination that could be economically and safely remediated. Further, it could be the size of an area of contamination in an otherwise uncontaminated site or an area of greater contamination (for example, above some guideline "trigger" concentration) within a site that is generally contaminated.

The two approaches to designing the sampling grid take into account the same broad issues:

- The need for more frequent sampling to provide higher levels of confidence, and
- To characterise areas with smaller contaminant sources.

The statistical approach applied in EURSSEM is the more rigorous approach. However, the information needed to parameterise the model can only be obtained from a conceptual model of the site. The statistical approach proposed also addresses the identification of an appropriate sampling pattern (e.g., square grid, random, herringbone), stating that the "efficient sampling pattern should satisfy four conditions".

- It should be stratified (i.e., the area to be sampled should be partitioned into regular sub-areas).
- Each sub-area should carry only one sampling point.
- It should be systematic.
- Sampling points should not be aligned.

A square grid pattern satisfies 1-3 above but, because sampling points are aligned, reduces the ability to detect elongated hot spots aligned parallel with the grid. A herringbone pattern is considered to be the optimum type of non-targeted grid pattern. In practice, on operational sites there will be restrictions on the possible positions of sampling points due to the presence of underground services, buildings, etc. This aspect is discussed further in Section 3.7.2. The consequence will be that the actual non-targeted sampling grid will probably not conform to the ideal pattern. A judgement then has to be made as to whether deviations from the ideal grid geometry are so great as to render the statistical measures of confidence invalid.

3.5.1.1 Determining sampling frequencies

The survey grid should be designed to take into account:

- The proposed measurement technique.
- The size of the area to be surveyed.
- The anticipated size of anomalies that may be present.
- Desk study information on potential sources of contamination in the area.

The majority of radiological surveys are carried out using a grid of some type. The scale of the grid should be selected to ensure that it is unlikely that features of interest will be missed, but should be compatible with the proposed survey instrumentation and with the scale of the overall survey area. The scale of the grid may vary over the site of interest, to allow for focused surveying in the areas of most interest. The statistical design of surveys is discussed below for the following situations:

- Contaminant present in background - determining numbers of data points for statistical tests;
- Contaminant not present in background - determining numbers of data points for statistical tests;
- Determining data points for small areas of elevated activity.

<u>Contaminant present in background - determining numbers of data points for statistical tests</u>

The comparison of measurements from the reference area and survey unit is made using the Wilcoxon Rank Sum test (WRS), which should be conducted for each survey unit. In addition, the elevated measurement comparison (EMC) is performed against each measurement to ensure that the measurement result does not exceed a specified investigation level. Decisions have to be defined if any measurement of a survey exceeds the specified investigation level. As an example, if it is a measurement of a remediated survey unit, then additional investigation is recommended, at least locally, regardless of the outcome of the WRS test.

The WRS test is most effective when residual radioactivity is uniformly present throughout a survey unit. The test is designed to detect whether or not this activity exceeds the $DCGL_W$. The advantage of this non-parametric test is that it does not assume the data are normally or log-normally distributed. The WRS test also allows for "less than" measurements to be present in the reference area and the survey units. As a general rule, this test can be used with up to 40 % "less than" measurements in either the reference area or the survey unit. However, the use of "less than" values in data reporting is not recommended. Wherever possible, the actual result of a measurement, together with its uncertainty, should be reported.

This section introduces several terms and statistical parameters that will be used to determine the number of data points needed to apply the non-parametric tests. An example is provided to better illustrate the application of these statistical concepts.

Calculate the Relative Shift. The lower bound of the gray region (LBGR) is selected during the DQO Process along with the target values for α and β. The width of the gray region, equal to (DCGL - LBGR), is a parameter that is central to the WRS test. This parameter is also referred to as the shift, Δ. The absolute size of the shift is actually of less importance than the relative shift, Δ/σ, where σ is an estimate of the standard deviation of the measured values in the survey unit. This estimate of σ includes both the real spatial variability in the quantity being measured and the precision of the chosen measurement system. The relative shift, Δ/σ, is an expression of the resolution of the measurements in units of measurement uncertainty.

The shift ($\Delta = DCGL_W$ - LBGR) and the estimated standard deviation in the measurements of the contaminant (σ_r and σ_s) are used to calculate the relative shift, Δ/σ (see 0). The standard deviations in the contaminant level will likely be available from previous survey data (*e.g*., scoping or characterization survey data for un-remediated survey units or remedial action support surveys for remediated survey units). If they are not available, it may be necessary to:

- Perform some limited preliminary measurements to estimate the distributions, or
- Make a reasonable estimate based on available site knowledge.

If the first approach above is used, it is important to note that the scoping or characterization survey data or preliminary measurements used to estimate the standard deviation should use the same technique as that to be used during the final status survey. When preliminary data are not obtained, it may be reasonable to assume a coefficient of variation on the order of 30%, based on experience.

The value selected as an estimate of σ for a survey unit may be based on data collected only from within that survey unit or from data collected from a much larger area of the site. Note that survey units are not finalized until the planning stage of the final status survey. This means that there may be some difficulty in determining which individual measurements from a preliminary survey may later represent a particular survey unit. For many sites, the most practical solution is to estimate σ for each area classification (*i.e*., Class 1, Class 2, and Class 3) for both interior and exterior survey units. This will result in all exterior Class 3 survey units using the same estimate of σ, all exterior Class 2 survey units using a second estimate for σ, and all exterior Class 1 survey units using a third estimate for σ. If there are multiple types of surfaces within an area classification, additional estimates of σ may be required. For example, a Class 2 concrete floor may require a different estimate of σ than a Class 2 cinder block wall, or a Class 3 unpaved parking area may require a different estimate of σ than a

Class 3 lawn. In addition, EURSSEM recommends that a separate estimate of σ be obtained for every reference area.

The importance of choosing appropriate values for σ_r and σ_s must be emphasized. *If the value is grossly underestimated*, the number of data points will be too few to obtain the desired power level for the test and a resurvey may be recommended (see Section 3.10.8). If, on the other hand, *the value is overestimated*, the number of data points determined will be unnecessarily large.

Values for the relative shift that are less than one will result in a large number of measurements needed to demonstrate compliance. The number of data points will also increase as Δ becomes smaller. Since the DCGL is fixed, this means that the lower bound of the gray region also has a significant effect on the estimated number of measurements needed to demonstrate compliance. When the estimated standard deviations in the reference area and survey units are different, the larger value should be used to calculate the relative shift (Δ/σ).

Determine P_r. The probability that a random measurement from the survey unit exceeds a random measurement from the background reference area by less than the $DCGL_W$ when the survey unit median is equal to the LBGR above background is defined as P_r. P_r is used in Equation 3-16 for determining the number of measurements to be performed during the survey. Table 3.33 lists relative shift values and values for Pr. Using the relative shift calculated in the preceding section, the value of P_r can be obtained from Table 3.33.

Table 3.33 Values of P_r for given values of the relative shift, Δ/σ when the contaminant is present in background

Δ/σ	**P_r**	**Δ/σ**	**P_r**
0.1	0.528182	1.4	0.838864
0.2	0.556223	1.5	0.855541
0.3	0.583985	1.6	0.871014
0.4	0.611335	1.7	0.885299
0.5	0.638143	1.8	0.898420
0.6	0.664290	1.9	0.910413
0.7	0.689665	2.0	0.921319
0.8	0.714167	2.25	0.944167
0.9	0.737710	2.5	0.961428
1.0	0.760217	2.75	0.974067
1.1	0.781627	3.0	0.983039
1.2	0.801892	3.5	0.993329
1.3	0.820978	4.0	0.997658

If Δ/σ > 4.0, use P_r = 1.000000

Table 3.34 Percentiles represented by selected values of α and β

α and β	**$Z_{1-\alpha}$ (or $Z_{1-\beta}$)**	**α and β**	**$Z_{1-\alpha}$ (or $Z_{1-\beta}$)**
0.005	2.576	0.10	1.282
0.01	2.326	0.15	1.036
0.015	2.241	0.20	0.842
0.025	1.960	0.25	0.674
0.05	1.645	0.30	0.524

If the actual value of the relative shift is not listed in Table 3.33, always select the next lower value that appears in the table. For example, $\Delta/\sigma = 1.67$ does not appear in Table 3.20. The next lower value is 1.6, so the value of P_r would be 0.871014.

Determine Decision Error Percentiles. The next step in this process is to determine the percentiles $Z_{1-\alpha}$ and $Z_{1-\beta}$, represented by the selected decision error levels, α and β, respectively (Table 3.34). $Z_{1-\alpha}$ and $Z_{1-\beta}$ are standard statistical values.

Calculate Number of Data Points for WRS Test. The number of data points, N, to be obtained from each reference area/survey unit pair for the WRS test is next calculated using:

$$N = \frac{(Z_{1-\alpha} + Z_{1-\beta})^2}{3\,(P_r - 0.5)^2} \qquad (3\text{-}16)$$

The value of N calculated using Equation 3-16 is an approximation based on estimates of σ and P_r, so there is some uncertainty associated with this calculation. In addition, there will be some missing or unusable data from any survey. The rate of missing or unusable measurements, R, expected to occur in survey units or reference areas and the uncertainty associated with the calculation of N should be accounted for during survey planning. The number of data points should be increased by 20%, and rounded up, over the values calculated using Equation 3-16 to obtain sufficient data points to attain the desired power level with the statistical tests and allow for possible lost or unusable data. The value of 20% is selected to account for a reasonable amount of uncertainty in the parameters used to calculate N and still allow flexibility to account for some lost or unusable data. The recommended 20% correction factor should be applied as a minimum value. Experience and site-specific considerations should be used to increase the correction factor if required. If the user determines that the 20% increase in the number of measurements is excessive for a specific site, a retrospective power curve should be used to demonstrate that the survey design provides adequate power to support the decision (see 0).

N is the total number of data points for each survey unit/reference area combination. The N data points are divided between the survey unit, n, and the reference area, m. The simplest method for distributing the N data points is to assign half the data points to the survey unit and half to the reference area, so n=m=N/2. This means that N/2 measurements are performed in each survey unit, and N/2 measurements are performed in each reference area. If more than one survey unit is associated with a particular reference area, N/2 measurements should be performed in each survey unit and N/2 measurements should be performed in the reference area.

Obtain Number of Data Points for WRS Test from Table 3.35. Table 3.35 provides a list of the number of data points used to demonstrate compliance using the WRS test for selected values of α, β and Δ/σ. The values listed in Table 3.35 represent the number of measurements to be performed in each survey unit as well as in the corresponding reference area. The values were calculated using Equation 3-16 and increased by 20% for the reasons discussed in the previous section.

<u>*Example 3.14: Calculation of the number of data points for a survey unit and reference area when the contaminant is present in background*</u>

A site has 14 survey units and 1 reference area, and the same type of instrument and method is used to perform measurements in each area. The contaminant has a $DCGL_W$ which when converted to cpm equals 160 cpm. The contaminant is present in background at a level of 45 ± 7 (1σ) cpm. The standard deviation of the contaminant in the survey area is ± 20 cpm, based on previous survey results for the same or similar contaminant distribution. When the estimated standard deviation in the reference area and the survey units are different, the larger value, 20 cpm in this example, should be used to calculate the relative shift. During the DQO process the LBGR is selected to be one-half the $DCGL_W$ (80 cpm) as an arbitrary *starting point for developing an acceptable survey design[19], and Type I and Type II error values (α and β) of 0.05 have been selected. Determine the number of data points to be obtained from the reference area and from each of the survey units for the statistical tests.*

The value of the relative shift for the reference area, Δ/σ, is (160-80)/20 or 4. From Table 3.20, the value of P_r is 0.997658. Values of percentiles, represented by the selected decision error levels, are obtained from Table 3.34. In this case $Z_{1-\alpha}$ (for α = 0.05) is 1.645 and $Z_{1-\beta}$ (β = 0.05) is also 1.645.

Table 3.35 Values of N/2 for use with the Wilcoxon Rank Sum Test

	α = 0.01					**α = 0.025**					**α = 0.05**					**α = 0.10**					**α = 0.25**				
	β					**β**					**β**					**β**					**β**				
Δ/σ	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**
0.1	5452	4627	3972	3278	2268	4627	3870	3273	2646	1748	3972	3273	2726	2157	1355	3278	2646	2157	1655	964	2268	1748	1355	964	459
0.2	1370	1163	998	824	570	1163	973	823	665	440	998	823	685	542	341	824	665	542	416	243	570	440	341	243	116
0.3	614	521	448	370	256	521	436	369	298	197	448	369	307	243	153	370	298	243	187	109	256	197	153	109	52
0.4	350	297	255	211	146	297	248	210	170	112	255	210	175	139	87	211	170	139	106	62	146	112	87	62	30
0.5	227	193	166	137	95	193	162	137	111	73	166	137	114	90	57	137	111	90	69	41	95	73	57	41	20
0.6	161	137	117	97	67	137	114	97	78	52	117	97	81	64	40	97	78	64	49	29	67	52	40	29	14
0.7	121	103	88	73	51	103	86	73	59	39	88	73	61	48	30	73	59	48	37	22	51	39	30	22	11
0.8	95	81	69	57	40	81	68	57	46	31	69	57	48	38	24	57	46	38	29	17	40	31	24	17	8
0.9	77	66	56	47	32	66	55	46	38	25	56	46	39	31	20	47	38	31	24	14	32	25	20	14	7
1.0	64	55	47	39	27	55	46	39	32	21	47	39	32	26	16	39	32	26	20	12	27	21	16	12	6
1.1	55	47	40	33	23	47	39	33	27	18	40	33	28	22	14	33	27	22	17	10	23	18	14	10	5
1.2	48	41	35	29	20	41	34	29	24	16	35	29	24	19	12	29	24	19	15	9	20	16	12	9	4
1.3	43	36	31	26	18	36	30	26	21	14	31	26	22	17	11	26	21	17	13	8	18	14	11	8	4
1.4	38	32	28	23	16	32	27	23	19	13	28	23	19	15	10	23	19	15	12	7	16	13	10	7	4
1.5	35	30	25	21	15	30	25	21	17	11	25	21	18	14	9	21	17	14	11	7	15	11	9	7	3
1.6	32	27	23	19	14	27	23	19	16	11	23	19	16	13	8	19	16	13	10	6	14	11	8	6	3
1.7	30	25	22	18	13	25	21	18	15	10	22	18	15	12	8	18	15	12	9	6	13	10	8	6	3
1.8	28	24	20	17	12	24	20	17	14	9	20	17	14	11	7	17	14	11	9	5	12	9	7	5	3
1.9	26	22	19	16	11	22	19	16	13	9	19	16	13	11	7	16	13	11	8	5	11	9	7	5	3
2.0	25	21	18	15	11	21	18	15	12	8	18	15	13	10	7	15	12	10	8	5	11	8	7	5	3
2.25	22	19	16	14	10	19	16	14	11	8	16	14	11	9	6	14	11	9	7	4	10	8	6	4	2
2.5	21	18	15	13	9	18	15	13	10	7	15	13	11	9	6	13	10	9	7	4	9	7	6	4	2
2.75	20	17	15	12	9	17	14	12	10	7	15	12	10	8	5	12	10	8	6	4	9	7	5	4	2
3.0	19	16	14	12	8	16	14	12	10	6	14	12	10	8	5	12	10	8	6	4	8	6	5	4	2
3.5	18	16	13	11	8	16	13	11	9	6	13	11	9	8	5	11	9	8	6	4	8	6	5	4	2
4.0	18	15	13	11	8	15	13	11	9	6	13	11	9	7	5	11	9	7	6	4	8	6	5	4	2

The number of data points, N, for the WRS test of each combination of reference area and survey units can be calculated using Equation 3-16:

$$N = \frac{(1.645 + 1.645)^2}{3\,(0.997658 - 0.5)^2} = 14.6$$

[19] Section 3.10 provides more detailed guidance on the selection of the LBGR.

Adding an additional 20% gives 17.5 which is then rounded up to the next even number, 18. This yields 9 data points for the reference area and 9 for each survey unit.

Alternatively, the number of data points can be obtained directly from Table 3.35. For $\alpha = 0.05$, $\beta = 0.05$, and $\Delta/\sigma = 4.0$ a value of 9 is obtained for N/2. The table value has already been increased by 20% to account for missing or unusable data.

Contaminant not present in background - determining numbers of data points for statistical tests

For the situation where the contaminant is not present in background or is present at such a small fraction of the $DCGL_W$ (release criteria) as to be considered insignificant, a background reference area is not necessary. Instead, the contaminant levels are compared directly with the DCGL value. The general approach closely parallels that used for the situation when the contaminant is present in background as described above. However, the statistical tests differ slightly. The one-sample Sign test replaces the two-sample Wilcoxon Rank Sum test described below.

Calculate the Relative Shift. The initial step in determining the number of data points in the one-sample case is to calculate the relative shift, Δ/σ_s = (DCGL-LBGR)/ σ_s, from the DCGL value, the lower bound of the gray region (LBGR), and the standard deviation of the contaminant in the survey unit, σ_s, as described above. Also as described above, the value of σ_s may be obtained from earlier surveys, limited preliminary measurements, or a reasonable estimate. Values of the relative shift that are less than one will result in a large number of measurements needed to demonstrate compliance.

Determine Sign p. Sign p is the estimated probability that a random measurement from the survey unit will be less than the $DCGL_W$ when the survey unit median is actually at the LBGR. The Sign p is used to calculate the minimum number of data points necessary for the survey to meet the DQOs. The value of the relative shift calculated in the previous section is used to obtain the corresponding value of Sign p from Table 3.36.

Table 3.36 Values of Sign p for given values of the relative shift, Δ/σ, when the contaminant is not present in background

Δ/σ	**Sign p**	**Δ/σ**	**Sign p**
0.1	0.539828	1.2	0.884930
0.2	0.579260	1.3	0.903199
0.3	0.617911	1.4	0.919243
0.4	0.655422	1.5	0.933193
0.5	0.691462	1.6	0.945201
0.6	0.725747	1.7	0.955435
0.7	0.758036	1.8	0.964070
0.8	0.788145	1.9	0.971284
0.9	0.815940	2.0	0.977250
1.0	0.841345	2.5	0.993790
1.1	0.864334	3.0	0.998650

If $\Delta/\sigma > 3.0$, use Sign p = 1.000000

Determine Decision Error Percentiles. The next step in this process is to determine the percentiles, $Z_{1-\alpha}$ and $Z_{1-\beta}$, , represented by the selected decision error levels, α and β, respectively (see Table 3.34).

Calculate Number of Data Points for Sign Test. The number of data points, N, to be obtained for the Sign test is next calculated using the following formula:

$$N = \frac{(Z_{1-\alpha} + Z_{1-\beta})^2}{4\,(Sign\ p - 0.5)^2} \qquad (3\text{-}17)$$

Finally, the number of anticipated data points should be increased by at least 20% as discussed before to ensure sufficient power of the tests and to allow for possible data losses.

Obtain Number of Data Points for Sign Test from Table 3.24. Table 3.24 provides a list of the number of data points used to demonstrate compliance using the Sign test for selected values of α, β, and Δ/σ. The values listed in Table 3.37 represent the number of measurements to be performed in each survey unit. These values were calculated using Equation 3-17 and increased by 20% to account for missing or unusable data and uncertainty in the calculated value of N.

Table 3.37 Values of N for use with the Sign test

	α = 0.01					**α = 0.025**					**α = 0.05**					**α = 0.10**					**α = 0.25**				
	β					**β**					**β**					**β**					**β**				
Δ/σ	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**
0.1	4095	3476	2984	2463	1704	3476	2907	2459	1989	1313	2984	2459	2048	1620	1018	2463	1989	1620	1244	725	1704	1313	1018	725	345
0.2	1035	879	754	623	431	879	735	622	503	333	754	622	518	410	258	623	503	410	315	184	431	333	258	184	88
0.3	468	398	341	282	195	398	333	281	227	150	341	281	234	185	117	282	227	185	143	83	195	150	117	83	40
0.4	270	230	197	162	113	230	192	162	131	87	197	162	136	107	68	162	131	107	82	48	113	87	68	48	23
0.5	178	152	130	107	75	152	126	107	87	58	130	107	89	71	45	107	87	71	54	33	75	58	45	33	16
0.6	129	110	94	77	54	110	92	77	63	42	94	77	65	52	33	77	63	52	40	23	54	42	33	23	11
0.7	99	83	72	59	41	83	70	59	48	33	72	59	50	40	26	59	48	40	30	18	41	33	26	18	9
0.8	80	68	58	48	34	68	57	48	39	26	58	48	40	32	21	48	39	32	24	15	34	26	21	15	8
0.9	66	57	48	40	28	57	47	40	33	22	48	40	34	27	17	40	33	27	21	12	28	22	17	12	6
1.0	57	48	41	34	24	48	40	34	28	18	41	34	29	23	15	34	28	23	18	11	24	18	15	11	5
1.1	50	42	36	30	21	42	35	30	24	17	36	30	26	21	14	30	24	21	16	10	21	17	14	10	5
1.2	45	38	33	27	20	38	32	27	22	15	33	27	23	18	12	27	22	18	15	9	20	15	12	9	5
1.3	41	35	30	26	17	35	29	24	21	14	30	24	21	17	11	26	21	17	14	8	17	14	11	8	4
1.4	38	33	28	23	16	33	27	23	18	12	28	23	20	16	10	23	18	16	12	8	16	12	10	8	4
1.5	35	30	27	22	15	30	26	22	17	12	27	22	18	15	10	22	17	15	11	8	15	12	10	8	4
1.6	34	29	24	21	15	29	24	21	17	11	24	21	17	14	9	21	17	14	11	6	15	11	9	6	4
1.7	33	28	24	20	14	28	23	20	16	11	24	20	17	14	9	20	16	14	10	6	14	11	9	6	4
1.8	32	27	23	20	14	27	22	20	16	11	23	20	16	12	9	20	16	12	10	6	14	11	9	6	4
1.9	30	26	22	18	14	26	22	18	15	10	22	18	16	12	9	18	15	12	10	6	14	10	9	6	4
2.0	29	26	22	18	12	26	21	18	15	10	22	18	15	12	8	18	15	12	10	6	12	10	8	6	3
2.5	28	23	21	17	12	23	20	17	14	10	21	17	15	11	8	17	14	11	9	5	12	10	8	5	3
3.0	27	23	20	17	12	23	20	17	14	9	20	17	14	11	8	17	14	11	9	5	12	9	8	5	3

Example 3.15: Calculation of the number of data points for a survey unit and a reference area when the contaminant is not present in background

A site has 1 survey unit. The DCGL level for the contaminant of interest is 140 Bq/kg (3.9 pCi/g) in soil. The contaminant is not present in background; data from previous investigations indicate average residual contamination at the survey unit of 3.7 ± 3.7 (1σ) Bq/kg. The lower bound of the gray region was selected to be 110 Bq/kg. A value of 0.05 is next selected for the probability of Type I decision errors (α) and a value of 0.01 is selected *for the probability of Type II decision errors (β) based on the survey objectives. Determine the number of data points to be obtained from the survey unit for the statistical tests.*

The value of the shift parameter, Δ/σ, is (140-110)/3.7 or 8. From Table 3.36, the value of Sign p is 1.0. Since Δ/σ > 3, the width of the gray region can be reduced. If the LBGR is raised to 125, then Δ/σ is (140-125)/3.7 or 4. The value of Sign p remains at 1.0. Thus, the number of data points calculated will not change. The probability of a Type II error is now specified at 125 Bq/kg (3.4 pCi/g) rather than 110 Bq/kg (3.0 pCi/g). As a consequence, the probability of a Type II error at 110 Bq/kg (3.0 pCi/g) will be even smaller.

Values of percentiles represented by the selected decision error levels are obtained from Table 3.21. $Z_{1-\alpha}$ *(for α = 0.05) is 1.645, and* $Z_{1-\beta}$ *(β = 0.01) is 2.326.*

The number of data points, N, for the Sign test can be calculated using Equation 3-17:

$$N = \frac{(1.645 + 2.326)^2}{4\,(1.0 - 0.5)^2}$$

Adding an additional 20% gives 19.2 and rounding up yields 20 data points for the survey unit.

Alternatively, the number of data points can be obtained directly from Table 3.37. For α = 0.05, β = 0.01, and Δ/σ > 3.0 a value of 20 is obtained for N. The table value has already been increased by 20% to account for missing or unusable data and uncertainty in the calculated value of N.

Determining data points for small areas of elevated activity

The statistical tests described above (also see Section 3.10 and 0) evaluate whether or not the residual radioactivity in an area exceeds the $DCGL_W$ for contamination conditions that are approximately uniform across the survey unit. In addition, there should be a reasonable level of assurance that any small areas of elevated residual radioactivity that could be significant relative to the $DCGL_{EMC}$ are not missed during the final status survey. The statistical tests introduced in the previous sections may not successfully detect small areas of elevated contamination. Instead, systematic measurements and sampling, in conjunction with surface scanning, are used to obtain adequate assurance that small areas of elevated radioactivity will still satisfy the release criterion or the $DCGL_{EMC}$. The procedure is applicable for all radionuclides, regardless of whether or not they are present in background, and is implemented for survey units classified as Class 1.

The number of survey data points needed for the statistical tests discussed in the above alineas dealing with ‘Determining numbers of data points for areas with and without contaminant present in background’ is identified (the appropriate section depends on whether the contaminant is present in background or not). These data points are then positioned throughout the survey unit by first randomly selecting a start point and establishing a systematic pattern. This systematic sampling grid may be either triangular or square. The triangular grid is generally more efficient for locating small areas of elevated activity. 0 includes a brief discussion on the efficiency of triangular and square grids for locating areas of elevated activity.

The number of calculated survey locations, n, is used to determine the grid spacing, L, of the systematic sampling pattern (see Section 3.5.1.2). The grid area that is bounded by these survey locations is given by $A = 0.866 \times L^2$ for a triangular grid and $A = L^2$ for a square grid. The risk of not sampling a circular area - equal to A - of elevated activity by use of a random-start grid pattern is illustrated in Figure A.5 in 0.

One method for determining values for the $DCGL_{EMC}$ is to modify the $DCGL_W$ using a correction factor that accounts for the difference in area and the resulting change in dose or risk. The area factor is the magnitude by which the concentration within the small area of elevated activity can exceed $DCGL_W$ while maintaining compliance with the release criterion. The area factor is determined based on specific regulatory agency guidance.

Table 3.25 and Table 3.26 [2], [26], [27] provide examples of area factors generated using exposure pathway models. For each radionuclide, all exposure pathways were calculated assuming a concentration of 37 Bq/kg for outdoor and assuming a concentration of 37 Bq/m^2. The EURSSEM user should consult with the responsible regulatory agency for guidance on acceptable techniques to determine area factors.

The minimum detectable concentration (MDC) of the scan procedure - needed to detect an area of elevated activity at the limit determined by the area factor - is calculated as follows:

$$\text{Scan MDC (required)} = (DCGL_W) \times (\text{Area Factor}) \quad (3\text{-}18)$$

The actual MDC's of scanning techniques are then determined for the available instrumentation (see Section 3.3.7.5 and Section 3.3.7.6). The actual MDC of the selected scanning technique is compared to the required scan MDC. If the actual scan MDC is less than the required scan MDC, no additional sampling points are necessary for assessment of small areas of elevated activity. In other words, the scanning technique exhibits adequate sensitivity to detect small areas of elevated activity.

Table 3.38 Illustrative examples of outdoor area dose factors*

	Area Factor								
Nuclide	1 m^2	3 m^2	10 m^2	30 m^2	100 m^2	300 m^2	1000 m^2	3000 m^2	10000 m^2
^{241}Am	208.7	139.7	96.3	44.2	13.4	4.4	1.3	1.0	1.0
^{60}Co	9.8	4.4	2.1	1.5	1.2	1.1	1.1	1.0	1.0
^{137}Cs	11.0	5.0	2.4	1.7	1.4	1.3	1.1	1.1	1.0
^{63}Ni	1175.2	463.7	154.8	54.2	16.6	5.6	1.7	1.5	1.0
^{226}Ra	54.8	21.3	7.8	3.2	1.1	1.1	1.0	1.0	1.0
^{232}Th	12.5	6.2	3.2	2.3	1.8	1.5	1.1	1.0	1.0
^{238}U	30.6	18.3	11.1	8.4	6.7	4.4	1.3	1.0	1.0

* The values listed in Table 3.38 are for illustrative purposes only. Consult regulatory guidance to determine area factors to be used for compliance demonstration.

Table 3.39 Illustrative examples of indoor area dose factors*

	Area Factor					
Nuclide	1 m^2	4 m^2	9 m^2	16 m^2	25 m^2	36 m^2
^{241}Am	36.0	9.0	4.0	2.2	1.4	1.0
^{60}Co	9.2	3.1	1.9	1.4	1.2	1.0
^{137}Cs	9.4	3.2	1.9	1.4	1.2	1.0
^{63}Ni	36.0	9.0	4.0	2.3	1.4	1.0
^{226}Ra	18.1	5.5	2.9	1.9	1.3	1.0
^{232}Th	36.0	9.0	4.0	2.2	1.4	1.0
^{238}U	35.7	9.0	4.0	2.2	1.4	1.0

* The values listed in Table 3.39 are for illustrative purposes only. Consult regulatory guidance to determine area factors to be used for compliance demonstration.

If the actual scan MDC is greater than the required scan MDC (*i.e.*, the available scan sensitivity is not sufficient to detect small areas of elevated activity), then it is necessary to calculate the area factor that corresponds to the actual scan MDC:

$$\text{Area Factor} = \text{scan MDC (actual)} / DCGL \quad (3\text{-}19)$$

The size of the area of elevated activity (in m^2) that corresponds to this area factor is then obtained from specific regulatory agency guidance, and may be similar to those illustrated Table 3.38 or Table 3.39. The data needs for assessing small areas of elevated activity can then be determined by dividing the area of elevated activity acceptable to the regulatory agency into the survey unit area. For example, if the area of elevated activity is 100 m^2 (from Table 3.38) and the survey unit area is 2,000 m^2, then the calculated number of survey locations is 20. The calculated number of survey locations, n_{EA}, is used to determine a revised spacing, L, of the systematic pattern (refer to Section 3.5.1.2). Specifically, the spacing, L, of the pattern (when driven by the areas of elevated activity) is given by:

$$L = \sqrt{(A / (0.866\ n_{EA}))} \quad \textit{for a triangular grid} \quad (3\text{-}20)$$

$$L = \sqrt{(A / n_{EA})} \quad \textit{for a square grid} \quad (3\text{-}21)$$

where A is the area of the survey unit. Grid spacings should generally be rounded *down* to the nearest distance that can be conveniently measured in the field.

If the number of data points required to identify areas of elevated activity (n_{EA}) is greater than the number of data points calculated using Equation 3-16 (N/2) or Equation 3-17 (N), L should be calculated using Equation 3-20 or Equation 3-21. This value of L is then used to determine the measurement locations as described in Section 3.5.1.2. If n_{EA} is smaller than N/2 or N, L is calculated using Equation 3-22 or Equation 3-23 as described in Section 3.5.1.2. The statistical tests are performed using this larger number of data points. If residual radioactivity is found in an isolated area of elevated activity - in addition to residual radioactivity distributed relatively uniformly across the survey unit - the unity rule (described in Section 3.3.6.3) can be used to ensure that the total dose or risk does not exceed the release criterion (see Section 3.10.8.8). If there is more than one elevated area, a separate term should be included for each. As an alternative to the unity rule, the dose or risk due to the actual residual radioactivity distribution can be calculated if there is an appropriate exposure pathway model available. Note that these considerations generally apply only to Class 1 survey units, since areas of elevated activity should not exist in Class 2 or Class 3 survey units.

When the detection limit of the scanning technique is very large relative to the $DCGL_{EMC}$, the number of measurements estimated to demonstrate compliance using the statistical tests may become unreasonably large. In this situation perform an evaluation of the survey objectives and considerations. These considerations may include the survey design and measurement methodology, exposure pathway modeling assumptions and parameter values used to determine the DCGLs, historical site assessment conclusions concerning source terms and radio-nuclide distributions, and the results of scoping and characterization surveys. In most cases the result of this evaluation is not expected to justify an unreasonably large number of measurements.

Example 3.16: Determining data points for small areas of elevated activity; Class 1 area potentially contaminated with ^{60}Co (example 1)

A Class 1 land area survey unit of 1,500 m^2 is potentially contaminated with ^{60}Co. The $DCGL_W$ value for ^{60}Co is 110 Bq/kg and the scan sensitivity for this radio-nuclide has been determined to be 150 Bq/kg. Calculations indicate the number of data points needed for statistical testing is 27. The distance between measurement locations for this number of data points and the given land area is 8 m. The area encompassed by a triangular sampling pattern of 8 m is approximately 55.4 m^2. From Table 3.38 an area factor of about 1.4 is determined by interpolation. The acceptable concentration in a 55.4 m^2 area is therefore 160 Bq/kg (1.4 × 110 Bq/kg). Since the scan sensitivity of the procedure to be used is less than the $DCGL_W$ times the area factor, no additional data points are needed to demonstrate compliance with the elevated measurement comparison criteria.

Example 3.17: Determining data points for small areas of elevated activity; Class 1 area contaminated with ^{60}Co (example 2)

A Class 1 land area survey unit of 1500 m^2 is potentially contaminated with ^{60}Co. The DCGL for ^{60}Co is 110 Bq/kg. In contrast to Example 1, the scan sensitivity for this radio-nuclide has been determined to be 170 Bq/kg. Calculations indicate the number of data points needed for statistical testing is 15. The distance between measurement locations for this number of data points and land area is 10 m. The area encompassed by a triangular sampling pattern of 10 m is approximately 86.6 m^2. From Table 3.38 an area factor of about 1.3 is determined by interpolation. The acceptable concentration in a 86.6 m^2 area is therefore 140 Bq/kg (1.3 × 110 Bq/kg). Since the scan sensitivity of the procedure to be used is greater than the $DCGL_W$ times the area factor, the data points obtained for the statistical testing may not be sufficient to demonstrate compliance using the elevated measurement comparison. The area multiplier for elevated activity that would have to be achieved is 1.5 (170/110 Bq/kg). This is equivalent to an area of 30 m^2 (Table 3.38) which would be obtained with a spacing of about 6 m. A triangular pattern of 6 m spacing includes 50 data points, so 50 measurements should be performed in the survey unit.

3.5.1.2 Determining locations and patterns

A scale drawing of the survey unit is prepared, along with the overlying planar reference coordinate system or grid system. Any location within the survey area is thus identifiable by a unique set of coordinates. The maximum length, X, and width, Y, dimensions of the survey unit are then determined. Identifying and documenting a specific location for each measurement performed is an important part of a final status survey to ensure that measurements can be reproduced if necessary. The reference coordinate system described in Section 3.5.1.4 provides examples for relating measurements to a specific location within a survey unit.

If the same values for α, β, and Δ/σ are used in Equations 3-16 or Equation 3-17, the required number of measurements is independent of survey unit classification. This means that the same number of measurements could be performed in a Class 1, Class 2, or Class 3 survey unit. While this is a best case scenario, it points out the importance of identifying appropriate survey units (*e.g.*, size, classification) in defining the level of survey effort. The spacing of measurements is affected by the number of measurements, which is independent of classification. However, the spacing of measurements is also affected by survey unit area, the variability in the contaminant concentration, and the interface with the models used to develop the DCGLs which are dependent on classification.

Land Areas. Measurements and samples in Class 3 survey units and reference areas should be taken at random locations. These locations are determined by generating sets of random numbers (2 values, representing the X-axis and Y-axis distances). Random numbers can be generated by calculator or computer, or can be obtained from mathematical tables. Sufficient sets of numbers will be needed to identify the total number of survey locations established for the survey unit. Each set of random numbers is multiplied by the appropriate survey unit dimension to provide coordinates, relative to the origin of the survey unit reference grid pattern. Coordinates identified in this manner, which do not fall within the survey until area or which cannot be surveyed, due to site conditions, are replaced with other survey points determined in the same manner. Figure 3.7 is an example of a random sampling pattern. In this example, 8 data points were identified using the appropriate formula based on the statistical tests (i.e., Equation 3-16 or Equation 3-17). The locations of these points were determined using the table of random numbers found in 0, Table D.13.

Class 2 areas are surveyed on a random-start systematic pattern. The number of calculated survey locations, n, based on the statistical tests, is used to determine the spacing, L, of a systematic pattern by:

$$L = \sqrt{A / (0.866\, n)} \qquad \textit{for a triangular grid} \qquad (3\text{-}22)$$

$$L = \sqrt{A / n} \qquad \textit{for a square grid} \qquad (3\text{-}23)$$

where A is the area of the survey unit.

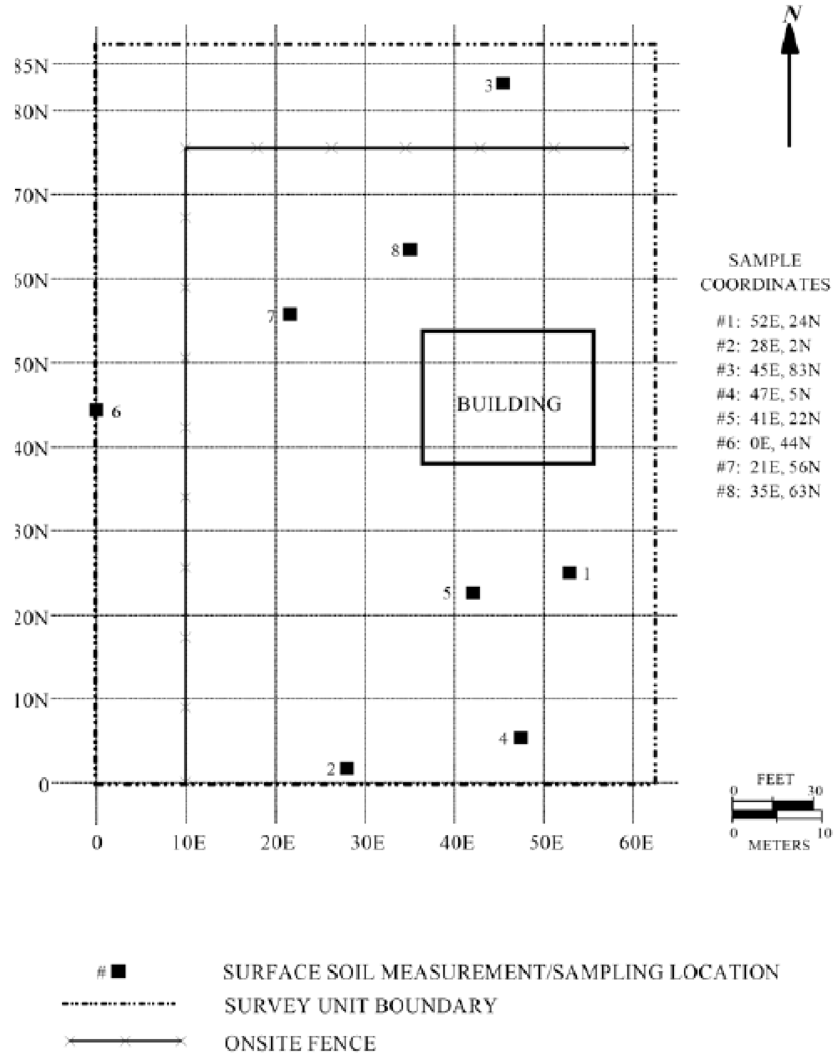


Figure 3.7 Example of a random measurement pattern

After L is determined, a random coordinate location is identified, as described previously, for a survey pattern starting location. Beginning at the random starting coordinate, a row of points is identified, parallel to the X-axis, at intervals of L.

For a triangular grid, a second row of points is then developed, parallel to the first row, at a distance of 0.866 × L from the first row. Survey points along that second row are midway (on the X-axis) between the points on the first row. This process is repeated to identify a pattern of survey locations throughout the affected survey unit. If identified points fall outside the survey unit or at locations which cannot be surveyed, additional points are determined using the random process described above, until the desired total number of points is identified.

An example of such a survey pattern is shown in Figure 3.8. In this example, the statistical test calculations estimate 20 samples (Table 3.37, $\alpha = 0.01$, $\beta = 0.05$, $\Delta/\sigma > 3.0$). The random-start coordinate was 27E, 53N. The grid spacing was calculated using Equation 3.22:

$$L = \sqrt{(5{,}100\ m^2 / (0.866 \times 20))} = 17\ m$$

Two points were identified on a row parallel to the X-axis, each 17 m from the starting point. The subsequent rows were positioned 0.866 × L, or 15 m, from the initial row. This random-start triangular sampling process resulted in 21 sampling locations, one of which was inaccessible because of the building location, which yields the desired number of data points.

For Class 1 areas a systematic pattern, having dimensions determined in Section 3.5.1.1, alinea 'Determining data points for small areas of elevated activity', is installed on the survey unit. The starting point for this pattern is selected at random, as described above for Class 2 areas. The same process as described above for Class 2 areas applies to Class 1, only the estimated number of samples is different.

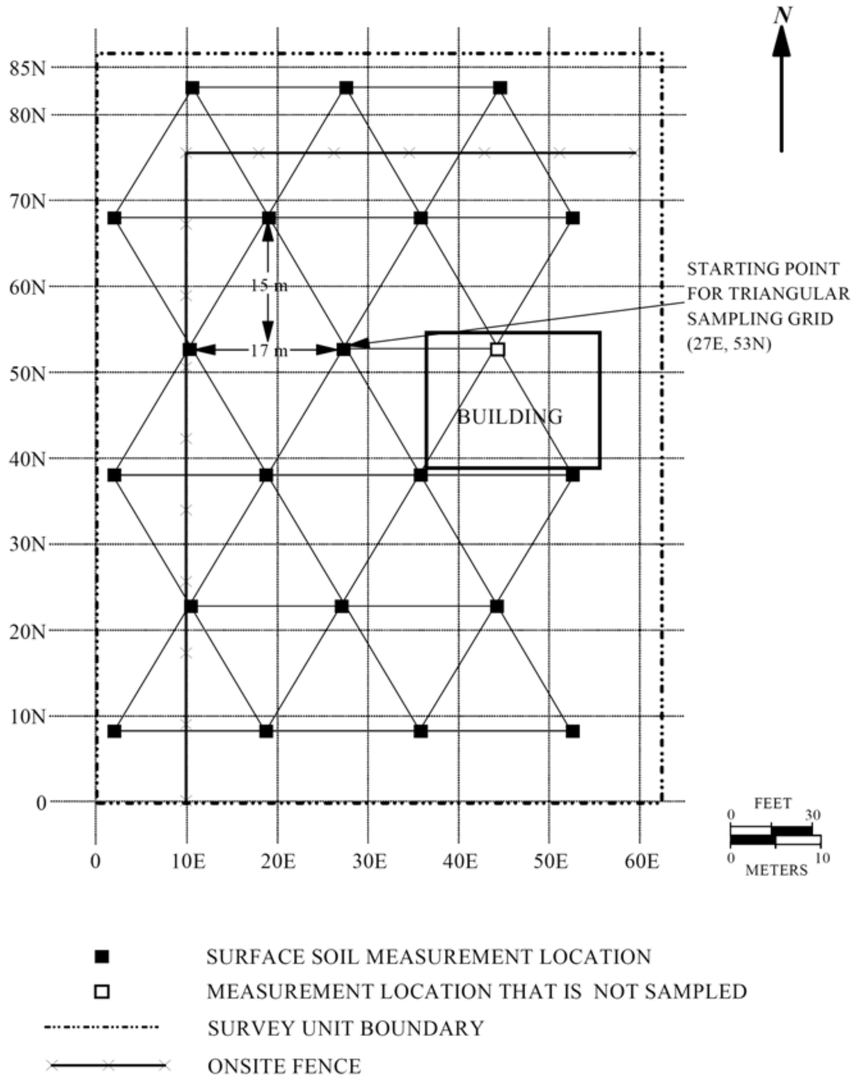


Figure 3.8 Example of a random-start triangular grid measurement pattern

All structure surfaces for a specific survey unit are included on a single reference grid system for purposes of identifying survey locations. The same methods as described above for land areas are then used to locate survey points for all classifications of areas.

In addition to the survey locations identified for statistical evaluations and elevated measurement comparisons, data will likely be obtained from judgment locations that are selected due to unusual appearance, location relative to contamination areas, high potential for residual activity, general supplemental information, historical site assessment, *etc*. Data points selected based on professional judgment are not included with the data points from the random-start triangular grid for statistical evaluations; instead they are compared individually with the established DCGLs and conditions. Measurement locations selected based on professional judgment violate the assumption of unbiased measurements used to develop the statistical tests described in Section 3.10.

3.5.1.3 Determining geographical location of survey data points

Some the sites covered by this guidance will have a long history of industrial development. In some cases, redevelopment or decommissioning of the site will be in progress. Significant amounts of environmental data may have already been obtained from routine environmental monitoring programmes and previous site investigations.

Given these factors, it is important that survey points are accurately located using a consistent convention. Survey points should be preferable referenced to national grid coordinates. If a local site grid is used instead, as is found on a number of nuclear licensed and industrial sites, then a conversion method to national grid co-ordinates should be provided.

Surveys should not be located relative to local landmarks, which, particularly on sites being decommissioned or redeveloped, have a tendency to disappear.

Record keeping issues are discussed in Section 3.5.2. On licensed sites as example nuclear sites, there is a requirement to retain all records relevant to compliance with the site licence. As a result, there may be a preference to store data in electronic format using geographical information systems (GIS).

3.5.1.4 Techniques for determining location of survey data points

The accurate location of measurements made during a survey is important for a number of reasons:

- To ensure that no parts of the survey area have been missed.
- To allow areas of contamination to be relocated at a later date.
- To allow the data to be accurately topographical plotted and presented.

This allows the radiological collected data to be properly coordinated and analysed. Reproducible knowledge of the coordinates of measurements may negate the need to repeat work in the future and may provide a standard of quality assurance which is more readily accepted by stakeholders (e.g., regulators). Consideration should be given to whether a locally defined frame of reference is acceptable (for instance measuring locations relative to buildings or roads) or whether (perhaps if extensive site demolition is envisaged) a more permanent frame of reference (e.g., latitude and longitude) will be required.

The positioning techniques vary in both sophistication and performance and have different fields of application. Traditional surveying techniques require trained personnel and can be slow.

Modern technology has provided methods which can assist considerably in the characterisation process.

Reference coordinate system

Reference coordinate systems are established at the site:

- To facilitate selection of measurement and sampling locations;
- To provide a mechanism for referencing a measurement to a specific location so that the same survey point can be relocated.

A survey reference coordinate system consists of a grid of intersecting lines, referenced to a fixed site location or benchmark. Typically, the lines are arranged in a perpendicular pattern, dividing the survey location into squares or blocks of equal area; however, other types of patterns (*e.g*., three-dimensional, polar) have been used.

The reference coordinate system used for a particular survey should provide a level of reproducibility consistent with the objectives of the survey. For example, a commercially available global positioning system will locate a position within tens of meters, while a differential global positioning system (DGPS), see the section below, provides precision on the order of a few centimetres. On the other hand, a metal bar can be driven into the ground to provide a long-term reference point for establishing a local reference coordinate system.

Reference coordinate system patterns on horizontal surfaces are usually identified numerically on one axis and alphabetically on the other axis or in distances in different compass directions from the grid origin. Grids on vertical surfaces may include a third designator, indicating position relative to floor or ground level. Overhead measurement and sampling locations (*e.g.*, ceiling and overhead beams) are referenced to corresponding floor grids.

For surveys of Class 1 and Class 2 areas, basic grid patterns at 1 to 2 meter intervals on structure surfaces and at 10 to 20 meter intervals of land areas may be sufficient to identify survey locations with a reasonable level of effort, while not being prohibitive in cost or difficulty of installation. Gridding of Class 3 areas may also be necessary to facilitate referencing of survey locations to a common system or origin but, for practical purposes, may typically be at larger intervals - *e.g.*, 5 to 10 meters for large structural surfaces and 20 to 50 meters for land areas.

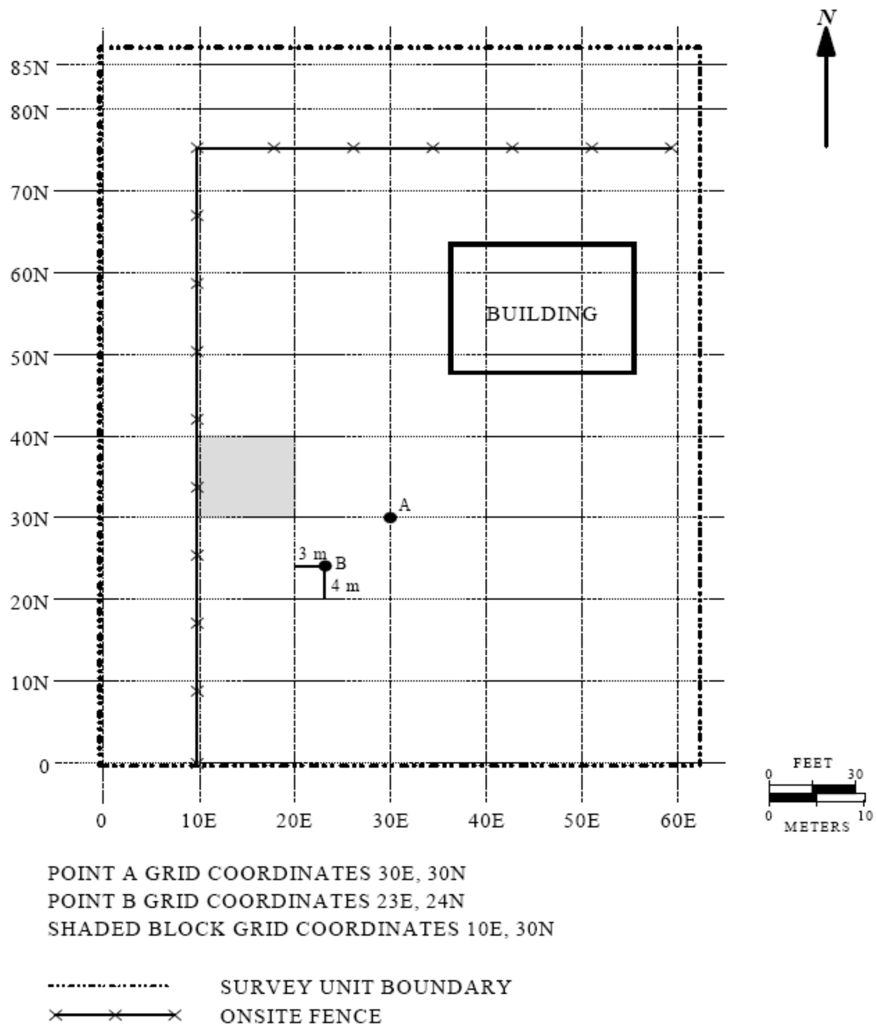


Figure 3.9 Example of a grid system for survey of site grounds using compass directions

Reference coordinate systems on structure surfaces are usually marked by chalk line or paint along the entire grid line or at line intersections. Land area reference coordinate systems are usually marked by wooden or metal stakes, driven into the surface at reference line intersections. The selection of an appropriate marker depends on the characteristics and routine uses of the surface. Where surfaces prevent installation of stakes, the reference line intersection can be marked by painting.

Three basic coordinate systems are used for identifying points on a reference coordinate system.

- References grid locations using numbers on the vertical axis and letters on the horizontal axis;
- Reference grid locations using reference distances from the 0,0 point using the compass directions N (north), S (south), E (east), and W (west), see example in Figure 3.9;
- Reference grid locations using reference distances along and to the R (right) or L (left) of the baseline.

In addition, a less frequently used reference system is the polar coordinate system, which measures distances along transects from a central point. Polar coordinate systems are particularly useful for survey designs to evaluate effects of stack emissions, where it may be desirable to have a higher density of samples collected near the stack and fewer samples with increasing distance from the stack.

Traditional positioning techniques

Traditional radiological topographical survey methods can generally provide the accuracy required for site characterisation methods and can give good standards of quality assurance provided that they can be linked to a series of well-defined and permanent reference objects. However, such measurements may be time consuming and labour intensive and may limit the speed at which measurements can be made in the field. Good measurements may be possible using only limited equipment (e.g., tape measures, surveyor wheels, grid marking, marking areas of contamination detected on-site using spray paint etc.) but will require that personnel have adequate training.

Global positioning system (GPS)

The United States Department of Defense operates a satellite-based system of absolute positioning (known as the global positioning system, GPS) which allows a low-cost hand-held device to give locations anywhere in the world to an absolute accuracy of about 10 m. The signals from the satellite are usually deliberately perturbed to improve the accuracy. By obtaining correction signals from one or more base-stations at known locations, positioning over a large area, such as a city or even continent, to an accuracy down to as little as 1 m is possible, with accuracy relative to a local datum of as little as 1 cm. Measurements may be taken from moving vehicles, and the equipment can be used to navigate to a series of waypoints or along a predetermined path. Such a system, called Differential GPS (DGPS) can be operated entirely by the user, either in real time or by post-processed corrections. DGPSs can record and retrieve location data with a precision in the centimetre range.

Alternatively, correction signals are provided by commercial organizations for a fee (e.g., Trimble™, Novatel™, Garmin™). The corrections can be broadcast over a local radio network, multiplexed with other signals or transmitted over satellite links. The overall result is a portable system that can be carried by a person or fitted to a vehicle and can provide accurate locations. GPS or DGPS requires, however, a clear view of the sky and cannot be used inside buildings or under dense tree cover, and may suffer from inaccuracies caused by reflections when used close to buildings. Positional data obtained from these measurements will be repeatable to an absolute frame of reference and so are of special value where major site engineering operations which would otherwise destroy reference objects are likely to take place.

DGPS can be used to provide position information on surface features in areas being surveyed, linking the survey results to previously published maps and aerial photographs. In addition, survey results may be positioned using the DGPS readings to accurately and precisely locate the results as well as the results of any subsequent analyses to these same maps or photographs. A process called way-pointing uses the DGPS to locate specific points and allows the user to find pre-determined locations and set up gridded locations for measurements based on location data that are tied into local or state coordinate systems.

Limitations on the use of DGPS are related to the number of satellite beacons available to the system. When three or fewer satellites are available the accuracy and precision of the location data will be reduced. There are short periods of time (usually less than one hour even on the worst days) when a limited number of satellites are overhead in the continental United States. Satellites may also be blocked by excess tree cover or tall buildings. Distance between the moving locator and the stationary base station may be several kilometres or may be limited to line-of-sight. This limitation can be mitigated through the strategic use of repeater stations to re-transmit the signal between the moving locator and the base station.

Microwave ranging systems

Local microwave or sonar beacons and receivers may provide useful location data in small areas, tree-covered locales. Various other techniques are available for providing relative positions over distances of tens of kilometers using microwaves. By measuring the time delays for a transmitted signal to be returned from two or more transponders, locations accurate to a few meters can be obtained.

One example of a sonar-based system is the ultrasonic ranging and data system (USRADS). With a number of fixed beacons in place, a roving unit can be oriented and provide location data with similar accuracy and precision as the DGPS. If the beacons are located at known points, the resulting positions can be determined using simple calculations based on the known reference locations of the beacons.

The logistics of deploying the necessary number of beacons properly and the short range of the signals are the major limitations of the system. In addition, multi-pathing of signals within wooded areas can cause jumps in the positioning data.

In many cases, however, DGPS would now be the preferred technique because it is absolute and does not require the accurate placing of transponders and a clear signal path to them.

Ultrasound ranging systems

For relatively small sites, such as a disused factory, inside or outside, and where good spatial resolution is required, positioning systems based on ultrasound time-of-flight measurements are available. Such systems can provide locations to better than 1 m over distances of the order of 100 m. It is necessary to place and accurately locate several ultrasound transducers around the area to be surveyed.

Advanced surveying techniques: laser ranging

Modern surveying equipment includes fully automatic total stations which use a laser device to measure the range and angle from a base station to a prism located at a mobile survey point. The accuracy of this equipment is typically in the mm range over distances of up to several km. The laser ranging equipment will track the prism and so is of use in moving vehicles provided that a line of sight between base and prism survey point can be maintained. The equipment needs two or more reference objects to be available to establish the position of the station but otherwise can give results comparable to DGPS. Single-handed operation is often feasible and the equipment could be used for surveying large indoor areas as well as outdoor areas in the vicinity of buildings where DGPS may be unusable.

3.5.1.5 Depth-dependent sampling

Key considerations for depth-dependent sampling of soil

The sampling approaches described above consider only a 2-D (area) distribution of contaminants. It is essential to understand the 3-D structure of the site and the distribution of contaminants within that volume if valid conclusions are to be drawn from the survey. To achieve this, the soil sampling strategy needs to address the required depth of boreholes and trial pits and the approach to collecting samples from them.

The required depth of boreholes/trial pits and the strategy for collecting soil samples from them depend on the reason for characterising the site, and take into account issues such as:

- The expected depth distribution of contaminants in the source areas. This is dependent on:
  - The mechanism(s) of contamination (e.g., surface deposition, depth of made ground sub-surface leakage from storage tanks).
  - The geological and hydro-geological properties of the soils and rocks (e.g., the presence of major fracture zones, which may act as pathways for deeper penetration, or of low-permeability horizons, which may act as barriers to contaminant migration).
  - The water balance at the site (e.g., the effective infiltration rate or the presence of rising groundwater).
  - The physical properties of the contaminant (e.g., dissolved in groundwater, light or heavy non-aqueous-phase liquids, colloids/particulates).
  - The chemical properties of the contaminants (e.g., its solubility and sorption characteristics in the sub-surface environment at the site).
- The potential contaminant migration pathways identified in the conceptual model:
  - Analysis of the immediate surface layer of soil would invariably be required, because of human health issues such as ingestion and inhalation of soil. This surface layer should be defined on a site specific basis related to the conceptual model. Sampling depths may vary between the surface and 0.5 m, and may require sampling at more than one level.
  - Samples from each distinctive horizon of made ground, fill and natural strata should be collected.
  - The focus placed on sampling deeper soils would depend upon the expected significance of subsurface pathways in transporting contaminants from the source area to potential receptors, particularly off-site.
  - Any additional testing requirements (e.g., geotechnical characterisation of the site).

Downhole radiological measurements

Downhole radiological measurements complement non-intrusive radiological surveys (see Section 3.6) and radiological monitoring during intrusive investigations (see Section 3.7). The technique, which gives information on the distribution of radioactivity along the borehole axis, can be used in three situations:

- In conjunction with permanent monitoring points (for example, downhole logging of groundwater monitoring boreholes).
- During construction of conventional temporary sampling boreholes from which soil and/or water samples are being collected (see Section 3.4.2.9).

- In conjunction with temporary percussive holes from which no waste or samples are produced at surface (for example, cone penetrometer testing).

Downhole radiological measurements can be used to improve targeting of samples taken for subsequent laboratory analysis or to provide interpolation between sparse data from borehole samples (for example, where contamination of bedrock is focused in fractures that may be difficult to sample, or where drilling conditions lead to depth intervals where no solid material is returned to surface for sampling). In addition, the third situation, above, is useful for characterising areas where there is relatively high contamination by gamma emitting radionuclides, because measurements can be made without the need to produce waste.

In all applications of downhole measurements, it is necessary to consider the following:

- *The penetrating power of the ionising radiation in the soil or rock around the borehole, in any borehole construction materials (such as casing) and in the air or water filling the borehole*. Downhole logging is most appropriate to determining the distribution of gamma emitting radionuclides.
- *Calibration of results*. The technique provides information on the distribution of areas of elevated radioactivity. Accurate calibration to derive specific activities (e.g., Bq/g of soil) requires information on source-detector geometry, on the spatial distribution of the radionuclide and on the attenuation characteristics of the radiation. If quantitative information on specific activities is required, laboratory analysis of samples will be needed to build confidence in the calibration.
- *The susceptibility of the approach to any external contamination of the detector assembly*. It is important to monitor for surface contamination on the detector at frequent intervals and to evaluate results with caution if surface contamination is detected.

It is also necessary to consider the consequence of repeated purging of groundwater monitoring boreholes on downhole radiological measurements. Purging leads to some of the fine-grained material from the formation being drawn into the filter materials placed around the well screen (if these are present) or into the borehole itself. In the latter case, the material settles to the bottom of the borehole (silting up the well). Because radioactive contamination is often concentrated on the fine-grained fraction of the soil or rock, this redistribution of material can have a significant effect on downhole radiological measurements. In the extreme case, downhole measurements may be dominated by radioactivity from contaminated silt at the bottom of the borehole. For this reason, it is best practice to undertake downhole radiological measurements prior to groundwater sampling. Where this is not possible, data from downhole radiological measurements should be interpreted with caution.

3.5.1.6 Other sampling/measurement locations

In addition to land surface areas surveys and structure surveys, there are numerous other locations where measurements and/or sampling may be necessary during remedial actions. Examples include items of drains, ducts, piping, equipment and furnishings, and building fixtures.Many of these items or locations have both internal and external surfaces with potential residual radioactivity. Subsurface measurements and/or sampling may also be necessary.

Special situations may be evaluated by judgment sampling and measurements. Data from such surveys should be compared directly with DCGLs developed for the specific situation. Areas of elevated direct radiation identified by surface scans are typically followed by direct measurements or samples. These direct measurements and samples are not included in the non-parametric tests described in this manual, but rather, should be compared directly with DCGLs developed for the specific situation.

Quality control measurements are recommended for all surveys, as described in Section 3.3.9. These additional measurements should be considered during survey planning.

3.5.2 Sample tracking/record keeping

Sample tracking refers to the identification of samples, their location, and the individuals responsible for their custody and transfer of the custody. This process covers the entire process from collection of the samples and remains intact through the analysis and final holding or disposal. It begins with the taking of a sample where its identification and the designation of the sample are critical to being able to relate the analytical result to a site location.

Tracking samples from collection to receipt at the analytical laboratory is normally done through a Chain of Custody process, and documented on a Chain-of-Custody (COC) record. Once samples are received by the laboratory, internal tracking (*e.g.*, Chain-of-Custody) procedures should be in place and codified through standard operation procedures that assure integrity of the samples. Documentation of changes in the custody of a sample(s) is important. This is especially true for samples that may be used as evidence to establish compliance with a release criterion. In such cases, there should be sufficient evidence to demonstrate that the integrity of the sample is not compromised from the time it is collected to the time it is analyzed. During this time, the sample should either be under the positive control of a responsible individual or secured and protected from any activity that could change the true value of the results or the nature of the sample. When this degree of sample handling or custody is necessary, written procedures should be developed for field operations and for interfacing between the field operations and the analytical laboratory. This ensures that a clear transfer of the custodial responsibility is well documented and no questions exist as to who is responsible for the sample at any time.

3.5.2.1 Field tracking considerations

Field personnel are responsible for maintaining field logbooks with adequate information to relate the sample identifier (sample number) to its location and for recording other information necessary to adequately interpret results of sample analytical data.

The sample collector is responsible for the care and custody of the samples until they are properly transferred or dispatched. This means that samples are in their possession, under constant observation, or secured. Samples may be secured in a sealed container, locked vehicle, locked room, *etc.*

Sample labels should be completed for each sample using waterproof ink.

The survey manager or designee determines whether or not proper custody procedures were followed during the field work, and decides if additional sampling is indicated.

If photographs are included as part of the sampling documentation, the name of the photographer, date, time, site location, and site description should be entered sequentially in a logbook as the photos are taken. After the photographs are developed, the prints should be serially numbered.

3.5.2.2 Photography

Photographs provide a valuable record of a contaminated land survey. However, there are often significant restrictions to the use of cameras on nuclear-licensed sites, defense and industrial sites. Prior to use of a camera on these sites, permission should be sought from the site operator. Ideally photographs should be taken of:

- Contaminant source areas.
- All sampling locations before sampling.

- All sampling locations during sampling.
- All sampling locations after sampling and reinstatement.
- Trial pit walls.
- Any exposed in-situ geological materials.
- Core samples prior to them being divided up for analysis.

3.5.2.3 Sample labelling and transport

Samples should be clearly labelled in a manner that cannot be removed during handling. The labels should include the following minimum information:

- Location number.
- Depth interval.
- Date of sampling.
- Hazard information.

Transport of samples to the laboratory should take place as soon as possible after sample collection to minimise the potential for degradation to occur. Advice on storage conditions should be sought from the analyst.

Radioactively contaminated samples containing greater than 70 Bq/g total radioactivity become subject to the radioactive substances (road transport) regulations [29]. If this is the case, samples are required to be labelled, packaged and transported in accordance with the regulations. However, the total radioactivity of a sample is not known until is analysed. If it is suspected that some samples may contain greater than 70 Bq/g of radioactivity, it may be necessary to undertake onsite screening analysis, for example using a portable gamma spectrometer, to determine the appropriate method of transport. If this is not possible, then samples should be transported in accordance with the requirements of the radioactive substances (road transport) regulations [29].

3.5.2.4 Transfer of custody

A chain of custody document should be prepared for each sample or batch of samples and should record collection in the field, off-site consignment to the testing laboratory and receipt by the testing laboratory:

- All samples leaving the site should be accompanied by a Chain-of-Custody record. This record documents sample custody transfer from the sampler, often through another person, to the laboratory. The individuals relinquishing the samples should sign and date the record. The record should include a list, including sample designation (number), of the samples in the shipping container and the analysis requested for each sample.
- Shipping containers should be sealed and include a tamper indicating seal that will indicate if the container seal has been disturbed. The method of shipment, courier name, or other pertinent information should be listed in the Chain-of-Custody record.
- The original Chain-of-Custody record should accompany the samples. A copy of the record should be retained by the individual or organization relinquishing the samples.
- Discuss the custody objectives with the shipper to ensure that the objectives are met. For example, if the samples are sent by mail and the originator of the sample requires a record that the shipment was delivered, the package should be registered with return receipt requested. If, on the other hand, the objective is to simply provide a written record of the shipment, a certificate of mailing may be a less expensive and appropriate alternative.

- The individual receiving the samples should sign and date the record. The condition of the container and the tamper indicating seal should be noted on the Chain-of-Custody record. Any problems with the individual samples, such as a broken container, should be noted on the record.
- Subsequent to testing, the surplus portions of the samples may be returned to the site operator (for long term archiving, storage or disposal) or may be disposed by the principal contractor or analytical testing laboratory in accordance with national or European legislation. The chain of custody document should record these transfers. The disposal of radioactively contaminated samples should be considered as part of the site characterisation works waste management plan in Section 2.
- A copy of the Chain-of-Custody document should be kept in the project file.

3.5.2.5 Laboratory tracking

When the samples are received by the laboratory they are prepared for radiochemical analyses. This includes the fractionation of the sample into aliquots. The tracking and Chain-of-Custody documentation within the laboratory become somewhat complicated due to the fact that several portions of the original sample may exist in the laboratory at a given time. The use of a computer based laboratory information system can greatly assist in tracking samples and fractions through the analytical system.

The minimal laboratory tracking process consists of the following:

- Transfer of custody on receipt of the samples (original Chain-of-Custody form is retained by the laboratory and submitted with the data package for the samples).
- Documentation of sample storage (location and amount).
- Documentation of removal and return of sample aliquots (amount, date and time, person removing or returning, and reason for removal).
- Transfer of the samples and residues to the receiving authority (usually the site from which they were taken).

The procedure for accomplishing the above varies from laboratory to laboratory, but the exact details of performing the operations of sample tracking should be contained in a standard operating procedure (SOP).

3.6 Site characterisation: Non-intrusive methods

3.6.1 Introduction

Non-intrusive survey techniques are used in the first instance to rapidly obtain information about the site, in order to focus intrusive methods of investigation and sampling. However, due to gained experiences and improvement of the non-intrusive survey techniques, they are sometimes now also applied for main radiological investigations. Methods commonly employed are:

- Radiological surveys.
- Geophysics.
- Drain surveys.

3.6.2 Non-intrusive radiological surveys

Ionising radiations (in particular, gamma radiation) can be detected in the field in real time, as example, with hand-held instruments. In contrast, most chemical contaminants can only be detected at some later time through laboratory measurement. As a consequence, non-intrusive radiation surveys (or ‘radiological surveys’) are a key component of any investigation on a potentially radioactively contaminated site. At present, there are no routinely used counterparts for detecting chemical contamination (with the possible exception of the use of gas monitoring equipment).

Radiological surveys, as with the other characterisation methods described in this section, should only be carried out by organisations experienced in undertaking such work. The guidance given below is not prescriptive or a method statement for carrying out a radiological survey, but a set of pointers to highlight important issues and good practice and to identify some common problems and mistakes.

The discussion summarised here is primarily from two references, which provide extensive information on the subject:

- MARSSIM: The Multi-Agency Radiation Survey and Site Investigation Manual [2], [10] and www.marssim.com).
- Environment Agency, Technical support material for the regulation of radioactively contaminated land [102].

Detailed information about existing non-intrusive radiological is provided later in this section.

Radiological surveys in the field can be broadly divided into two types: scanning surveys and direct (or point) measurements:

- *Scanning surveys*. Radiation scanning surveys (sometimes called walkover radiation surveys, because they are typically undertaken on foot) are carried out using portable radiation detection equipment that responds rapidly to the presence of primarily gamma emitting radionuclide contamination on or close to the ground surface mostly nowadays combined with a global positioning system. The aim of these surveys is to identify rapidly the areal distribution of contamination at a site in order to focus further investigations. The results of the survey are generally presented in iso-plots or in tables and can give a good indication of the average value and of the relative levels of radioactivity across the site.
- *Direct (point) measurements*. Direct measurements are carried out on the site to determine absolute values for certain parameters or to provide a better understanding of which radionuclides are present. Direct measurements tend to use instrumentation that is slower to respond or bulkier than that used for scanning surveys.

In general, a scanning radiological survey is carried out first, followed by point measurements (if necessary and sometimes called verification measurements) in areas of interest highlighted during the scanning survey.

The decision to use a measurement method as part of the survey design is determined by the survey objectives and the survey unit classification.

It should be noted that surveys in which data are recorded as equivalent dose (in, for example, µSv/hr) may be directly compared with other surveys. In contrast, surveys in which data are recorded as counts per second are not directly comparable with each other unless the same instrument has been used.

3.6.2.1 Design of non-intrusive radiological surveys

The first stage of designing the radiological survey is to identify the objectives of the work (see also Table 3.1, Examples of linkages between site characterisation design aspects and conceptual model). In most cases, this will consist of one or more of the following:

- To determine if radiation levels (e.g., dose rate, contamination) on the site present are a hazard to site personnel or for the environment.
- To determine the spatial distribution of radiation levels on the site.

- To determine if radionuclides on the site present are a hazard to site personnel (if necessary):
  - To determine the spatial distribution of radionuclides on the site (if necessary).
  - To determine the degree of heterogeneity in the distribution of any contamination.
  - To determine the fingerprint of the radionuclides on the site.
- To determine the size of the site to be surveyed.

Having identified the objectives, the questions in Table 3.40 can be of help to design the survey. The detailed survey design and equipment selection will depend on the site conditions and the radiation levels and/or radionuclides expected to be present. In general, three aspects will be considered: the type of radiation detector, its method of use and the scale of the survey grid.

Table 3.40 Design Issues to be considered by non-intrusive radiation surveys

Issue		**Remark**
Radiation levels	Which radiation levels are likely to be present?	- Based on environmental monitoring, primarily desk study (previous usage of radionuclides and amounts used).
		- Important because it is the primary drive in the selection of radiological monitoring equipment (see Section 3.8 and 0).
	What are the natural background radiation levels at the site?	- From previous monitoring from the area. If inadequate background information exists, it will be necessary to make measurements to assess this.
	What is the detection limit required for the first action level?	- Based on the derived guideline levels for background radiation (see Section 2.2.2.4, Section 2.5 and Section 3.3.6).
Radionuclides	Which radionuclides are likely to be present and at what activity levels?	- Based on environmental monitoring, primarily desk study (previous usage of radionuclides and amounts used). - Important because it is the primary drive in the selection of radiological monitoring equipment (see Section 3.8 and 0).
	What are the natural background levels of radioactivity at the site?	- From previous monitoring from the area. If inadequate background information exists, it will be necessary to make measurements to assess this.
	What are the detection limits required for the radionuclides of interest?	- Based on the derived guideline levels for the radionuclides of interest (see Section 2.2.2.4, Section 2.5 and Section 3.3.6).
		- If the radionuclide fingerprint[20] is known, it may be possible to infer the presence of a radionuclide by measuring the most easily detectible radionuclide in the fingerprint.
Size of the site	What is the size of the site to be surveyed?	- Minimum the entire area of ground that has the potential to be contaminated and/or to assess the background.
		- Depending on the type of characterisation (see section 3.1.4) the design can be focused on known or suspected problems.
		- Important because this will drive selection of radiological monitoring equipment (see Section 3.8 and 0), transportation and grid size.
Time and costs	What are the time/cost limitations on the job?	- Financial and time constraints will often have a significant impact on the type of survey selected.

3.6.2.2 Scanning surveys

Scanning is the process by which the operator uses portable radiation detection instruments to detect the presence of radio-nuclides on a specific surface (*i.e.*, ground, wall, floor,

20 A fingerprint of radionuclides is a method by which difficult to measure radionuclides are linked to a more easily detectable radionuclide (see Section 3.3.6.2).

equipment). The term scanning survey is used to describe the process of moving portable radiation detectors across a suspect surface with the intent of locating radionuclide contamination. Investigation levels for scanning surveys are determined during survey planning to identify areas of elevated activity. Scanning surveys are performed to locate radiation anomalies indicating residual gross activity that may require further investigation or action. These investigation levels may be based on the $DCGL_W$, the $DCGL_{EMC}$, or some other level as discussed in Section 3.3.2.7.

Small areas of elevated activity typically represent a small portion of the site or survey unit. Thus, random or systematic direct measurements or sampling on the commonly used grid spacing may have a low probability of identifying such small areas. Scanning surveys are often relatively quick and inexpensive to perform. For these reasons, scanning surveys are typically performed before direct measurements or sampling. This way time is not spent fully evaluating an area that may quickly prove to be contaminated above the investigation level during the scanning process. Scans are conducted which would be indicative of all radio-nuclides potentially present, based on the historical site assessment, surfaces to be surveyed, and survey design objectives. Surrogate measurements may be utilized where appropriate (see Section 3.3.6.2). Documenting scanning results and observations from the field is very important. For example, a scan that identified relatively sharp increases in instrument response or identified the boundary of an area of increased instrument response should be documented. This information is useful when interpreting survey results.

The following sections briefly describe techniques used to perform scanning surveys for different types of radiation. The instruments used to perform these measurements are described in more detail in 0.

There are three main methods by which radiological monitoring equipment may be transported:

- By hand.
- In a ground-based vehicle (e.g., hand trolley, car).
- By air.

The relative advantages and disadvantages of each approach are given below.

Walkover survey

This consists of a single person or two persons carrying up to approximately 15 kg of equipment. The walkover survey is suitable for areas up to a few hectares (both inside and outside buildings), and may be undertaken over relatively rough ground. As the equipment is carried by a single person, lightweight probes with little collimation are in general used. Due to technical improvement light weight computer controlled real-time spectrometry systems becomes available so that also multiple detectors can be employed.

Vehicle survey

This consists of a ground-based vehicle, either hand-pushed or motorised, carrying up to approximately 500 kg of equipment. The vehicle survey is suitable for large (tens of hectares), flat open areas, for example, airfields or roadways. The vehicle survey has a number of advantages over the walkover survey, which are predominantly due to the increased mass that can be carried and the fact that the vehicle is weather-proof. Sophisticated electronics may be carried that allow real-time spectrometry, multiple detectors may be employed and large-area scintillation detectors can be used to achieve low detection limits. The main disadvantage of the vehicle survey compared to the walkover survey is that the site must be flat and open.

Airborne survey

In situations involving widespread contamination with sufficient gamma radiation emissions, aerial surveys can be a cost effective method for rapidly delineating and quantifying such areas. Helicopters are used for low-level work where maximum sensitivity is required, while an aeroplane or helicopter will be applied at higher attitudes. Positioning is generally accomplished with commercial navigation systems (e.g., GPS) which feed indicators to guide the pilot accurately along pre-selected routes. Gamma radiation, flight path, altitude and meteorological data are fed into an inboard data acquisition system for real time or post-flight analysis. Gamma radiation data including spectral data overlaid on aerial photographs indicate the location of the contamination very accurately.

The airborne survey is a rapid method, suitable for very large (thousands of hectares), rough or inaccessible areas. However, it has the disadvantage that individual measurements will be averaged over tens to hundreds of square metres.

In addition, overflying restrictions may apply on nuclear-licensed and defence sites, limiting the applicability of this technique. The IAEA TECDOC-1363 gives a state of the art overview of this technique [40].

Scanning for photon emitting radio-nuclides

Sodium iodide survey meters (NaI(Tl) detectors) are normally used for scanning areas for gamma emitters because they are sensitive to gamma radiation, easily portable and relatively inexpensive. The detector is held at a certain distance from the ground surface (~6 cm or 2.5 in up to 1 m or 40 in.) and moved in a meander or a serpentine (*i.e.*, snake like, “S” shaped) pattern while walking at a speed that allows the investigator to detect the desired investigation level. A scan rate of approximately 0.5 m/s is typically used for distributed gamma emitting contaminants in soil; however, this rate must be adjusted depending on the expected detector response and the desired investigation level. Discussion of scanning rates versus detection sensitivity for gamma emitters is provided in Section 3.3.7.2.

Sodium iodide survey meters are also used for scanning to detect areas with elevated areas of low-energy gamma and X-ray emitting radio-nuclides such as ^{241}Am and ^{239}Pu. These sodium iodide detectors are specified in such a way that they are more sensitive for low-energy gammas and X-rays.

Scanning for alpha emitting radionuclides

Alpha scintillation survey meters and thin window gas-flow proportional counters are typically used for performing alpha surveys. Alpha radiation has a very limited range and, therefore, instrumentation must be kept close to the surface - usually less than 1 cm (0.4 in.). For this reason, alpha scans are generally performed on relatively smooth, impermeable surfaces (*e.g.*, concrete, metal, drywall) and not on porous material (*e.g.*, wood) or for volumetric contamination (*e.g.*, soil, water). In most cases, porous and volumetric contamination cannot be detected by scanning for alpha activity and meet the objectives of the survey because of high detection sensitivities. Under these circumstances, samples of the material are usually collected and analyzed as discussed in Section 3.3.7. Determining scan rates when surveying for alpha emitters is discussed in 0 and 0.

Scanning for beta emitting radio-nuclides

Thin window gas-flow proportional counters are normally used when surveying for beta emitters, although solid scintillators designed for this purpose are also available. Typically, the beta detector is held less than 2 cm from the surface and moved at a rate such that the desired investigation level can be detected. Low-energy (< 100 keV) beta emitters are subject to the same interferences and self-absorption problems found with alpha emitting radio-nuclides, and scans for these radio-nuclides are performed under similar circumstances. Determination of scan rates when surveying for beta emitters is discussed in Section 6.7.2.1.

3.6.2.3 Direct measurements

To conduct direct measurements of alpha, beta, and photon surface activity, instruments and techniques providing the required detection sensitivity are selected. The type of instrument and method of performing the direct measurement are selected as dictated by the type of potential contamination present, the measurement sensitivity requirements, and the data quality objectives of the radiological survey. Direct measurements are taken by placing the instrument at the appropriate distance[21] above the surface, taking a discrete measurement for a pre-determined time interval (*e.g.*, 10 s, 60 s, *etc.*), and recording the reading. A one minute integrated count technique is a practical field survey procedure for most equipment and provides detection sensitivities that are below most derived concentration guideline levels (DCGLs). However, longer or shorter integrating times may be warranted (see Section 3.3.7.2 for information dealing with the calculation of direct measurement detection sensitivities).

Direct measurements may be collected at random locations in the survey unit. Alternatively, direct measurements may be collected at systematic locations and supplement scanning surveys for the identification of small areas of elevated activity (see Section 3.5.1.2). Direct measurements may also be collected at locations identified by scanning surveys as part of an investigation to determine the source of the elevated instrument response. Professional judgment may also be used to identify location for direct measurements to further define the areal extent of contamination and to determine maximum radiation levels within an area, although these types of direct measurements are usually associated with preliminary surveys (*i.e.*, scoping, characterization, remedial action support). All direct measurement locations and results should be documented.

If the equipment and methodology used for scanning is capable of providing data of the same quality required for direct measurement (*e.g.*, detection limit, location of measurements, ability to record and document results), then scanning may be used in place of direct measurements. Results should be documented for at least the number of locations required for the statistical tests. In addition, some direct measurement systems may be able to provide scanning data, provided they meet the objectives of the scanning survey.

The following sections briefly describe methods used to perform direct measurements in the field. The instruments used to perform these measurements are described in more detail in Section 3.8 and 0.

Direct measurements for photon emitting radio-nuclides

There are a wide variety of instruments available for measuring photons in the field (see 0) but all of them are used in essentially the same way. The detector is set up at a specified distance from the surface being measured and data are collected for a specified period of time. The distance from the surface to the detector is generally determined by the calibration of the instrument because photons do not interact appreciably with air. When measuring X-rays or low-energy gamma rays, the detector is often placed closer to the surface to increase the counting efficiency. The time required to perform a direct measurement may vary from very short (*e.g.*, 10 seconds) to very long (*e.g.*, several days or weeks) depending on the type of detector and the required detection limit. In general, the lower the required detection limit the longer the time required to perform the measurement. A collimator may be used in areas where activity from adjacent or nearby areas might interfere with the direct measurement. The collimator (usually lead, tungsten, or steel) shields the detector from extraneous photons but allows activity from a specified area of the surface to reach the detector.

Example 3.18: Direct measurement of gamma emitting radionuclide concentrations in the field

[21] Measurements at several distances may be needed. Near-surface or surface measurements provide the best indication of the size of the contaminated region and are useful for model implementation. Gamma measurements at 1 m provide a good estimate of potential direct external exposure.

The portable germanium detector, or in-situ gamma spectrometer, can be used to estimate gamma emitting radionuclide concentrations in the field. As with the laboratory-based germanium detector with multi-channel analyzer, in-situ gamma spectrometry can discriminate among various radio-nuclides on the basis of characteristic gamma and X-ray energies to provide a nuclide-specific measurement. A calibrated detector measures the fluence rate of primary photons at specific energies that are characteristic of a particular radionuclide. This fluence rate can then be converted to units of concentration. Under certain conditions the fluence rate may be converted directly to dose or risk for a direct comparison to the release criterion rather than to the $DCGL_W$. Although this conversion is generally made, the fluence rate should be considered the fundamental parameter for assessing the level of radiation at a specific location because it is a directly measurable physical quantity.

For outdoor measurements, where the contaminant is believed to be distributed within the surface soil, it may be appropriate to assume a uniform depth profile when converting the fluence rate to a concentration. At sites where the soil is plowed or overturned regularly, this assumption is quite realistic because of the effects of homogenization. At sites where the activity was initially deposited on the surface and has gradually penetrated deeper over time, the actual depth profile will have a higher activity at the surface and gradually diminish with depth. In this case, the assumption of a uniform depth profile will estimate a higher radionuclide concentration relative to the average concentration over that depth. In cases where there is an inverted depth profile (*i.e.*, low concentration at the surface that increase with depth), the assumption of a uniform depth profile will underestimate the average radionuclide concentration over that depth. For this reason, EURSSEM recommends that soil cores be collected to determine the actual depth profile for the site. These soil cores may be collected during the characterization or remedial action support survey to establish a depth profile for planning a final status survey. The cores may also be collected during the final status survey to verify the assumptions used to develop the fluence-to-concentration correction.

For indoor measurements, un-collimated *in-situ* measurements can provide useful information on the low-level average activity across an entire room. The position of the measurement within the room is not critical if the radionuclide of interest is not present in the building materials. A measurement of peak count rate can be converted to fluence rate, which can in turn be related to the average surface activity. The absence of a discernible peak would mean that residual activity could not exceed a certain average level. However, this method will not easily locate small areas of elevated activity. For situations where the activity is not uniformly distributed on the surface, a series of collimated measurements using a systematic grid allows the operator to identify general areas of elevated contamination.

In-situ spectrometry is provided as one example of a useful tool for performing direct measurements for particular scenarios, but interpretation of the instrument output in terms of radionuclide distributions is dependent on the assumptions used to calibrate the method site-specifically. The depth of treatment of this technique in this example is not meant to imply that *in-situ* gamma spectrometry is preferred *a priori* over other appropriate measurement techniques described in this manual.

Direct measurements for alpha emitting radionuclides

Direct measurements for alpha-emitting radio-nuclides are generally performed by placing the detector on or near the surface to be measured. The limited range of alpha particles (*e.g.*, about 1 cm or 0.4 in. in air, less in denser material) means that these measurements are generally restricted to relatively smooth, impermeable surfaces such as concrete, metal, or drywall where the activity is present as surface contamination. In most cases, direct measurements of porous (*e.g.*, wood) and volumetric (*e.g.*, soil, water) material cannot meet the objectives of the survey. However, special instruments such as the long range alpha detector (see 0) have been developed to measure the concentration of alpha emitting radionuclides in soil under certain conditions. Because the detector is used in close proximity to the potentially contaminated surface, contamination of the detector or damage to the detector caused by irregular surfaces need to be considered before performing direct measurements for alpha emitters.

Direct measurements for beta emitting radionuclides

Direct measurements for beta emitting radio-nuclides are generally performed by placing the detector on or near the surface to be measured, similar to measurements for alpha emitting radio-nuclides. These measurements are typically restricted to relatively smooth, impermeable surfaces where the activity is present as surface contamination. In most cases, direct measurements of porous (*e.g.*, wood) and volumetric (*e.g.*, soil, water) material cannot meet the objectives of the survey. However, special instruments such as large area gas-flow proportional counters (see 0) and arrays of beta scintillators have been developed to measure the concentration of beta emitting radio-nuclides in soil under certain conditions. Similar to direct measurements for alpha emitting radio-nuclides, contamination of the detector and damage to the detector need to be considered before performing direct measurements for beta emitters.

Direct radon measurements

Direct radon measurements are performed by gathering radon into a chamber and measuring the ionizations produced. A variety of methods have been developed, each making use of the same fundamental mechanics but employing different measurement processes. The first step is to get the radon into a chamber without collecting any radon progeny from the ambient air. A filter is normally used to capture charged aerosols while allowing the radon gas to pass through. Most passive monitors rely on diffusion of the ambient radon in the air into the chamber to establish equilibrium between the concentrations of radon in the air and in the chamber. Active monitors use some type of air pump system for the air exchange method.

Once inside the chamber, the radon decays by alpha emission to form ^{218}Po which usually takes on a positive charge within thousandths of a second following formation. Some monitor types collect these ionic molecules and subsequently measure the alpha particles emitted by the radon progeny. Other monitor types, such as the electret ion chamber, measure the ionization produced by the decay of radon in the air within the chamber by directly collecting the ions produced inside the chamber. Simple systems measure the cumulative radon during the exposure period based on the total alpha decays that occur. More complicated systems actually measure the individual pulse height distributions of the alpha and/or beta radiation emissions and derive the radon plus progeny isotopic concentration in the air volume.

Care must be taken to accurately calibrate a system and to understand the effects of humidity, temperature, dust loading, and atmospheric pressure on the system. These conditions create a small adverse effect on some systems and a large influence on others.

3.6.3 Non-intrusive geological surveys

3.6.3.1 The application of geophysical techniques

Geophysical techniques provide an indirect means of characterising a site prior to any intrusive works. For contaminated land sites, geophysical methods that identify variations in the near surface structure or chemistry of the ground are required.

Many nuclear-licensed sites, e.g., defense and NORM industrial sites have a long history of development, and it is possible that records on the exact locations of disused disposal sites, underground storage tanks and demolished buildings have been mislaid. Operational sites have many sub-surface services (including electrical supplies, water supplies, gas mains, trade waste drains, radioactive waste drains, telephone lines and fibre optic cables), some of which may not be accurately located on site plans.

On nuclear-licensed sites, geophysical methods have two principal uses:

- Identification of sub-surface services (and munitions only for defense sites), which may be a hazard for intrusive investigations.
- Characterisation of the geological structure of the site and identification of sub-surface structures (such as buried tanks or foundations) or potential waste disposal pits.

A geophysical survey will not necessarily identify all features associated with the contaminated land or all services in an area. Safe excavation practices must be employed during the intrusive phases of the work (see Section 3.7.2 and Section 4 for information on procedures for undertaking excavations).

3.6.3.2 Commonly applied geophysical techniques

The three methods that are of most use for the investigation of potentially contaminated land on nuclear-licensed sites are:

- Electrical methods.
- Magnetic methods.
- Microgravity.
- Ground penetrating radar (GPR).

These techniques provide characterisation of the near-surface environment, typically within 3 m of ground surface. Other techniques, such as seismic reflection/refraction and other gravitational surveys, provide information on the deeper structure at the site. These techniques are less likely to be used in contaminated land investigations and are not discussed further here.

Features that can be identified by the geophysical techniques discussed below include:

- Buried objects (in particular concrete and metallic wastes).
- Areas of disturbed ground (such as waste disposal pits).
- Services (in particular metallic pipes or electrical supplies).
- Buried foundations and sub-surface voids.

Also, but less reliably, variations in geology, plumes of contamination and groundwater saturation may be detected.

Recent innovations linking geophysical data acquisition with GPS data through sophisticated data processing software has significantly improved the visualisation and presentation of information. Transfer of the information to GIS formats with other layered data allows interpretation against mapped and digital layouts, particularly existing and historical building footprints and services.

Electrical methods are divided into two types: electromagnetic surveying and resistivity profiling.

Electromagnetic surveying uses electromagnetic induction to measure the subsurface electrical properties. Electromagnetic surveys generally produce an areal plot of apparent resistivity over the area surveyed and can be configured to look, with limited resolution, at different depths. These surveys can often identify buried objects (such as concrete foundations), disturbed ground and metallic services.

They are significantly affected by surface metallic structures and care is needed to avoid anomalous readings adjacent to features such as fences. Resistivity profiling is carried out by inserting an array of electrodes into the ground surface, passing electrical current through pairs of these electrodes and measuring electrical potential between other pairs. Interpretation of the results gives a depth profile or, using imaging methods, a cross-section of ground resistivity. Resistivity profiling is employed where resistivity data of good vertical and horizontal definition are required or where above-ground metallic objects reduce the effectiveness of electromagnetic methods. Resistivity profiling may detect buried metallic objects and changes in ground conductivity.

Magnetic methods are used to map variations in the earth's local magnetic field caused by ferrous objects. Magnetic methods are primarily used to detect buried metallic objects such as cables, drums, pipes or waste materials. They can sometimes also be used to locate areas of fill material. Magnetic surveys can be used to estimate both the depth and mass of an object. The resolution of the method decreases with depth. Surface metallic objects may affect the results of magnetic surveys.

Microgravity techniques are based on measuring extremely small variations in the earth's gravitational field which are caused by the presence of materials of different densities, or voids, in the subsurface. The presence of an anomalously high (or low) density buried object causes a localised high (or low) anomaly in the gravitational field. This technique is useful for establishing buried foundations, basements of tanks.

Ground penetrating radar (GPR) systems transmit pulses of electromagnetic energy at microwave frequencies into the ground and measure the amplitude and travel time of the returned signals. The systems are used to detect buried ferrous and non-ferrous objects including plastic pipes, void spaces, drums and concrete. The penetration depth of the electromagnetic radiation, and hence the maximum detection depth for buried objects, depends on the electrical properties of the soil.

3.6.3.3 Selection of geophysical techniques

The geophysical survey design will depend both on the survey objectives and the site and ground conditions. In most cases, a specialist geophysical consultant should be employed to carry out the geophysical survey and to provide input into its design. As a guideline, a list of typical survey objectives and some appropriate geophysical techniques are listed in Table 3.41 below.

Table 3.41 Typical objectives of geophysical surveys and illustrative techniques to provide the required data

Objective	**Proposed technique**
Locates services (Note: no technique will guarantee to detect all services. Safe digging practices must be used if services may be present).	Electromagnetic profiling (both in-phase and out-of-phase components) on a 2 x 1 m grid across all accessible areas of the site to detect metallic services and cables.
	Targeted GPR on a 2 x 1 m grid to detect the most significant plastic and ceramic services (such as gas services).
	Cable avoidance tool (CAT) and signal generator, to be used at all proposed excavation positions to confirm absence of services.
Detection of buried pits.	Electromagnetic profiling on a 2 x 1 m grid across all accessible areas of the site.
Locate underground structures (e.g., building foundations).	Electromagnetic profiling on a 2 x 1 m grid across all accessible areas of the site.
	Ground penetrating radar (GPR) targeted into the areas of interest.
	Microgravity surveys targeted at the areas of interest.
Locate non-ferrous and ferrous metal items that could relate to buried munitions.	Electromagnetic profiling on a 2 x 1 m grid across all accessible areas of the site.
	Metal detector survey at sampling locations.

Guidance on use of geophysical techniques for groundwater pollution studies is given in Environment Agency [30], [33], [36].

3.6.3.4 Down-hole geophysics

Geophysical logging of boreholes provides a range of measurement of various physical characteristics of the formations penetrated, physicochemical indicators of the groundwater flows and quality. A detailed description of all the techniques available can be obtained from standard geophysical texts and an industry summary is provided in [30], [33], [36]. It is recommended that logs are run in all boreholes to maximise the data gathered.

Logging should be undertaken before borehole installations are fitted, and therefore sufficient time in the field characterisation program should be allowed. The data supplied by the logging is essential to good monitoring well design, to allow well screens to be accurately placed in flow horizons. For low flow sampling equipment to work effectively, placement of pumps and well screens should be dictated by accurate geological and geophysical information.

Logging of existing boreholes with closed-circuit television (CCTV) is a useful tool to ascertain borehole construction and condition, where installations are old and records poor. It is also a technique which can be used to verify installations on newly installed boreholes.

3.6.4 Non-intrusive drain surveys

Drains and sediments within them may be radioactively and/or chemically and/or microbiologically contaminated. Further, leaks from drains are a potential source of contamination of the surrounding ground. The current and past uses of drains on a site should be determined in order to identify those drains that may have been used to carry chemically or radioactively contaminated liquids. In addition, historical incidents or past practice on a site may have resulted in contamination of drains that were not designated to carry contaminated effluents. The desk study (see Section 2.4) should be designed to obtain such information.

Drain surveys comprise:

- Radiological surveying of selected manhole chambers and the collection and analysis of drain sediments.
- Surveying of drain runs using in-drain devices.
- Closed-circuit television can be used to identify breaks in the drains.
- Radiological surveying (typically total gamma probes) can be used to identify areas of increased levels of radioactivity.

Various in-drain devices can be used for drains surveys. Remotely operated vehicles (ROV’s) are suitable for larger diameter drains; probes manually pushed along the drain using rods are used for smaller-diameter drains.

Some issues that should be considered when designing drain surveys are listed below:

- Sediment build-up in drain runs may prevent deployment of in-drain devices. There may be a requirement for washing down the drains prior to the survey. Facilities should be available to handle, and if necessary treat, the sediments washed out during this process.
- The impact of continued use of the drains after the survey should be considered (in particular, the impact of connections to drains outside the survey area should be established).
- Calibration of in-drain gamma devices is not straightforward, and depends on the size of the drain and the distribution of any radioactive contamination. The confidence in the quantification of radioactive contamination should be established. If necessary, in situ sampling may be undertaken using in-drain devices.

The results from the drains survey should be used to determine (i) whether the drains and sediments within them are radioactive substances and (ii) whether drains may be sources of contamination of the surrounding ground. In the latter case, targeted sampling of the ground along the drain run should be undertaken using trial pits or boreholes.

3.6.5 Limitations to non-intrusive methods

Non-intrusive radiological surveys are limited in their applicability by three main issues:

- *The type of radionuclides present*. In general the equipment used by a non-intrusive field survey detects and quantifies mainly high-energy beta and gamma emissions. This limitation is due to the varying detection geometry. At this moment, new methods are under development, which make use of the variation of the low-energy gamma emission flux. This flux indicates qualitatively the presence of radionuclides.
- *The depth of burial/shielding of the radioactivity*. Burial/shielding of the radioactivity will influence the detection limit of radionuclides.
- *'Radiation' emitted from nearby buildings/facilities/pavement*. This radiation influences the background by non-intrusive radioactivity surveys by giving rise to elevated levels of radiation in an area that is being surveyed for radioactive contamination. In this case, in the survey design, this has to be taken into account by increased measuring times, or increased shielding on the detector (with consequent weight increase) or samples would have to be removed to a low radiation area for monitoring or analysis.

3.6.6 Radar, magnetometer, and electromagnetic sensors

The number of sensors and sensor systems applicable to the detection and location of buried waste have increased in use and reliability in recent years. These systems are typically applicable to scoping and characterization surveys where the identification of subsurface contamination is a primary concern. However, the results of these surveys may be used during final status survey planning to demonstrate that subsurface contamination is not a concern for a particular site or survey unit. Some of the major technologies are briefly described in the following sections.

3.6.6.1 Ground penetrating radar

For most sites, ground penetrating radar (GPR) is the only instrument capable of collecting images of buried objects *in-situ*, as compared to magnetometers (see Section 3.6.6.2) and electromagnetic sensors (see Section 3.6.6.3) which detect the strength of signals as measured at the ground surface. Additionally, GPR is unique in its ability to detect both metallic and non-metallic (*e.g.*, plastic, glass) containers.

Subsurface radar detection systems have been the focus of study for locating and identifying buried or submerged objects that otherwise could not be detected. There are two major categories of radar signals: 1) time domain, and 2) frequency domain. Time-domain radar uses short impulses of radar-frequency energy directed into the ground being investigated. Reflections of this energy, based on changes in dielectric properties, are then received by the radar. Frequency-domain radar, on the other hand, uses a continuous transmission where the frequency of the transmission can be varied either stepwise or continuously. The changes in the frequency characteristics due to effects from the ground are recorded. Signal processing, in both cases, converts this signal to represent the location of radar reflectors against the travel time of the return signal. Greater travel time corresponds to a greater distance beneath the surface. Table 3.42 lists the typical penetration depth for various geologic materials (fresh water is included as a baseline for comparison).

Examples of existing GPR technologies currently being applied to subsurface investigations include:

- Narrow-band radar;
- Ultra-wideband radar;
- Synthetic aperture radar;
- Frequency modulated continuous radar;
- Polarized radar waves.

Table 3.42 Typical radar penetration depths for various geologic materials

Material	Penetration depth [m]
Fresh Water	100
Sand (desert)	5
Sandy Soil	3
Loam Soil	3
Clay Soil	2
Salt Flats (dry)	1
Coal	20
Rocks	20
Walls	0.3

The major limitation to GPR is the difficulty in interpreting the data, which is often provided in the form of hazy, 'waterfall-patterned' data images requiring an experienced professional to interpret. Also, GPR can vary depending on the soil type as shown in Table 3.42. Highly conductive clay soils often absorb a large amount of the radar energy, and may even reflect the energy. GPR can be deployed using ground-based or airborne systems.

3.6.6.2 Magnetometers

Although contaminated soil and most radioactive waste possess no ferromagnetic properties, the containers commonly used to hold radioactive waste (*e.g.*, 220-litre drums) are made from steel. These containers possess significant magnetic susceptibility making the containers detectable using magnetometry.

Magnetometers sense the pervasive magnetic field of the earth. This field, when encountering an object with magnetic susceptibility, induces a secondary magnetic field in that object. This secondary field creates an increase or decrease in earth's ambient magnetic field. Magnetometers measure these changes in the expected strength of the ambient magnetic field. Some magnetometers, called "vector magnetometers," can sense the direction as well as the magnitude of these changes. However, for subsurface investigations only the magnitude of the changes is used.

The ambient magnetic field on earth averages 55,000 gamma in strength. The variations caused by the secondary magnetic fields typically range from 10 to 1,000 gamma, and average around 100 gamma. Most magnetometers currently in use have a sensitivity in the 0.1 to 0.01 gamma range and are capable of detecting these secondary fields.

An alternate magnetometer survey can be performed using two magnetometers in a gradiometric configuration. This means that the first magnetometer is placed at the ground surface, while the second is mounted approximately 0.5 meters above the first. Data is recorded from both sensors and compared. When the readings from both detectors are nearly the same, it implies that there is no significant disturbance in the earth's ambient magnetic field or that such disturbances are broad and far away from the gradiometer. When a secondary magnetic field is induced in an object, it affects one sensor more strongly than the other, producing a difference in the readings from the two magnetometers. This approach is similar to the use of a guard detector in anti-coincidence mode in a low-background gas-flow proportional counter in a laboratory (see 0 for a description of gas-flow proportional counters). The gradiometric configuration filters out the earth's ambient magnetic field, large scale variations, and objects located far from the sensor to measure the effects of nearby objects, all without additional data processing.

220-l drums buried 5 to 7 meters below the surface may be detectable using a magnetometer. At many sites, multiple drums have been buried in trenches or pits and detection is straightforward. A single operator carrying a magnetometer with the necessary electronics in a backpack can cover large areas in a relatively small amount of time.

The limitations on the system are related to the size of the objects and their depth below the surface. Objects that are too small or buried too deep will not provide a secondary magnetic field that can be detected at the ground surface.

3.6.6.3 Electromagnetic sensors

Electromagnetic sensors emit an electromagnetic wave, in either a pulsed or continuous wave mode, and then receive the result of that transmission. The result of the transmission is two signals; quadrature and in-phase. As the wave passes through some material other than air, it is slowed down by a resistive medium or sped up by a conductor through dielectric effects. This produces the quadrature signal. If the electromagnetic wave encounters a highly conductive object it induces a magnetic field in the object. This induced electromagnetic field returns to the sensor as a reflection of the original electromagnetic wave and forms the in-phase signal.

The in-phase signal is indicative of the presence, size, and conductivity of nearby objects (*e.g.*, 220-litre drums), while the quadrature signal is a measure of the dielectric properties of the nearby objects such as soil. This means that electromagnetic sensors can detect all metallic objects (including steel, brass, and aluminum), such as the metal in waste containers, and also sample the soil for changes in properties, such as those caused by leaks of contaminants.

Depths of interest are largely determined by the spacing between the coil used to transmit the primary electromagnetic wave, and the receiver used to receive that transmission. The rule of thumb is that the depth of interest is on the order of the distance between the transmitter and the receiver. A system designed with the transmitter and receiver placed tens of meters apart can detect signals from tens of meters below the surface. A system with the transmitter and receiver collocated can only detect signals from depths on the order of the size of the coil, which is typically about one meter. The limitations of electromagnetic sensors include a lack of clearly defined signals, and decreasing resolution of the signal as the distance below the surface increases.

3.7 Site characterisation: Intrusive methods

3.7.1 Introduction

Intrusive investigations are carried out to characterise sub-surface materials in order to obtain information on contaminant distribution and on the geological and hydro-geological environment. In addition, sub-surface investigations may be used to collect samples for geotechnical testing. Geotechnical sampling and testing is beyond the scope of this guidance document, although limited mention is made later in this section.

Sample material retrieved from intrusive investigations should be regarded as a resource for other phases in the project. Later stages of the EURSSEM process such as options comparison may need samples for small scale pilot testing of remediation methods. Geotechnical studies for subsequent new build may also require samples.

The cost and benefit of storage of retrieved samples and their preservation should be considered against the resources to obtain intrusive investigation samples in the future.

Intrusive investigations divide into three main aspects:

- Health and safety.
- Techniques.
- Sample collection.

Samples collected during the site characterisation will be of the following types:

- *Soils and rocks*. Soil samples are collected either manually, by hand-digging or by using an auger, or mechanically, using an excavator (for trial pits), window sampler, cone penetrometer (CPT) or drilling rig (for boreholes).
- *Surface waters and groundwaters*. Groundwater samples are generally collected from boreholes that are either temporarily or permanently cased, or on occasion from trial pits.
- *Soil gases*. Gas samples are generally collected from temporary shallow probes or from boreholes completed as ground gas monitoring points.

Safe digging practices is an important safety issue by intrusive investigations, therefore this aspect is dealt with in Section 3.7.2, Safe digging practices.

3.7.1.1 Intrusive investigation methods

There are several methods of excavating into the sub-surface. Many of these methods have been described in great detail in other guidance. A summary is given in the following alineas. An outline of the methods that are applicable to nuclear-licensed sites and defense sites is given in Table 3.43.

Particular reference is made to the specific details that make techniques more or less suitable for use on potentially radioactively contaminated sites. Of particular relevance are excavation techniques that minimise the amount of spoil generated and minimise the potential for contamination to be spread around the excavation area. All of the methods described are technically valid, but their applicability will vary depending on site conditions and on the requirements of the survey.

Because trial pits generate large quantities of spoil, their use should be minimised in areas known to be radioactively contaminated. Key aspects to be considered by intrusive investigation methods are:

- Field logging.
- Minimising cross contamination.
- Backfilling with and disposal of soil.
- Development pumping.
- Radiological pumping.
- Radiological clearance of equipment.

These are discussed in the following sections.

Borehole drilling

While investigating contaminated areas one of the main objectives will be to ensure the acquisition of an undisturbed sample, preferably with a 100% recovery rate. When samples may be taken using drilling equipment, caution must be taken that cross contamination of samples below more active strata does not take place. This can occur if activity is carried on the coring bit or if cutting fluids are used during the operation. The influence of cross-contamination on individual samples can be reduced if the outer layer of the core sample is carefully removed before analysis takes place.

Once a core has been recovered it is important to carefully cut open the liner and expose the undisturbed core on a work bench. This should then be photographed, logged and sampled at a constant frequency (0.5 m may suffice in short length cores, although it may be appropriate to analyze at closer intervals if, say, the contamination is believed to have leached downwards from the surface and is concentrated near to the top layer of soil) and, in addition, at any particular features of interest. It is often advisable to confirm the size of the required sample with the laboratory and ensure that a duplicate sample is taken.

Trial pitting and trenching

Trial pits and trenches are often used as a relatively cheap yet quick method of viewing and sampling the subsurface strata. Stratigraphic and structural changes can be seen more clearly than in cored material and samples are easy to obtain. The approximate maximum depth of 4 m is one of the disadvantages of trenching. Sample points at one-half meter intervals are normally sufficient for contaminant analysis, and once the sample has been obtained the procedures prior to laboratory analysis are similar to that for cores. When done with care, trenching can be used to obtain subsurface samples free of cross-contamination but it is labour intensive and may be unacceptable for environmental or safety reasons. Trenching may generate unacceptable quantities of waste and may expose workers to both physical hazards from unstable ground formations as well as high levels of radiation from the exposed surface.

Cone Penetrometer or Direct-Push Technology

Cone penetrometer testing (CPT) or, more generally, direct-push technology provides an opportunity for subsurface measurement without coring or boring. It depends on hydraulically pushing a small-diameter instrumented probe from the ground surface downward. Depending on the soil conditions and size of the pushing device, the depth of penetration can reach tens of meters.

CPT probes include a variety of sensors to identify different contaminants. They are often used to screen contaminated areas for later placement of monitoring wells. Sensors for radioactivity are presently under development and in testing.

The primary advantages of direct push technology over boring are small disturbances, relatively rapid sampling, low cost, and no creation of waste. The limitations are requirements for site access for the truck-mounted device, resistance of some lithologies to penetration, and semi-quantitative nature of the measurements from present sensors.

3.7.1.2 Field logging

It is important to log all relevant information when carrying out an intrusive investigation. Such information should consist of, as a minimum:

- Location of excavation and location number.
- Type and depth of excavation.
- Date and time of excavation.
- Descriptions of the soil/rock/made ground with depths.
- The depths, numbers and types of samples collected.
- Field monitoring information (gamma monitoring, dose monitoring).
- Backfilling details.
- Photographs taken.

Table 3.43 Techniques for intrusive sampling

Technique	Outline of method	Advantages	Disadvantages
Hand-digging	Use of trowel to collect samples to < 0.5m up to hand-dug pits to approximately 1m	- Samples can be collected from any surface location. - Base of hole can be monitored during excavation. - Little equipment is required. - Low potential for contamination to be spread. - Low risk of damaging services. - Cheap.	- Disturbed samples are collected. - Maximum depth of surface samples ~ 0.5 m. - Maximum depth of hand dug pits ~ 1.0 m.
Hand-augering	Use of hand auger to drill holes in soft materials to a depth of approximately 1m	- Samples can be collected in areas with poor access. - Little equipment required. - Cheap.	- Only appropriate for fine grained soft sediments. - Samples are significantly disturbed and there is a high potential for cross contamination of layers. - Maximum depth of sampling 1-2 m.
Trial pitting	Use of tracked or wheeled excavator to dig trial pit to < 6 m depth	- Large volume of soil exposed. - Sampling and logging more representative. - Observations of base of trial pit can be used to identify potential hazards. - Base of excavation may be monitored for services and contamination as trial pit progresses.	- Monitoring undertaken on disturbed samples brought to surface. - Large quantities of potentially contaminated waste materials brought to ground service. - Medium risk of damaging services (unless banksman identifies marker tape, etc.). - Maximum depth 6 m. Note: The trial hole will often collapse when groundwater is encountered. - Excavation sides unstable - unsupported excavation may require shoring.
Borehole drilling	Window sampling	- Small quantities of waste produced. - Core can be produced in clear plastic sleeves. - Simple to monitor cores to select samples and for health and safety purposes. - Relatively quick. - Cheap.	- Not very reliable in granular soils. - Samples are usually compacted. - Small quantities of samples are recovered. - Samples are not suitable for many geotechnical tests. - Maximum depth usually < 5 m. - Possible to use in special restricted areas. - Difficult to identify water strikes.
	Cone penetrometer (CPT)	- Small quantities of waste produced. - CPT equipment can be used to drive monitoring installations into the ground. - Provides CPT geotechnical information in situ from shear strength and relative density to stiffness and dynamic properties of the soil. - Geo-environmental cones can be used alongside to detect presence of: ∗ Landfill leachate. ∗ Methane. ∗ Ionic chemicals. ∗ Hydrocarbons. ∗ Chlorinated solvents. ∗ Radioactive contamination. ∗ Relatively quick. ∗ Cheap.	- Penetration largely depends on geology. Unable to penetrate dense materials or deposits containing cobbles or boulders. - No sample recovery. - Unable to seal off discrete layers. - Risk of smearing clays and blocking drive-in monitoring wells. - Maximum depth usually < 30 m. - Difficult to identify water strikes.

Technique	Outline of method	Advantages	Disadvantages
	Solid stem rotary augering in soils/weak rocks	- Relatively fast. - Little or no drilling fluids required. - Suitable for the installation of permanent groundwater or gas monitoring installations. - Can undertake inclined drilling for sampling under buildings, etc.	- Not appropriate for coarse gravely materials. - High potential for cross-contamination of samples. - Depth resolution poor.
	Microdrilling (small volume drilling) – various approaches	- All material collected by drilling is sample. - Ideal for immediate analysis. - Less accessible places. - Rapid. - No secondary wastes. - Cheap.	- Shallow samples < 1 m.
	Sonic drilling	- Sample recovery excellent. - No need for drilling fluids. - Rapid progress in 'suitable deposits'. - Less waste spoil generated.	- Vibration of drill bit can cause heating of the bit and volatilisation of volatile organics.
	Cable percussive in soils/weak rocks	- Suitable for a wide range of materials. - Suitable for in-situ geotechnical testing and geotechnical sampling. - Good definition of depth of materials. - Little or no use of drilling fluid. - Suitable for the installation of permanent groundwater or gas monitoring installations. - Possible to use low-head room rigs for sampling in difficult areas.	- Drilling process produces relatively large quantities of spoil (although less than trial pitting). - Driller's mate closely involved with drilling process and has relatively high potential to become contaminated. - Relatively slow. - Can be regarded as noisy. - Maximum depth tens of metres depending on material.
	Hollow stem rotary augering in soils/weak rocks	- Relatively fast. - Good quality samples. - Good depth definition. - Suitable for the installation of permanent groundwater or gas monitoring installations. - Can undertake inclined drilling for sampling under buildings.	- Not appropriate for coarse gravely materials.
	Rotary drilling in rock (truck or mini-rig mounted)	- Rapid drilling possible. - Can be used to drill through overburden using rotary percussive drilling. - Maximum depth hundreds of metres. - Good quality core and samples. - Suitable for the installation of permanent groundwater or gas monitoring installations.	- Expensive drilling fluids may contaminate samples and surrounding rock. - Additional space needed for management of drilling fluids. - Difficult to dispose of drilling fluids and cuttings. - Difficult to monitor drilling cuttings. - Truck-mounted rigs not suitable for spacially restricted areas.

3.7.2 Safe digging practice

Safe digging on a nuclear-licensed site has three main aspects associated with it:

- Avoidance of underground services.
- Avoidance of buried (dangerous) materials, e.g., munitions.
- Radiological monitoring to protect workers and minimise the spread of contamination.

The avoidance of underground services and materials are discussed below. Radiological monitoring issues during intrusive investigations are discussed in Section 3.7.2.1. In addition to these aspects, hazards appropriate to working on a conventionally contaminated site must also be considered (for example, civil engineering risks and protection against chemical contamination).

3.7.2.1 Avoidance of underground services

Safe digging practices should be used during the intrusive investigation, as underground services typically present the greatest hazard during the intrusive phase of a site investigation. Because of this, the general process for determining if it is safe to excavate is repeated below:

- Collect and review service plans of the area in which the works are to be undertaken (either from the site owners/occupiers or from appropriate utility companies).
- Identify the positions of all services using non-intrusive techniques (geophysical surveys, a cable avoidance tool (CAT) and signal generator and tracing of services between visible features such as manhole covers).
- If a planned excavation is close to the location of services, consider relocating it (provided the location is not critical to the site investigation).
- If excavating close to the position of a suspected service dig carefully by hand.
- Excavate carefully and stop should anything unusual be discovered.

It should be noted that:

- Service plans may be inaccurate.
- Not all services may be shown on the service plans.

Nuclear-licensed sites will generally have site procedures for excavations, which must be followed. A typical procedure for undertaking excavations at a nuclear-licensed site is given in Table 3.44. The quality of service plans for land outside the main security fence of a nuclear-licensed site may be poorer than those for services within the site. If excavating in public access areas owned by a nuclear-licensee, it is recommended that the main utilities providers for the region are contacted. This is to ensure that their service location plans can be checked for agreement with the site plans.

3.7.2.2 Avoidance of buried (dangerous) materials

Buried (dangerous or hazardous) materials may be present on nuclear-licensed sites. If the desk study has indicated that these materials could be a potential hazard at a site, a procedure must be put into place to ensure that drilling into such objects does not occur. It is recommended that site-specific advice be sought from a specialist.

During site characterisation, the greatest hazard could arise from drilling into the soil and encountering (dangerous) materials especially at defense sites, e.g., munitions. Therefore it is advised to take into account in the historical site assessment to review a list of locations where possible (dangerous) materials can be buried or present in the sub-surface and at greater depths.

In some circumstance, the obstruction to drilling may not be identified and drilling may continue on the assumption that a piece of concrete has been encountered. The hazard can be decreased by trial pitting on such sites, e.g., munitions could be rapidly identified and works stopped.

Table 3.44 A typical procedure for undertaking excavations at a nuclear licensed site

Step	Description
1	Production of a plan showing the areas of proposed excavations.
2	Production of service plans of the areas.
3	Selection of proposed excavation positions by the contractor, taking into account the service plans. Agreement of this plan with the stakeholders.
4	Cable avoidance tool survey of the proposed excavation positions. If the proposed excavation positions are free of services, excavation positions are marked out using spray paint (i.e., avoid penetrating the ground at this stage). If services are found to be present, alternative positions are agreed with the stakeholders.
5	Confirmation by the stakeholders that the excavation positions marked on the ground correspond with the proposed positions, and that the cable avoidance tool survey has been completed.
6	Production of an excavation permit by the site owner. The excavation permit would typically include a second set of service drawings and approvals from all interested parties (health physicists, appropriate building managers, etc.) for the excavations to proceed.
7	Issue and signing off of excavation permit by the site owner.
8	Issue and signing off of permit to work by the site owner's project manager.

Notes:

- In addition to the procedures listed above, a cable avoidance tool should be on site and used regularly during the excavations by a suitable qualified and experienced person.
- Should any excavation need to be relocated, this entire procedure would need to be repeated for the new location. However, the permits would only require modification rather than re-issue.
- Approvals are required from interested parties such as health physicists so that, if necessary, special instructions can be given on issues such as radiological hazards and monitoring requirements.

A procedure for investigating a site containing possible buried (dangerous or hazardous) materials is given below:

- Undertake a historical site assessment (see Section 2.4) of the area to evaluate the potential for (dangerous or hazardous) materials to be present. If the historical site assessment indicates a high potential for (dangerous or hazardous) materials to be present it is advisable to consult a specialist on the expected materials. The results of the historical site assessment would be unlikely to change the overall characterisation approach. However, if there is a high risk that (dangerous or hazardous) materials may be present, greater care should be taken during the excavation process.
- Undertake a geophysical survey across the site to identify the positions of buried metallic (ferrous) objects. Appropriate geophysical techniques for detecting buried metallic objects are described in Section 3.6.3. However, advice from a specialist geophysical contractor should be sought in order that the most appropriate geophysical technique for the site is employed. The geophysical survey should produce a map showing the locations of buried metallic and other objects.
- The results of the geophysical survey can be used either to plan the site characterisation so as to avoid all areas with buried metallic objects, or to ensure that, if excavation must be undertaken in the vicinity of buried metallic objects, the appropriate level of caution is exercised. In the majority of cases, buried metallic objects will not be munitions.
- Excavation to identify buried metallic object should be undertaken with care. Borehole drilling methods are not appropriate. An appropriate method would be to use an

excavator to carefully remove approximately 20 cm thick layers of soil to expose the metallic object(s). A banksman should be present.

- To observe the excavation and determine if the object has been located. This method of approach should allow (dangerous) materials to be identified at an early stage, prior to them being significantly disturbed or punctured. If the (dangerous) materials discovered, are munitions or objects that may be munitions, the site police must be informed. The site police will then involve the appropriate civilian and military authorities. It should be noted that the civilian authorities will make the occurrence public, and media interest may result. The licensee should inform national regulatory agencies according to the national procedures.

3.7.3 Monitoring during intrusive investigations

Monitoring is undertaken during intrusive investigations for three purposes:

- To protect the health and safety of workers.
- To minimise the spread of contamination.
- To provide environmental data.

Monitoring can be distinguished between radiological and non-radiological.

3.7.3.1 Radiological

Radiological monitoring should be undertaken during all intrusive investigations where radioactive contamination may be present. In the context of this guidance, this means that radiological monitoring should be undertaken during all site investigations.

An appropriate monitoring regime for an intrusive investigation is given in Table 3.45 below.

3.7.3.2 Non-radiological

Information available in literature about this topic will be included in a later edition of EURSSEM.

3.8 Site characterisation: Field survey and laboratory equipment used to measure radiation levels and radioactive material concentrations

Measurement is used in EURSSEM to mean:

- The act of using a detector to determine the level or quantity of radioactivity on a surface or in a sample of material removed from a media being evaluated;
- The quantity obtained by the act of measuring.

Three methods are available for collecting radiation data while performing a survey: direct measurements, scanning, and sampling.

Selecting instrumentation to apply one of the above three methods requires evaluation of both site and radionuclide specific parameters and conditions. Selected instruments should be stable and reliable under the environmental and physical conditions where they will be used, and their physical characteristics (size and weight) should be compatible with the intended application. The instrument and measurement method should be able to detect the type of radiation of interest, and should, in relation to the survey or analytical technique, be capable of measuring levels that are less than the derived concentration guideline level (DCGL). Numerous commercial firms offer a wide variety of instruments appropriate for the radiation measurements described in this manual. These firms can provide thorough information regarding capabilities, operating characteristics, limitations, *etc.*, for specific equipment.

Table 3.45 A typical procedure for an appropriate monitor regime during undertaking excavations at a nuclear licensed site

Issue	Proposed regime
Selection of appropriate monitoring equipment.	- Should be determined by an appropriately trained person, such as a radiation protection advisor. - Monitors should be selected to detect the radionuclides expected to be present on the excavation area and on the site. - Monitors should be selected to be sensitive enough to detect the background radiation level at the excavation area. - Monitors should be sensitive enough to ensure the safety of workers, to enable on-site screening and selection of samples and to enable waste segregation (if required).
Monitoring of the ground surface prior to excavation at that location.	- Should be carried out in addition to any previous radiological surveying works over the area, to ensure that the extent of the surface radioactive contamination is known/verified.
Regular monitoring of the excavation.	- *Trial pits*. In trial pits, a probe can be lowered into the excavation to detect if radioactivity is present. This provides a sensitive measure of the first occurrence of radioactive contamination, which is detected before the contaminated material is excavated. (Note that the background level of radioactivity detected during excavation will alter as the excavation becomes deeper, because of geometrical effects and because different soil horizons are encountered). - *Temporary shallow boreholes*. In temporary shallow boreholes used for soil sampling, an appropriate narrow diameter probe would be required for down-hole measurements. Although this would provide useful depth-dependent information with better sensitivity than could be achieved from monitoring spoil or samples, it is limited by issues such as borehole stability. Down-hole radiological monitoring is discussed further in Section 3.6.3. As with monitoring of trial pits, the background level of radioactivity may alter with depth because different soil horizons are encountered.
Regular monitoring of the spoil generated during the excavation process.	- Ensuring that any buried radioactive contamination will be detected in the spoil produced by the excavation process. - The spoil should be monitored at regular intervals, and any changes in radiological contamination should be noted.
Regular monitoring of soils to aid in the sample selection process.	- See Section 3.6.3.
Monitoring on completion of each excavation.	- Personnel should be monitored to ensure that they have not been contaminated with radioactivity. - The ground surface around the excavation area should be monitored to ensure that it has not been contaminated with radioactivity. - The excavation equipment should be monitored to determine if it has become contaminated with radioactivity (in which case decontamination will be required, in addition to any routine cleaning procedures taken to minimise any new cross-contamination). - The outside of the sample containers should be monitored to ensure that (i) there is no loose surface radioactive contamination, and (ii) any external radiation levels do not present a hazard to personnel.
Monitoring on completion of the intrusive phase of the site investigation.	- All equipment used in the investigation should be monitored and a radiological clearance certificate issued by the relevant health physicist. - All samples should be monitored and issued with the appropriate documentation (e.g., a radiological clearance certificate for uncontaminated samples) prior to being transported to the laboratory.

However, certain radionuclides or radionuclide mixtures may necessitate the measurement of alpha, beta, and gamma radiations. In addition to assessing each survey unit as a whole, any small areas of elevated activity should be identified and their extent and activities determined. Due to numerous detector requirements, no single instrument (detector and readout combination) is generally capable of adequately measuring all of the parameters required to satisfy the release criterion or meet all the data quality objectives of a survey.

If the field instruments and measurement methods cannot detect radiation levels below the DCGLs, laboratory methods should be used. A discussion of detection limits and detection levels for some typical instruments is presented in Section 3.3.7. There are certain radio-nuclides that will be essentially impossible to measure at the DCGLs *in-situ* using current state-of-the-art instrumentation and techniques because of the types, energies, and abundances of their radiations. Examples of such radio-nuclides include very low energy, pure beta emitters such as ^{3}H and ^{63}Ni and low-energy photon emitters such as ^{55}Fe and ^{125}I. Pure alpha emitters dispersed in soil or covered with some absorbing layer may not be detectable because alpha radiation will not penetrate through the media or covering to reach the detector. A common example of such a condition would be ^{230}Th surface contamination, covered by paint, dust, oil, or moisture.

3.8.1 Radiation detection instrumentation

A wide range of instruments is available for the detection of radioactivity. EURSSEM gives guidance and detailed description of instruments available and this is presented in 0 (not claiming to be 100% complete). A competent person, such as a specialist in radiological measurements or a radiological protection adviser, should select appropriate radiation detectors. Instruments should be used by suitably qualified and experienced staff (such as a health physics surveyor, or a radiation protection supervisor) that is capable of carrying out the survey whilst adhering to the appropriate quality control and health and safety rules.

The selected instrumentation should be appropriate to obtain the data required.

Different radiation detectors will be in general required to detect different types of radioactivity (alpha, beta and gamma). However, in most cases field radiological surveys focus on detection of gamma emitting radionuclides and, to some extent, of high-energy beta emitters. This is primarily because these are the most penetrating radiations and are easily detectable at distances of tens of centimetres to metres from the ground surface. Identification of alpha emitters or low-energy beta and gamma emitters is generally not possible during an on-site radiological survey of a contaminated site.

0 contains:

- Aspects to consider by selection of field survey and laboratory equipment;
- Advised sensitivity of direct measurements and scanning survey techniques;
- Short summaries of radiation detection principles applied in instruments;
- Overview available α, β and γ instrumentation (not claiming to be 100% complete);
- The following specifications will be dealt with:
    - System name;
    - Applicability for laboratory or field measurements;
    - Radiation detected;
    - Applicability to site surveys;
    - Operation;
    - Specificity/sensitivity;
    - Cost of equipment (assessment);
    - Cost per measurement (assessment).

Radiation instruments consist in principle out of two components:

- A radiation detector;

- An electronic equipment to provide power to the detector and to display or record detected radiation events.

This section identifies and very briefly describes the types of radiation detectors and associated display or recording equipment that are applicable to survey activities in support of environmental assessment or remedial action. Each survey usually requires performing some direct field measurements using portable instrumentation and collection of samples for laboratory analysis. The selection and proper use of appropriate instruments for both direct measurements and laboratory analyses are important factors in assuring that the survey accurately determines the radiological status of a site and meets the radiological survey data quality objectives. Section 3.4.2 provides specific information on sampling of different materials and Section 3.9 provides specific information on laboratory analysis of collected samples. 0 contains instrument specific information for various types of field survey and laboratory analysis equipment currently in use and commercially available.

3.8.1.1 Radiation detectors

The particular capabilities of a radiation detector will establish its potential applications in conducting a specific type of survey. Radiation detectors can be divided into four general classes based on the detector material or the application. These categories are:

- Gas-filled detectors;
- Scintillation detectors;
- Solid-state detectors;
- Passive integrating detectors.

3.8.1.2 Gas-filled detectors

Radiation interacts with the fill gas, producing ion-pairs that are collected by charged electrodes. Commonly used gas-filled detectors are categorized as ionization, proportional, or Geiger-Mueller (GM), referring to the region of gas amplification in which they are operated. The fill gas varies, but the most common are:

- Air;
- Argon with a small amount of organic methane (usually 10% methane by mass, referred to as P-10 gas);
- Argon or helium with a small amount of a halogen such as chlorine or bromine added as a quenching agent.

3.8.1.3 Scintillation detectors

Radiation interacts with a solid or liquid medium causing electronic transitions to excited states in a luminescent material. The excited states decay rapidly, emitting photons that in turn are captured by a photomultiplier tube. The ensuing electrical signal is proportional to the scintillator light output, which, under the right conditions, is proportional to the energy loss that produced the scintillation. The most common scintillant materials are NaI(Tl), ZnS(Ag), Cd(Te), LaCl(Ce), LaBr and CsI(Tl) which are used in radiation instruments such as the NaI(Tl) detector used for gamma scanning surveys and direct measurements, and the ZnS(Ag) detector for alpha surveys, mostly direct measurements.

3.8.1.4 Solid-State Detectors

Radiation interacting with a semiconductor material creates electron-hole pairs that are collected by a charged electrode. The design and operating conditions of a specific solid-state detector determines the types of radiations (alpha, beta, and/or gamma) that can be measured, the detection level of the measurements, and the ability of the detector to resolve the energies of the interacting radiations. The semiconductor materials currently being used are germanium and silicon which are available in both n and p types in various configurations.

Spectrometric techniques using these detectors provide a marked increase in sensitivity in many situations. When a particular radionuclide contributes only a fraction of the total particle fluence or photon fluence, or both, from all sources (natural or man-made background), gross measurements are inadequate and nuclide-specific measurements are necessary. Spectrometry provides the means to discriminate among various radio-nuclides on the basis of characteristic energies. *In-situ* gamma spectrometry is particularly effective in field measurements since the penetrating nature of the radiation allows one to "see" beyond immediate surface contamination. The availability of large, high efficiency germanium detectors permits measurement of low abundance gamma emitters such as ^{238}U as well as low energy emitters such as ^{241}Am and ^{239}Pu.

3.8.1.5 Passive integrating detectors

There is an additional class of instruments that consists of passive, integrating detectors and associated reading/analyzing instruments. The integrated ionization is read using a laboratory or hand-held reader. This class includes thermo-luminescence dosimeters (TLDs) and electret ion chambers (EICs). Because these detectors are passive and can be exposed for relatively long periods of time, they can provide better sensitivity for measuring low activity levels such as free release limits or for continuing surveillance. The ability to read and present data on-site is a useful feature and such systems are comparable to direct reading instruments.

The scintillation materials in Section 3.8.1.3 are selected for their prompt fluorescence characteristics. In another class of inorganic crystals, called TLDs, the crystal material and impurities are chosen so that the free electrons and holes created following the absorption of energy from the radiation are trapped by impurities in the crystalline lattice thus locking the excitation energy in the crystal. Such materials are used as passive, integrating detectors. After removal from the exposure area, the TLDs are heated in a reader which measures the total amount of light produced when the energy is released. The total amount of light is proportional to the number of trapped, excited electrons, which in turn is proportional to the amount of energy absorbed from the radiation. The intensity of the light emitted from the thermo-luminescent crystals is thus directly proportional to the radiation dose. TLDs come in a large number of materials, the most common of which are LiF, CaF_2:Mn, CaF_2:Dy, $CaSO_4$:Mn, $CaSO_4$:Dy, Al_2O_3:C.

The electret ion chamber consists of a very stable electret (a charged Teflon® disk) mounted inside a small chamber made of electrically charged plastic. The ions produced inside this air filled chamber are collected onto the electret, causing a reduction of its surface charge. The reduction in charge is a function of the total ionization during a specific monitoring period and the specific chamber volume. This change in voltage is measured with a surface potential voltmeter.

3.8.2 Display and recording equipment

Radiation detectors are connected to electronic devices to:

- Provide a source of power for detector operation;
- Enable measurement of the quantity and/or quality of the radiation interactions that are occurring in the detector.

The quality of the radiation interaction refers to the amount of energy transferred to the detector. In many cases, radiation interacts with other material (*e.g.*, air) prior to interacting with the detector, or only partially interacts with the detector (*e.g.*, Compton scattering for photons). Because the energy recorded by the detector is affected, there is an increased probability of incorrectly identifying the radionuclide.

The most common recording or display device used for portable radiation measurement systems is a ratemeter - analog or digital. This device provides a display representing the number of events occurring over some time period (*e.g.*, counts per minute). The number of events can also be accumulated over a preset time period. The resulting information from a scaling device is the total number of events that occurred over a fixed period of time, where a ratemeter display varies with time and represents a short term average of the event rate. Determining the average level on a ratemeter will require judgment by the user, especially when a low frequency of events results in significant variations in the meter reading.

Pulse height analyzers are specialized electronic devices designed to measure and record the number of pulses or events that occur at different pulse height levels. These types of devices are used with detectors which produce output pulses that are proportional in height to the energy deposited within them by the interacting radiation. They can be used to record only those events occurring in a detector within a single band of energy or can simultaneously record the events in multiple energy ranges. In the former case, the equipment is known as a single-channel analyzer; the latter application is referred to as a multi-channel analyzer.

3.8.3 Radon detectors and measurement techniques

There are three radon isotopes in nature: ^{222}Rn (radon) in the ^{238}U decay chain, ^{220}Rn (thoron) in the ^{232}Th chain, and ^{219}Rn (actinon) in the ^{235}U chain. ^{219}Rn is the least abundant of these three isotopes, and because of its short half-life of 4 seconds it has the least probability of emanating into the atmosphere before decaying. ^{220}Rn with a 55 second half-life is somewhat more mobile. ^{222}Rn with a 3.8 d half-life is capable of migrating through several decimetres of soil or building material and reaching the atmosphere. Therefore, in most situations, ^{222}Rn should be the predominant airborne radon isotope.

Many techniques have been developed over the years for measuring radon and radon progeny in air [103]. In addition, considerable attention is given by EPA to measurement of radon and radon progeny in homes [104]. Radon and radon progeny emit alpha and beta particles and gamma rays. Therefore, numerous techniques can and have been developed for measuring these radio-nuclides based on detecting alpha particles, beta particles, or gamma rays, independently or in some combination. It is even difficult to categorize the various techniques that are presently in use. This section contains an overview of information dealing with the measurement of radon and radon progeny and is not claiming 100% complete. The information is focused on the measurement of ^{222}Rn. However, the information may be adapted for the measurement of ^{219}Rn and ^{220}Rn.

Two analytical end points are of interest when performing radon measurements:

- Most commonly used is radon concentration, which is stated in terms of activity per unit volume (Bq/m^3). Although this terminology is consistent with most federal guidance values, it only infers the potential dose equivalent associated with radon.
- The second analytical end point is the radon progeny working level. Radon progeny usually attach very quickly to charged aerosols in the air following creation. The fraction that remains unattached is usually quite small (*i.e.*, 5 - 10%). Since most aerosol particles carry an electrical charge and are relatively massive ($\geq$ 0.1 μm), they are capable of attaching to the surfaces of the lung. Essentially all dose or risk from radon is associated with alpha decays from radon progeny attached to tissues of the respiratory system. If an investigator is interested in accurately determining the potential dose or risk associated with radon in the air of a room, the radon progeny concentration must be known.

Radon progeny concentrations are usually reported in units of working levels (WL), where one working level is equal to the potential alpha energy associated with the radon progeny in secular equilibrium with 3.7 Bq/l (100 pCi/l) of radon. One working level is equivalent to

1.28 x 10^5 MeV/L of potential alpha energy. Given a known breathing rate and lung attachment probability, the expected mean lung dose from exposure to a known working level of radon progeny can be calculated.

Radon progeny are not usually found in secular equilibrium with radon indoors due to plating out of the charged aerosols onto walls, furniture, *etc.* The ratio of ^{222}Rn progeny activity to ^{222}Rn activity usually ranges from 0.2 to as high as 0.8 indoors. If only the ^{222}Rn concentration is measured and it is not practical to measure the progeny concentrations, then general practice is to assume a progeny to ^{222}Rn equilibrium ratio of 0.5 for indoor areas. This allows one to estimate the expected dose or risk associated with a given radon concentration.

In general, the following generic guidelines should be followed when performing radon measurements during site investigations:

- The radon measurement method used should be well understood and documented;
- Long term measurements are used to determine the true mean radon concentration;
- The impact of variable environmental conditions (*e.g*., humidity, temperature, dust loading, and atmospheric pressure) on the measurement process should be accounted for when necessary. Consideration should be given to effects on both the air collection process and the counting system;
- The background response of the detection system should be accounted for;
- If the quantity of interest is the working level, then the radon progeny concentrations should be evaluated. If this is not practical, then the progeny activities can be estimated by assuming they are 50% of the measured radon activity.

For a general overview, a list of common radiation detectors with their usual applications during radon surveys is provided in Table 3.46. Descriptions and costs for specific equipment used for the measurement of radon are contained in 0.

Table 3.46 Radiation detectors with applications to radon surveys

System	Description	Application	Remarks
Large area activated charcoal collector	A canister containing activated charcoal is twisted into the surface and left for 24 hours.	Short term radon flux measurements.	The LLD is 0.007 Bq $m^{-2}s^{-1}$.
Continuous radon monitor	Air pump and scintillation cell or ionization chamber.	Track the real time concentration of radon.	Takes 1 to 4 hours for system to equilibrate before starting. The LLD is 0.004-0.04 Bq/l.
Activated charcoal adsorption	Activated charcoal is opened to the ambient air, then gamma counted on a gamma scintillator or in a liquid scintillation counter.	Measure radon concentration in indoor air.	Detector is deployed for 2 to 7 days. The LLD is 0.007-0.04 Bq/l.
Electret ion chamber	This is a charged plastic vessel that can be opened for air to pass through.	Measure short term or long term radon concentration in indoor air.	Must correct reading for gamma background concentration. Electret is sensitive to extremes of temperature and humidity. LLD is 0.007-0.02 Bq/l.
Alpha track detection	A small piece of special plastic or film inside a small container. Damage tracks from alpha particles are chemically etched and tracks counted.	Measure indoor or outdoor radon concentration in air.	LLD is 0.04 Bq $l^{-1}d^{-1}$.

3.8.4 Aspects to consider by selection of field survey and laboratory equipment

Radiation survey parameters that might be needed for site release purposes include surface activities, exposure rates, and radionuclide concentrations in soil. To determine these parameters, field measurements and laboratory analyses may be necessary. For certain radio-nuclides or radio-nuclide mixtures, both alpha and beta radiations may have to be measured. In addition to assessing average radiological conditions, the survey objectives should address identifying small areas of elevated activity and determining the extent and level of residual radioactivity.

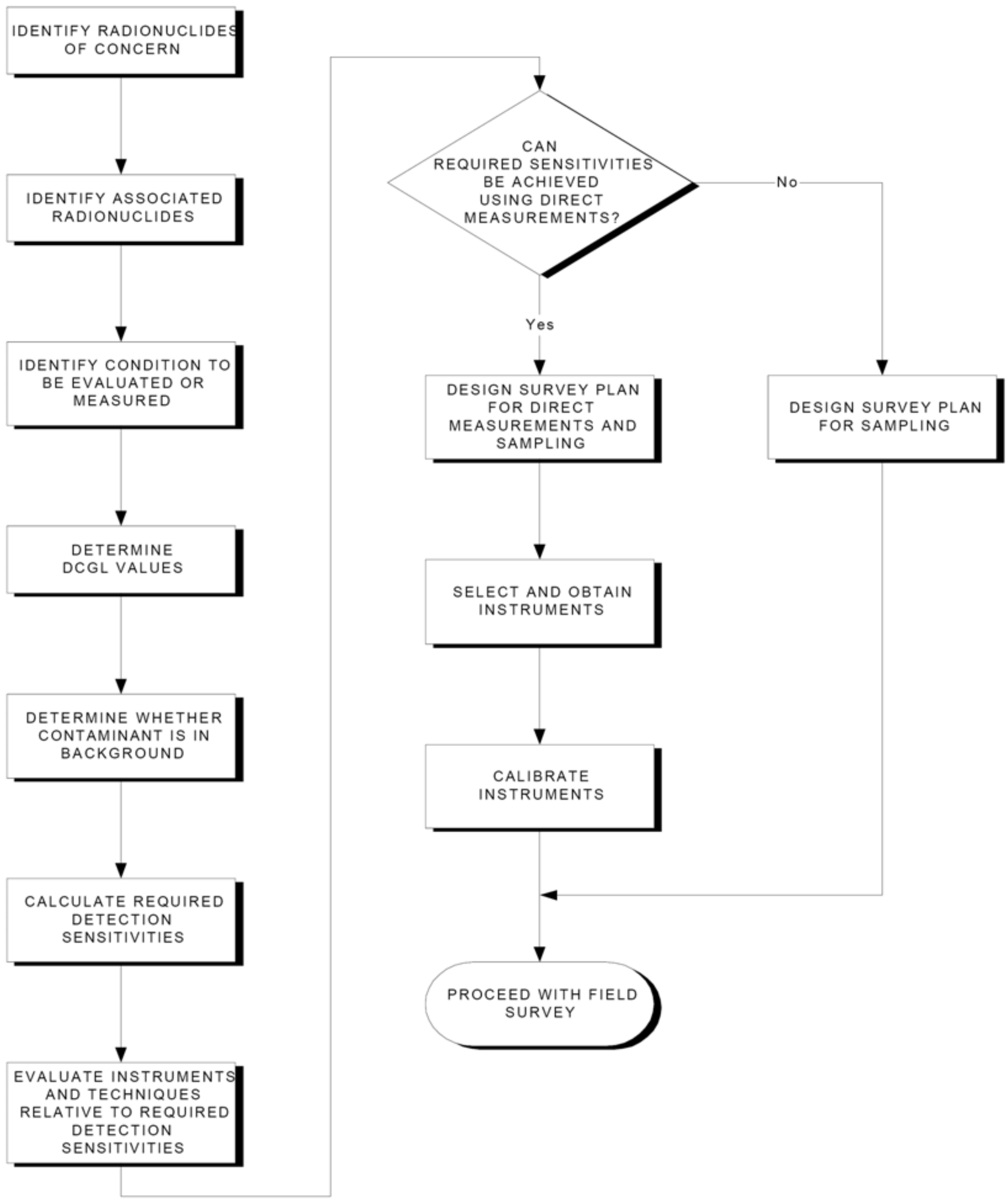


Figure 3.10 Flow diagram for selection of field survey instrumentation for direct measurements and analysis of samples

Additionally, the potential uses of radiation instruments can vary significantly depending on the specific design and operating criteria of a given detector type. For example, a NaI(Tl) scintillator can be designed to be very thin with a low atomic number entrance window (*e.g.*, beryllium) such that the effective detection capability for low energy photons is optimized. Conversely, the same scintillant material can be fabricated as a thick cylinder in order to optimize the detection probability for higher energy photons. On the recording end of a detection system, the output could be a ratemeter, scaler, or multi-channel analyzer as described in Section 3.8.2. Operator variables such as training and level of experience with specific instruments should also be considered.

With so many variables, it is highly unlikely that any single instrument (detector and readout combination) will be capable of adequately measuring all of the radiological parameters necessary to demonstrate that criteria for release have been satisfied. It is usually necessary to select multiple instruments to perform the variety of measurements required.

Selection of instruments will require an evaluation of a number of situations and conditions. Instruments must be stable and reliable under the environmental and physical conditions where they will be used, and their physical characteristics (size and weight) should be compatible with the intended application. The instrument must be able to detect the type of radiation of interest, and the measurement system should be capable of measuring levels that are less than the DCGL (see Section 3.3.7).

For gamma radiation scanning, a scintillation detector/ratemeter combination is a common instrument of choice. A large-area proportional detector with a ratemeter is recommended for scanning for alpha and beta radiations where surface conditions and locations permit; otherwise, an alpha scintillation or thin-window GM detector (for beta surveys) may be used.

For direct gamma measurements, a pressurized ionization chamber or *in-situ* gamma spectroscopy system is recommended. As an option, e.g., a NaI(Tl) scintillation detector may be used if cross-calibrated to a pressurized ion chamber or calibrated for the specific energy of interest. The same alpha and beta detectors identified above for scanning surveys are also recommended for use in direct measurements. In Figure 3.10 a flow diagram for the selection of field survey instrumentation for direct measurements and analysis of samples is given.

There are certain radio-nuclides that, because of the types, energies, and abundances of their radiations, will be essentially impossible to measure at the guideline levels, under field conditions, using state-of-the-art instrumentation and techniques. Examples of such radio-nuclides include very low energy pure beta emitters, such as ^{3}H and ^{63}Ni, and low energy photon emitters, such as ^{55}Fe and ^{125}I. Pure alpha emitters dispersed in soil or covered with

Table 3.47 Radiation detectors with applications to alpha surveys

Detector type	Detector description	Application	Remarks
Gas Proportional	< 1 mg/cm² window; probe area 50 to 1000 cm²	Surface scanning; surface contamination measurement	Requires a supply of appropriate fill gas
	< 0.1 mg/cm² window; probe area 10 to 20 cm²	Laboratory measurement of water, air, and smear samples	
	No window (internal proportional)	Laboratory measurement of water, air, and smear samples	
Air Proportional	< 1 mg/cm² window; probe area ~50 cm²	Useful in low humidity conditions	
Scintillation	ZnS(Ag) scintillator; probe area 50 to 100 cm²	Surface contamination measurements, smears	
	ZnS(Ag) scintillator; probe area 10 to 20 cm²	Laboratory measurement of water, air, and smear samples	
	Liquid scintillation cocktail containing sample	Laboratory analysis, spectrometry capabilities	
Solid State	Silicon surface barrier detector	Laboratory analysis by alpha spectrometry	
Passive, integrating electret ion chamber	< 0.8 mg/cm² window, also window-less, window area 50-180 cm², chamber volume 50-1,000 ml	Contamination on surfaces, in pipes and in soils	Useable in high humidity and temperature

Table 3.48 Radiation detectors with applications to beta surveys

Detector Type	Detector description	Application	Remarks
Gas Proportional	< 1 mg/cm² window; probe area 50 to 1,000 cm² < 0.1 mg/cm² window; probe area 10 to 20 cm² No window (internal proportional)	Surface scanning; surface contamination measurement Laboratory measurement of water, air, smear, and other samples Laboratory measurement of water, air, smear, and other samples	Requires a supply of appropriate fill gas Can be used for measuring very low-energy betas
Ionization (non-pressurized)	1-7 mg/cm² window	Contamination measurements; skin dose rate estimates	
Geiger-Mueller	< 2 mg/cm² window; probe area 10 to 100 cm² Various window thickness; few cm² probe face	Surface scanning; contamination measurements; laboratory analyses Special scanning applications	
Scintillation	Liquid scintillation cocktail containing sample Plastic scintillator	Laboratory analysis; spectrometry capabilities Contamination measurements	
Passive, integrating electret ion chamber	7 mg/cm² window, also window-less, window area 50-180 cm², chamber volume 50-1,000 ml	Low energy beta including ^{3}H contamination on surfaces and in pipes	Useable in high humidity and temperature

Table 3.49 Radiation detectors with applications to gamma surveys

Detector Type	Detector description	Application	Remarks
Gas Ionization	Pressurized ionization chamber; non-pressurized ionization chamber	Exposure rate measurements	
Geiger-Mueller	Pancake (< 2 mg/cm² window) or side window (~30 mg/cm²)	Surface scanning; exposure rate correlation (side window in closed position)	Low relative sensitivity to gamma radiation
Scintillation	NaI(Tl) scintillator; up to 5 cm by 5 cm NaI(Tl) scintillator; large volume and "well" configurations CsI or NaI(Tl) scintillator; thin crystal Organic tissue equivalent (plastics)	Surface scanning; exposure rate correlation Laboratory gamma spectrometry Scanning; low-energy gamma and X-rays Dose equivalent rate measurements	High sensitivity; cross calibrate with PIC (or equivalent) or for specific site gamma energy mixture for exposure rate measurements. Detection of low-energy radiation
Solid State	Germanium semi-conductor	Laboratory and field gamma spectrometry and spectroscopy	
Passive, integrating electret ion chamber	7 mg/cm² window, also window-less, window area 50-180 cm², chamber volume 50-1,000 ml		Useable in high humidity and temperature

some absorbing layer will not be detectable because the alpha radiation will not penetrate through the media or covering to reach the detector. A common example of such a condition would be ^{230}Th surface contamination covered by paint, dust, oil, or moisture. In such circumstances, sampling and laboratory analysis would be required to measure the residual activity levels unless surrogate radio-nuclides are present as discussed in Section 3.3.6.2.

The number of possible design and operating schemes for each of the different types of detectors is too large to discuss in detail within the context of this document. For a general overview, lists of common radiation detectors along with their usual applications during surveys are provided in Table 3.47, Table 3.48 and Table 3.49. 0 contains specific information for various types of field survey and laboratory analysis equipment currently in use. Continual development of new technologies will result in changes to these listings.

3.8.5 Instrument calibration

Calibration refers to the determination and adjustment of the instrument response in a particular radiation field of known intensity. Proper calibration procedures are an essential requisite toward providing confidence in measurements made to demonstrate compliance with clean-up criteria. Certain factors, such as energy dependence and environmental conditions, require consideration in the calibration process, depending on the conditions of use of the instrument in the field. Routine calibration of radiation detection instruments refers to calibration for normal use under typical field conditions.

Considerations for the use and calibration of instruments include:

- Use of the instrument for radiation of the type for which the instrument is designed;
- Use of the instrument for radiation energies within the range of energies for which the instrument is designed;
- Use under environmental conditions for which the instrument is designed;
- Use under influencing factors, such as magnetic and electrostatic fields, for which the instrument is designed;
- Use of the instrument in an orientation such that geotropic effects are not a concern;
- Use of the instrument in a manner that will not subject the instrument to mechanical or thermal stress beyond that for which it is designed.

Routine calibration commonly involves the use of one or more sources of a specific radiation type and energy, and of sufficient activity to provide adequate field intensities for calibration on all ranges of concern.

Actual field conditions under which the radiation detection instrument will be used may differ significantly from those present during routine calibration. Factors which may affect calibration validity include:

- The energies of radioactive sources used for routine calibration may differ significantly from those of radio-nuclides in the field;
- The source-detector geometry (*e.g.*, point source or large area distributed source) used for routine calibration may be different than that found in the field;
- The source-to-detector distance typically used for routine calibration may not always be achievable in the field;
- The condition and composition of the surface being monitored (*e.g.*, sealed concrete, scabbled concrete, carbon steel, stainless steel, and wood) and the presence of overlaying material (*e.g.*, water, dust, oil, paint) may result in a decreased instrument response relative to that observed during routine calibration.

If the actual field conditions differ significantly from the calibration assumptions, a special calibration for specific field conditions may be required. Such an extensive calibration need only be done once to determine the effects of the range of field conditions that may be encountered at the site. If responses under routine calibration conditions and proposed use conditions are significantly different, a correction factor or chart should be supplied with the instrument for use under the proposed conditions.

As a minimum, each measurement system (detector/readout combination) should be calibrated annually and response checked with a source following calibration, check national directives/regulations at this point. Instruments may require more frequent calibration if recommended by the manufacturer. Re-calibration of field instruments may also be required if an instrument fails a performance check or if it has undergone repair or any modification that could affect its response.

The user may decide to perform calibrations following industry recognized procedures [105], [106], [107], [108], [109], [110], [111], or the user can choose to obtain calibration by an outside service, such as a major instrument manufacturer or a health physics services organization.

Calibration sources should be traceable to national standards. Where national standards are not available, standards obtained from an industry recognized organization (*e.g.*, traceable standards from neighbouring countries) may be used.

Calibration of instruments for measurement of surface contamination should be performed such that a direct instrument response can be accurately converted to the 4π (total) emission rate from the source. An accurate determination of activity from a measurement of count rate above a surface in most cases is an extremely complex task because of the need to determine appropriate characteristics of the source including decay scheme, geometry, energy, scatter, and self-absorption. For the purpose of release of contaminated areas from radiological control, measurements must provide sufficient accuracy to ensure that clean-up standards have been achieved. Inaccuracies in measurements should be controlled in a manner that minimizes the consequences of decision errors. The variables that affect instrument response should be understood well enough to ensure that the consequences of decision errors are minimized. Therefore, the calibration should account for the following factors (where necessary):

- Calibrations for point and large area source geometries may differ, and both may be necessary if areas of activity smaller than the probe area and regions of activity larger than the probe area are present.
- Calibration should either be performed with the radionuclide of concern, or with appropriate correction factors developed for the radionuclide(s) present based on calibrations with nuclides emitting radiations similar to the radionuclide of concern.
- For portable instrumentation, calibrations should account for the substrate of concern (*i.e.*, concrete, steel) or appropriate correction factors developed for the substrates relative to the actual calibration standard substrate. This is especially important for beta emitters because backscatter is significant and varies with the composition of the substrate. Conversion factors developed during the calibration process should be for the same counting geometry to be used during the actual use of the detector.

For clean-up standards for building surfaces, the contamination level is typically expressed in terms of the particle emission rate per unit time per unit area, normally Bq/m² or disintegrations per minute (dpm) per 100 cm². In many facilities, surface contamination is assessed by converting the instrument response (in counts per minute) to surface activity using one overall total efficiency. The total efficiency may be considered to represent the product of two factors, the instrument (detector) efficiency, and the source efficiency. Use of the total efficiency is not a problem provided that the calibration source exhibits characteristics similar to the surface contamination (*i.e.*, radiation energy, backscatter effects, source geometry, self-absorption). In practice, this is hardly the case; more likely, instrument efficiencies are determined with a clean, stainless steel source, and then those efficiencies are used to determine the level of contamination on a dust-covered concrete surface. By separating the efficiency into two components, the surveyor has a greater ability to consider the actual characteristics of the surface contamination.

The instrument efficiency is defined as the ratio of the net count rate of the instrument and the surface emission rate of a source for a specified geometry. The surface emission rate is defined as the number of particles of a given type above a given energy emerging from the front face of the source per unit time. The surface emission rate is the 2π particle fluence that embodies both the absorption and scattering processes that effect the radiation emitted from the source. Thus, the instrument efficiency is determined by the ratio of the net count rate and the surface emission rate.

The instrument efficiency is determined during calibration by obtaining a static count with the detector over a calibration source that has a traceable activity or surface emission rate. In many cases, a source emission rate is measured by the manufacturer and has a traceable certification. The source activity is then calculated from the surface emission rate based on assumed backscatter and self-absorption properties of the source. The maximum value of instrument efficiency is 1.

The source efficiency is defined as the ratio of the number of particles of a given type emerging from the front face of a source and the number of particles of the same type created or released within the source per unit time. The source efficiency takes into account the increased particle emission due to backscatter effects, as well as the decreased particle emission due to self-absorption losses. For an ideal source (*i.e.*, no backscatter or self-absorption), the value of the source efficiency is 0.5.

Many real sources will exhibit values less than 0.5, although values greater than 0.5 are possible, depending on the relative importance of the absorption and backscatter processes.

Source efficiencies may be determined experimentally. Alternatively, ISO-7503-1 makes recommendations for default source efficiencies. A source efficiency of 0.5 is recommended for beta emitters with maximum energies above 0.4 MeV. Alpha emitters and beta emitters with maximum beta energies between 0.15 and 0.4 MeV have a recommended source efficiency of at least 0.25. Source efficiencies for some common surface materials and overlaying material are provided in [79].

Instrument efficiency may be affected by detector-related factors such as detector size (probe surface area), window density thickness, geotropism, instrument response time, counting time (in static mode), scan rate (in scan mode), and ambient conditions such as temperature, pressure, and humidity. Instrument efficiency also depends on solid angle effects, which include source-to-detector distance and source geometry.

Source efficiency may be affected by source-related factors such as the type of radiation emitted and its energy, source uniformity, surface roughness and coverings, and surface composition (*e.g.*, wood, metal, concrete).

The calibration of gamma detectors for the measurement of photon radiation fields should also provide reasonable assurance of acceptable accuracy in field measurements. Use of these instruments for demonstration of compliance with clean-up standards is complicated by the fact that most clean-up levels produce exposure rates of at most a few nSv/h. Several of the portable survey instruments currently commercial available for exposure rate measurements of ~10 nSv/h have full scale intensities of ~30 to 50 nSv/h on the first range. This is below the ambient background for most low radiation areas and most calibration laboratories. (A typical background dose equivalent rate of 1 mSv/y gives a background exposure rate of about 100 nSv/h.) Even on the second range, the ambient background in the calibration laboratory is normally a significant part of the range and must be taken into consideration during calibration. The instruments commonly are not energy-compensated and are very sensitive to the scattered radiation that may be produced by the walls and floor of the room or additional shielding required to lower the ambient background.

Low intensity sources and large distances between the source and detector can be used for low-level calibrations if the appropriate precautions are taken. Field characterization of low-level sources with traceable transfer standards is difficult because of the poor signal-to-noise ratio in the standard chamber. In order to achieve adequate ionization current, the distance between the standard chamber and the source generally will be as small as possible while still maintaining good geometry (5 to 7 detector diameters). Generally it is not possible to use a standard ionization chamber to characterize the field at the distance necessary to reduce the field to the level required for calibration. A high quality GM detector, calibrated as a transfer standard, may be useful at low levels.

Corrections for scatter can be made using a shadow-shield technique in which a shield of sufficient density and thickness to eliminate virtually all the primary radiation is placed about midway between the source and the detector. The dimensions of the shield should be the minimum required to reduce the primary radiation intensity (this primary radiation includes also build-up) at the detector location to less than 2% of its unshielded value. The change in reading caused by the shield being removed is attributed to the primary field from the source at the detector position.

For energy-dependent gamma scintillation instruments, such as NaI(Tl) detectors, calibration for the gamma energy spectrum at a specific site may be accomplished by comparing the instrument response to that of a pressurized ionization chamber, or equivalent detector, at different locations on the site. Multiple radio-nuclides with various photon energies may also be used to calibrate the system for the specific energy of interest.

In the interval between calibrations, the instrument should receive a performance check prior to use. In some cases, a performance check following use may also provide valuable information. This calibration check is merely intended to establish whether or not the instrument is operating within certain specified, rather large, uncertainty limits. The initial performance check should be conducted following the calibration by placing the source in a fixed, reproducible location and recording the instrument reading. The source should be identified along with the instrument, and the same check source should be used in the same fashion to demonstrate the instrument's operability on a daily basis when the instrument is in use. For analog readout (count rate) instruments, a variation of ± 20% is usually considered acceptable. Optionally, instruments that integrate events and display the total on a digital readout typically provide an acceptable average response range of 2 or 3 standard deviations. This is achieved by performing a series of repetitive measurements (10 or more is suggested) of background and check source response and determining the average and standard deviation of those measurements. From a practical standpoint, a maximum deviation of ± 20% is usually adequate when compared with other uncertainties associated with the use of the equipment. The amount of uncertainty allowed in the response checks should be consistent with the level of uncertainty allowed in the final data. Ultimately the stakeholders determine what level of uncertainty is acceptable.

Instrument response, including both the background and check source response of the instrument, should be tested and recorded at a frequency that ensures the data collected with the equipment is reliable. For most portable radiation survey equipment, EURSSEM recommends that a response check be performed twice daily when in use - typically prior to beginning the day's measurements and again following the conclusion of measurements on that same day. Additional checks can be performed if warranted by the instrument and the conditions under which it is used. If the instrument response does not fall within the established range, the instrument is removed from use until the reason for the deviation can be resolved and acceptable response again demonstrated. If the instrument fails the post-survey source check, all data collected during that time period with the instrument must be carefully reviewed and possibly adjusted or discarded, depending on the cause of the failure. Ultimately, the frequency of response checks must be balanced with the stability of the equipment being used under field conditions and the quantity of data being collected. For example, if the instrument experiences a sudden failure during the course of the day's work due to physical harm, such as a punctured probe, then the data collected up until that point is probably acceptable even though a post-use performance check cannot be performed. Likewise, if no obvious failure occurred but the instrument failed the post-use response check, then the data collected with that instrument since the last response check should be viewed with great skepticism and possibly re-collected or randomly checked with a different instrument. Additional corrective action alternatives are presented in Section 3.10.8. If re-calibration is necessary, acceptable response ranges must be re-established and documented.

Record requirements vary considerably and depend heavily on the needs of the user, while quality assurance and quality control programmes specify requirements.

3.9 Site characterisation: Analysis of samples

3.9.1 Selection of analytical method and detection limit

The selection of appropriate analytical methods based on detection limits is important to survey planning. The detection limit of the method directly affects the usability of the data because results near the detection limit have a greater possibility of false negatives and false positives. Results near the detection limit have increased measurement uncertainty. When the measurement uncertainty becomes large compared to the variability in the radio-nuclide concentration, it becomes more difficult to demonstrate compliance using the guidance provided in EURSSEM.

The detection limits (*i.e.*, minimum detectable concentrations; MDCs) have to be compared with radionuclide-specific results to determine their effectiveness in relation to the DCGL. Assessment of preliminary data reports provides an opportunity to review the detection limits early and resolve any detection sensitivity problems. When a radionuclide is reported as not detected, the result can only be used with confidence if the MDCs reported are lower than the DCGL.

It is not possible to analyse all samples for all possible contaminants, and a strategy is therefore needed to prioritise and sequence the chemical and radiochemical analyses undertaken. The strategy would take into account:

- The objectives of the site investigation (for example, is it to determine if a site is radioactively or chemically contaminated or to design a remediation strategy).
- The conceptual model of the site, which would identify the potential contaminants of concern, potential sources and mechanisms of contamination, and the potential pathways and receptors.
- The available budget and timescale for the site investigation/characterisation.

A phased approach is generally taken to the chemical and radiochemical testing. This is likely to involve:

- On-site screening of samples, for example:
    - Radioactivity, using hand-held alpha and beta/gamma monitors.
    - Volatile organic compounds (VOCs), using a photo-ionisation detector (PID) or gas chromatograph (GC).
- Laboratory screening techniques, for example:
    - Gamma spectrometry (which also provides detailed analysis for specific radionuclides).
    - Gross alpha/beta.
    - Tritium.
    - Hydrocarbon analyses (e.g., diesel range organics (DRO: C11 – ~C35) and petrol range organics (PRO: C4–C10)).
    - Polyaromatic hydrocarbon (PAH) and polychlorinated biphenyl (PCB) screens.
    - Beryllium.
- Detailed laboratory analysis, for example:
    - Gamma spectrometry (to determine the nuclide specific radioactivity with high accuracy).
    - Alpha spectrometry to determine activities of uranium and plutonium isotopes.
    - Chemical separation followed by specific radionuclide analysis (for example, ^{90}Sr).

- Trace metal analyses (e.g., Hg, Pb, Zn, hexavalent chromium).
- Analyses to determine the potential for in-situ degradation of organic contaminants (e.g., presence of electron acceptors (sulphate, ammonium, nitrate and iron) and indicators of microbial degradation (CO_2, methane, sulphide).
- Analysis to determine presence of potential degradation products, particularly if these are more toxic than the parent material.
- Analysis of colloids.

In general, for all types of analyses, uncertainty in the results increases with decreasing concentration or activity of contaminant.

Note that some laboratory screening can be undertaken on site. This may be required to confirm that samples are correctly packaged and labelled for off-site transport in accordance with the radioactive materials road transport regulations [29].

3.9.2 Analysis of radioactivity

The two principal non-intrusive analytical techniques used to detect radioactivity in samples are gamma spectrometry and gross alpha/beta analysis. The application of these techniques is discussed below as also the analysis of tritium in soils and waters.

Possible strategies (suggestions) for gross radioactivity and radiochemical analysis of samples are given in figures.

However, when measuring samples there should be always an awareness that there may be non-radiological contaminants present. Samples gathered for radiological purposes may also be suitable for assay of non-radioactive hazardous materials, in which case there may be special requirements for sample handling and storage. Conversely, samples gathered for non-radiological purposes may be suitable for radiometric investigations; even if the sample is required to be maintained intact, a non-destructive gamma spectrometry measurement may be possible.

Hazardous materials may also impact on how samples gathered for radiometric purposes are handled. There may be health and safety implications, if the material is hazardous, and care may be necessary to ensure that radiochemical assays are not affected.

However, the methods employed in a laboratory should be derived from a reliable source, such as those listed in Table 3.50.

Table 3.50 Examples of references for routine analytical methods

Methods of Air Sampling and Analysis [113];
Annual Book of ASTM Standards, Water and Environmental technology. Volume 11.04, Environmental Assessment; Hazardous Substances and Oil Spill Responses Waste Management; Environmental Risk Assessment [114];
Standard Methods for the Examination of Water and Wastewater [115];
EML Procedures Manual [116];
Radiochemical Analytical Procedures for Analysis of Environmental Samples [117];
Radiochemistry Procedures Manual [118];
Indoor Radon and Radon Decay Product Measurement Protocols [119];
USAEHA Environmental Sampling Guide [120].

3.9.2.1 Gamma spectrometry

Gamma spectrometry is the most used analysis method for quantifying nuclide specific radioactivity in samples. This method makes use of emitted gamma radiation, by a sample, which is produced during the decay of radionuclides. Gamma spectrometry provides no information on potential radioactive contaminants that emit only beta- or alpha radiation and whose presence cannot be inferred from short-lived gamma-emitting daughter radionuclides, such as ^{90}Sr.

The required sample size is in the range of grams to several kilograms. It is evident, that how smaller the sample size how larger the increase of the measuring time for getting the same analysis accuracy.

The sample size is in general larger than that required for gross alpha/beta analysis; hence sub-sampling errors will be smaller and results will probably be more representative of in-situ conditions. In particular, activities of common man-made radionuclides, such as ^{137}Cs and ^{60}Co, and of natural series decay chains (headed by ^{235}U, ^{238}U and ^{232}Th) can be measured or inferred. In the case of samples contaminated with natural series, e.g., phosphate ores, zirconium, etc. attention has to be given that for accurate measurements decay chains are in equilibrium.

However, because not all radionuclides will be detected using gamma spectrometry, e.g., radionuclides emitting very low gamma fluxes and/or pure alpha- and/or beta radiation. Therefore, it is advised that the technique should not be used in isolation unless the radionuclide fingerprint of the contaminated site is well understood and there is confidence that total levels of radioactive contamination can be derived from the gamma spectrometry data.

In waters, gamma spectrometry is typically used to provide more detailed analysis of contaminated samples. This is principally because gross alpha/beta analysis of waters provides accurate and precise measurement of detection limits below activity levels that are of radiological concern.

The detection limits of gamma spectrometry typically exceed those of the gross/alpha/beta technique.

Gamma spectrometers will usually be screened against background radiation to improve the minimum detectable activity of measurements. (The level of radon daughters inside a shield can be reduced further by allowing the liquid nitrogen Dewar usually used to cool high resolution gamma spectrometers to vent into the shield, thereby purging room air and replacing it with clean gas.)

3.9.2.2 Gross alpha and gross beta measurement

For health physic purposes will, in principle, a gross alpha and gross beta measurement (typically referred to as 'gross alpha/beta') be sufficient to characterise the total radioactivity of the sample. This is especially the case for analysis of environmental water samples, where accurate and precise detection to less than 0.1 $kBq.m^{-3}$ can be achieved. For assessment purposes the water analyses are compared to the Guideline Values produced by the World Health Organisation for radioactivity in drinking water.

In practice, gross alpha/beta analysis of soil samples is a screening technique, which enables distinction to be made between uncontaminated samples and those samples contaminated to levels of a few $kBq.kg^{-1}$ or more. The intervening region is more difficult to characterise because:

- The soil sample required for analysis is very small (< 1 g) and sub-sampling errors (arising from sample heterogeneity) may be significant.
- The typical sample preparation technique involves using the fine-grained (< 200 Qm portion of the soil. This can introduce a systematic bias in the result, because any radiation contamination tends to be associated with the fine fraction.

A more accurate measurement of gross alpha/beta activity in soil can be obtained if a 100 gram-sized sample of soil is homogenised and crushed so that there is no size separation prior to analysis.

Gross beta analysis does not detect weak beta-emitters such as emitted by ^{3}H, ^{14}C, ^{35}S, ^{129}I and so on. If these isotopes are potential contaminants in the soil or water samples, then additional isotope-specific analysis will be required.

3.9.2.3 Radiochemical analysis

When samples contain radioisotopes other than pure gamma emitters, some radiochemical preparation will usually be required [128], [129], [130], [131]. This may be a simple distillation to separate tritium or a long and complex assay to separate actinides or strontium. For environmental samples, even if gamma emitters are being quantified, there may be advantages in terms of improved sensitivity and reduction of counting time if sample preparation can concentrate the radioactivity. The ashing of biological samples, for instance, will reduce the volume enabling a more sensitive counting geometry to be used. For complex preparations, the addition of yield tracers may be useful to quantify how much nuclide has been lost in the procedure.

Radiochemistry will generally be useful when it is necessary to separate a ‘hard to measure’ or ‘difficult to measure’ radionuclide for analysis by alpha spectrometry or liquid scintillation counting (LSC), when an isotope is present at such low levels that it needs to be concentrated before counting is possible, or when it is necessary to separate an interfering radionuclide or one which overwhelms assay of another radionuclide of interest.

‘Fingerprinting’ techniques are often useful in reducing the number of samples which require complex chemical separations. ‘Fingerprinting’ involves using measurements of easy to measure radionuclides (usually gamma emitters) to quantify harder to measure nuclides. This could involve measurements of ^{241}Am to determine actinide inventories, or use of measurements of ^{137}Cs to indicate ^{90}Sr levels.

^{241}Am is formed as a decay product of ^{241}Pu. ^{241}Pu itself (and other plutonium isotopes) is difficult to measure, but ^{241}Am is a low energy (59.5 keV) gamma emitter.

Americium and plutonium (as well as other actinides) often behave in a similar manner in the environment (perhaps as insoluble particulates). Thus, if the ratio of ^{241}Am to other actinides can be established, a measurement of americium will serve to quantify the other actinides.

At least one measurement of the hard-to-measure radionuclide will usually be required, and it may be necessary to invest considerably more effort in order to establish the validity of the fingerprint.

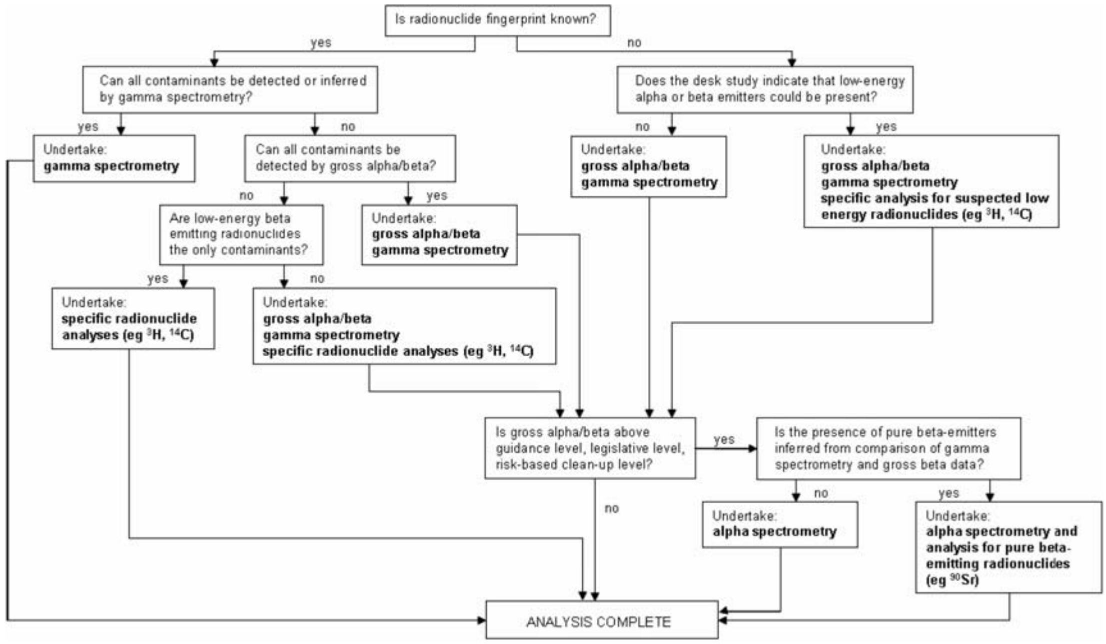
Fingerprints may be used in several ways. First, a firm correlation based on readily justifiable scientific grounds may be established between the easy to measure radionuclide and the hard-to-measure isotopes (such as may be the case in the relationship between ^{241}Am and ^{241}Pu, or between ^{137}Cs and ^{135}Cs).

Second, an empirical correlation may be made between two isotopes which may not be necessarily expected to behave in an identical manner: for instance, it may be established that ^{90}Sr levels can be linked to ^{137}Cs levels. Third, it may be possible to establish a bounding relationship between two isotopes. As a hypothetical example, if a correlation between ^{90}Sr and ^{137}Cs can be found at the surface of a site, and it can be shown that ^{137}Cs is less mobile than ^{90}Sr, measurements of ^{137}Cs in core samples could give an indication of the amount of ^{90}Sr in the subsoil.

3.9.2.4 Soil analysis for radionuclide determination

In Figure 3.11 a suggestion is presented for the radionuclide determination in soil.

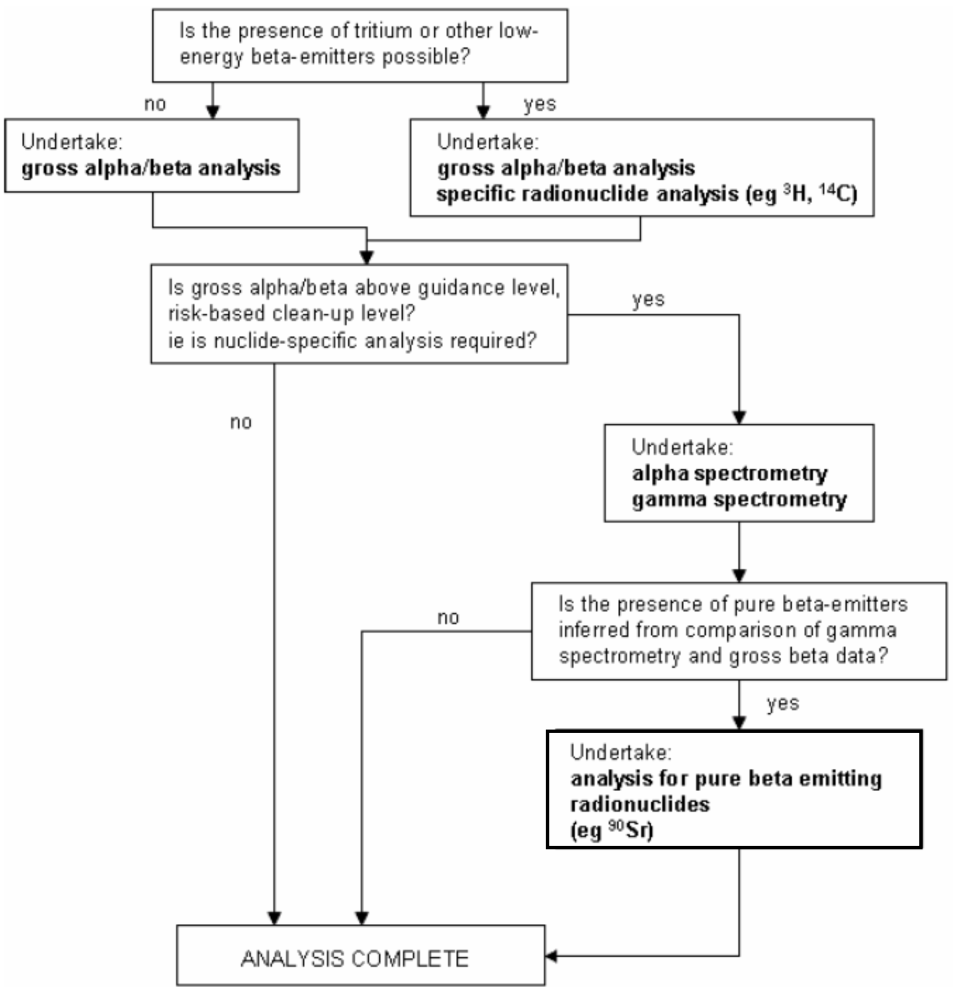
Figure 3.11 Soil analyses for radionuclide determination



3.9.2.5 Water analysis for radionuclide determination

In Figure 3.12 a suggestion is presented for the radionuclide determination in water.

Figure 3.12 Water analyses for radionuclide determination



Tritium

Tritium is a common contaminant on nuclear-licensed sites. It is present as tritiated water, which behaves in a chemically identical way to naturally occurring water (H_2O). As a consequence, it is highly mobile and commonly migrates from the near-surface environment into groundwater. The extent of migration is limited by the short half-life of tritium (12.3 years). Special precautions are needed when sampling and analyzing for tritium, to prevent evaporation of the sample and/or isotopic exchange with naturally occurring water. It is possible to analyse for tritium both in soil samples and in waters; in both cases, tritium is present in the aqueous phase. Quantification of tritium contamination in the unsaturated zone generally involves analysis of soil samples. The tritium activity can be expressed either as Bq/g of soil or as Bq/l of soil porewater. The latter is more informative, because it can be directly compared with the activity concentration of tritium in the underlying groundwater.

However, the moisture content of the soil sample must be measured to derive the porewater activity. In the saturated zone (i.e., below the water table), either soil samples or water samples can be collected and analysed. In practice, determination of tritium activities in soil or rock from beneath the groundwater table would only be undertaken if the samples were cohesive and fine-grained (i.e., porewater did not freely drain from the samples on collection).

It is preferable to determine tritium activity concentration directly in the groundwater although, in principle, the tritium activity concentration in the soil porewater and in the groundwater should be identical if the porewater and the mobile groundwater that is sampled by pump testing are in close contact. Analysis of tritium in soils may be appropriate at an early stage of a characterisation program, in order to evaluate whether a potential problem exists. If tritium contamination below the groundwater table is detected, it is best practice to install groundwater monitoring boreholes and to obtain groundwater samples for further analysis.

3.9.2.6 Autoradiography

Autoradiography can provide information about the nature of the contamination, e.g., whether it is homogenous or particulate, or both. Moreover, the combination of different techniques has the potential for identifying the particulate contamination as being that of uranium, plutonium, or fission products. If the detected particles are sufficiently large in size (> 20 μ), further investigations can be made to elucidate the physical/chemical and isotopic characteristics of the particles.

Autoradiography is based on the simple blackening of a sensitive film. After the exposure to radiation, the film is developed and shows a blackening where it has been exposed. Commercially available X-ray film (e.g., Kodak AG7) is suitable for the detection of fission products in samples obtained from different soil layers, ashed biota, air filters, etc. The limit of detection for a point source for film exposed overnight is typically equal to about 0.1 Bq of ^{137}Cs.

3.9.2.7 Neutron activation analysis

Another method which can provide valuable information on samples taken from a contaminated site is based on activation by neutrons. The nuclear track detection techniques for detection of uranium and plutonium particles are neutron induced fission track analysis and alpha track analysis. Both methods are commonly used and are well documented in the literature.

In neutron induced fission track analysis, a subsample of soil, ashed biota or air filter is brought onto a sticky plastic layer spread until all the material has covered the sticking layer. Then the sample is covered with mica film and tightly attached to the fission track detector. The detector is a polycarbonate foil. In this technique, the sample is irradiated with neutrons. A typical integrated flux of 10^9 n/s/cm^2 may be reached during the neutron irradiation; fissile isotopes, such as ^{235}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, etc., will absorb neutrons and thereby generate two fission-product nuclides with a shared kinetic energy of ca. 100 MeV. In the case where the fission product atom penetrates the detector, it will cause radiation damage along its path. In order to make the track visible, the detector is etched (this results in an increased diameter of the track hole). In the detector materials that are used mainly for neutron induced fission track analysis, alpha particles will not create tracks. After the detector has been developed, the distribution of fissile isotopes can be studied with a light microscope. The presence of particulate fissile produced isotopes is observed in a cluster of tracks. With standardization of the method, an estimation can be made of the particle size and the mass of fissile isotopes which are present in the particle. For the instrumented readout of the detectors, automated microscopic systems with an image analyzer are being used.

For the detection of alpha-emitting particles, the use of a material for registering the alpha radiation is required. Such materials are commercially available and the processing of the detectors is comparable to the above described procedure for fission track analysis. With alpha track detection, plutonium is much more effectively detected (on a mass basis) than uranium because of the large differences in specific activities between them. Comparing the number of alpha tracks and fission tracks for a single particle can give an initial indication of the elemental composition of the particle.

3.9.2.8 Other techniques

In cases where sites are contaminated with high concentrations of radioactive materials, gross alpha, beta and gamma measurements are able to produce a rough picture about the total inventory of contaminants and the extent of the contamination. If more detailed, qualitative and/or quantitative information is required, radiochemical methods will need to be applied. Due to the nature of radiochemical techniques, they allow only one or a small group of isotopes to be determined simultaneously. Depending on the method and detection system used, radiochemical methods may provide limited information about the elemental composition, especially in case of uranium and the actinides. For radionuclides with half lives longer than about 200 years, non-radiometric techniques can be more sensitive than their radiometric counterparts.

Non-radiometric techniques to be considered are:

- Glow discharge mass spectrometry is a technique that does not require dissolution of the sample and can measure in a described configuration a considerable number of elements in the periodic system with one measurement. The sensitivity reaches the parts per billion (ppb) level.
- Real time aerosol mass spectrometry performs qualitative elemental and isotopic characterisation from aerosols in air with sizes below 1 micrometer.
- Inductively coupled plasma mass spectrometry (ICPMS) can be used to detect trace levels of stable or long-lived radionuclides. In this context, it is particularly useful for assay of isotopes such as $^{36}C1$, ^{129}I and actinides.
- High performance ion liquid chromatography on-line with inductively coupled plasma mass spectrometry for qualitative and quantitative characterization of all uranium and actinide isotopes of interest in sample materials. In cases where only qualitative information is required, the uranium, plutonium and americium isotopic compositions can be determined in a single sample run.
- Many other standard chemical techniques may be found useful, particularly those aimed at determination of trace elements.
- X-ray fluorescence has been used for determination of many materials including uranium and plutonium, as well as for non-radioactive elements such as lead.

Non-radiometric techniques are not described in detail, but their possible application should be considered when it is necessary to determine a very long-lived radionuclide.

3.9.2.9 Errors and uncertainties in analyse results

When radiometric measurements are made, it is always important to maintain an awareness of uncertainties in the data and to take appropriate precautions so that the data which are obtained are adequate for their intended purpose. In this regard, pre-measurement consideration of the data quality objectives may be especially important.

Three limits of uncertainty are commonly quoted; there is much confusion as to the meaning of these limits:

- The *limit of confidence* (also known as limit of decision) is defined as the amount of a radionuclide that would be needed to be detected by a measurement in order to be confident that the identification is genuine.
- The *limit of detection* is the amount of radionuclide that one can be confident would be detected by a measurement.
- The *limit of quantification* (also known as limit of determination, and often referred to as minimum detectable activity (MDA)) is the amount of radionuclide that will have to be present in order to be confident that a measurement is adequate.

Whenever quoting results and uncertainties of counting measurements on low-activity samples, it is important to assure that one has specified and adhered to a consistent standard of reporting.

Before making a radiometric determination, it will be necessary to decide what sensitivity (limit of detection or limit of quantification) is required and to design the measurement such that this can be achieved. Failure to do so may result in having to repeat the measurement or in drawing an unwarranted conclusion that a particular isotope is not present.

If a given radioisotope is present in sufficient quantity, it may be possible to terminate the measurement early once the results have reached the desired statistical accuracy. An adaptive approach here can save much effort and time. Care should be taken that an overly conservative measurement (i.e., with an overly low level of uncertainty) is not required. In many cases, the overall uncertainty in a radiation measurement result will be dominated by factors other than counting statistics (in particular, there is the large variability which is inherent in sampling).

Measurement uncertainty (Error)

The quality of measurement data will be directly impacted by the magnitude of the measurement uncertainty associated with it. Some uncertainties, such as statistical counting uncertainties, can be easily calculated from the count results using mathematical procedures. Evaluation of other sources of uncertainty requires more effort and in some cases is not possible. For example, if an alpha measurement is made on a porous concrete surface, the observed instrument response when converted to units of activity will probably not exactly equal the true activity under the probe. Variations in the absorption properties of the surface for particulate radiation will vary from point to point and therefore will create some level of variation in the expected detection efficiency. This variability in the expected detector efficiency results in uncertainty in the final reported result. In addition, quality control (QC) measurement results provide an estimate of random and systematic uncertainties associated with the measurement process.

The measurement uncertainty for every analytical result or series of results, such as for a measurement system, should be reported. This uncertainty, while not directly used for demonstrating compliance with the release criterion, is used for survey planning and data assessment throughout the Radiation Survey and Site Investigation (RSSI) process. In addition, the uncertainty is used for evaluating the performance of measurement systems using quality control measurement results. Uncertainty can also be used for comparing individual measurements to the DCGL. This is especially important in the early stages of decommissioning (*i.e.*, scoping, characterization, remedial action support) when decisions are made based on a limited number of measurements.

For most sites, evaluations of uncertainty associated with field measurements are important only for data being used as part of the final status survey documentation. The final status survey data, which is used to document the final radiological status of a site, should state the uncertainties associated with the measurements. Conversely, detailing the uncertainties associated with measurements made during scoping or characterization surveys may or may not be of value depending on what the data will be used for - *i.e.,* the data quality objectives (DQOs). From a practical standpoint, if the observed data are obviously greater than the DCGL and will be eventually cleaned up, then the uncertainty may be relatively unimportant. Conversely, data collected during early phases of a site investigation that may eventually be used to show that the area is below the DCGL - and therefore does not require any clean-up action - will need the same uncertainty evaluation as the final status survey data. In summary, the level of effort needs to match the intended use of the data.

Systematic and random uncertainties

Measurement uncertainties are often broken into two sub-classes of uncertainty termed systematic (*e.g.*, methodical) uncertainty and random (*e.g.*, stochastic) uncertainty. Systematic uncertainties derive from a lack of knowledge about the true distribution of values associated with a numerical parameter and result in data that is consistently higher (or lower) than the true value. An example of a systematic uncertainty would be the use of a fixed counting efficiency value even though it is known that the efficiency varies from measurement to measurement but without knowledge of the frequency. If the fixed counting efficiency value is higher than the true but unknown efficiency - as would be the case for an unrealistically optimistic value - then every measurement result calculated using that efficiency would be biased low. Random uncertainties refer to fluctuations associated with a known distribution of values. An example of a random uncertainty would be a well documented chemical separation efficiency that is known to fluctuate with a regular pattern about a mean. A constant recovery value is used during calculations, but the true value is known to fluctuate from sample to sample with a fixed and known degree of variation.

To minimize the need for estimating potential sources of uncertainty, the sources of uncertainty themselves should be reduced to a minimal level by using practices such as:

- The detector used should minimize the potential uncertainty. For example, when making field surface activity measurements for ^{238}U on concrete, a beta detector such as a thin-window Geiger-Mueller 'pancake' may provide better quality data than an alpha detector depending on the circumstances. Less random uncertainty would be expected between measurements with a beta detector such as a pancake, since beta emissions from the uranium will be affected much less by thin absorbent layers than will the alpha emissions.

- Calibration factors should accurately reflect the efficiency of a detector being used on the surface material being measured for the contaminant radionuclide or mixture of radionuclides (see 0 and Section 3.8.5). For most field measurements, variations in the counting efficiency on different types of materials will introduce the largest amount of uncertainty in the final result.

- Uncertainties should be reduced or eliminated by use of standardized measurement protocols (*e.g.*, standard operating procedures) when possible. Special effort should be made to reduce or eliminate systematic uncertainties, or uncertainties that are the same for every measurement simply due to an error in the process. If the systematic uncertainties are reduced to a negligible level, then the random uncertainties, or those uncertainties that occur on a somewhat statistical basis, can be dealt with more easily.

- Instrument operators should be trained and experienced with the instruments used to perform the measurements.

- Quality assurance/Quality control should be conducted as described in Section 2.13 and Section 3.3.9.

Uncertainties that cannot be eliminated need to be evaluated such that the effect can be understood and properly propagated into the final data and uncertainty estimates. As previously stated, non-statistical uncertainties should be minimized as much as possible through the use of good work practices.

Overall random uncertainty can be evaluated using the methods described in the following sections. Section 3.9.2.9, 'Statistitical counting uncertainty' describes a method for calculating random counting uncertainty. Section 3.9.2.9, 'Uncertainty propagation' discusses how to combine this counting uncertainty with other uncertainties from the measurement process using uncertainty propagation.

Systematic uncertainty is derived from calibration errors, incorrect yields and efficiencies, non-representative survey designs, and 'blunders'. It is difficult - and sometimes impossible - to evaluate the systematic uncertainty for a measurement process, but bounds should always be estimated and made small compared to the random uncertainty, if possible. If no other information on systematic uncertainty is available, it is recommended to use 16% as an estimate for systematic uncertainties (1% for blanks, 5% for baseline, and 10% for calibration factors).

Statistical counting uncertainty

When performing an analysis with a radiation detector, the result will have an uncertainty associated with it due to the statistical nature of radioactive decay. To calculate the total uncertainty associated with the counting process, both the background measurement uncertainty and the sample measurement uncertainty must be accounted for. The standard deviation of the net count rate, or the statistical counting uncertainty, can be calculated by:

$$\sigma_n = \sqrt{(C_{s+b}/(T_{s+b})^2 + C_b/(T_b)^2)} \quad (3\text{-}24)$$

where:

σ_n	=	standard deviation of the net count rate result [ ].
C_{s+b}	=	number of gross counts (sample) [counts].
T_{s+b}	=	gross count time [s].
C_b	=	number of background counts [counts].
T_b	=	background count time [s].

Uncertainty propagation

Most measurement data will be converted to different units or otherwise included in a calculation to determine a final result. The standard deviation associated with the final result, or the total uncertainty, can then be calculated. Assuming that the individual uncertainties are relatively small, symmetric about zero and independent of one another, then the total uncertainty for the final calculated result can be determined by solving the following partial differential equation:

$$\sigma_u = \sqrt{((\partial u/\partial x)^2\sigma_x^2 + (\partial u/\partial y)^2\sigma_y^2 + (\partial u/\partial z)^2\sigma_z^2 + \dots)} \quad (3\text{-}25)$$

where:

u	=	function, or formula, that defines the calculation of a final result as a function of the collected data. All variables in this equation, *i.e.*, x, y, z..., are assumed to have a measurement uncertainty associated with them and do not include numerical constants.
σ_u	=	standard deviation, or uncertainty, associated with the final result.
$\sigma_x, \sigma_y, \dots$	=	standard deviation, or uncertainty, associated with the parameters x, y, z, ...

Equation 3-25, generally known as the error propagation formula, can be solved to determine the standard deviation of a final result from calculations involving measurement data and their associated uncertainties. The solutions for common calculations along with their uncertainty propagation formulas are included below.

Data calculation	Uncertainty propagation
$u = x + y$, or $u = x - y$:	$\sigma_u = \sqrt{(\sigma_x^2 + \sigma_y^2)}$
$u = x \div y$, or $u = x \times y$:	$\sigma_u = u \sqrt{((\sigma_x/x)^2 + (\sigma_y/y)^2)}$
$u = c \times x$, where c is a positive constant:	$\sigma_u = c\ \sigma_x$
$u = x \div c$, where c is a positive constant:	$\sigma_u = \sigma_x/c$

Note: In the above examples, x and y are measurement values with associated standard deviations, or uncertainties, equal to σ_x and σ_y respectively. The symbol 'c' is used to represent a numerical constant which has no associated uncertainty. The symbol σ_u is used to denote the standard deviation, or uncertainty, of the final calculated value u.

Reporting confidence intervals

Throughout this Section 3.9.2.9, the term 'measurement uncertainty' is used interchangeably with the term 'standard deviation'. In this respect, the uncertainty is qualified as numerically identical to the standard deviation associated with a normally distributed range of values. When reporting a confidence interval for a value, one provides the range of values that represent a pre-determined level of confidence (*i.e.*, 95%). To make this calculation, the final standard deviation, or total uncertainty σ_u as shown in Equation 3-25, is multiplied by a constant factor k representing the area under a normal curve as a function of the standard deviation. The value of k representing various intervals about a mean of normal distributions as a function of the standard deviation is given in Table 3.51. The following example illustrates the use of this factor in context with the propagation and reporting of uncertainty values.

Table 3.51 Areas under various intervals about the mean of a normal distribution

Interval $\mu \pm k\sigma$	Area
$\mu \pm 0.674\sigma$	0.500
$\mu \pm 1.00\sigma$	0.683
$\mu \pm 1.65\sigma$	0.900
$\mu \pm 1.96\sigma$	0.950
$\mu \pm 2.00\sigma$	0.954
$\mu \pm 2.58\sigma$	0.990
$\mu \pm 3.00\sigma$	0.997

Example 3.19: Calculation of an uncertainty propagation and confidence interval

Uncertainty Propagation and Confidence Interval: A measurement process with a zero background yields a count result of 28 ± 5 counts in 5 minutes, where the ± 5 counts represents one standard deviation about a mean value of 28 counts. The detection efficiency is 0.1 counts per disintegration ± 0.01 counts per disintegration, again representing one standard deviation about the mean.

Calculate the activity of the sample, in dpm, total measurement uncertainty, and the 95% confidence interval for the result.

The total number of disintegrations is:

28 counts/(0.1 c/d) = 280

Using the equation for error propagation for division, total uncertainty is:

280 $\sqrt{(5/28)^2 + (0.01/0.1)^2}$ *= 57 disintegrations*

The activity will then be 280 ÷ 5 minutes = 56 dpm and the total uncertainty will be 57 ÷ 5 minutes = 11 dpm. (Since the count time is considered to have trivial variance, this is assumed to be a constant.)

Referring to Table 3.51, a k value of ±1.96 represents a confidence interval equal to 95% about the mean of a normal distribution. Therefore, the 95% confidence interval would be 1.96 × 11 dpm = 22 dpm. The final result would be 56 ± 22 dpm.

3.10 Site characterisation: Data interpretation and drawing conclusions

The types of measurements that can be made in a survey unit are:

- Direct measurements at discrete locations;
- Samples collected at discrete locations;
- Survey scans.

Radiation survey data are usually obtained in units, such as the number of counts per unit time, that have no intrinsic meaning relative to derived concentration guideline levels (DCGLs). For comparison of survey data to DCGLs, the survey data from field and laboratory measurements should be converted to DCGL units. This section describes methods for converting survey data to appropriate units for comparison to radiological criteria.

3.10.1 Conversion of collected data to DCGL units

3.10.1.1 Surface activity: Conversion of counts to activity

When measuring surface activity, it is important to account for the physical surface area assessed by the detector in order to make probe area corrections and report data in the proper units (*i.e.*, Bq/m^2, $dpm/100\ cm^2$). This is termed the *physical probe area*. A common misuse is to make probe area corrections using the *effective probe area* which accounts for the amount of the physical probe area covered by a protective screen. Figure 3.13 illustrates the difference between the physical probe area and the effective probe area. The physical probe area is used because the reduced detector response due to the screen is accounted for during instrument calibration.

The conversion of instrument display in counts to surface activity units is obtained using the following equation:

$$Bq/m^2 = \frac{C_s/T_s}{(\varepsilon_T \times A)} \qquad (3\text{-}26)$$

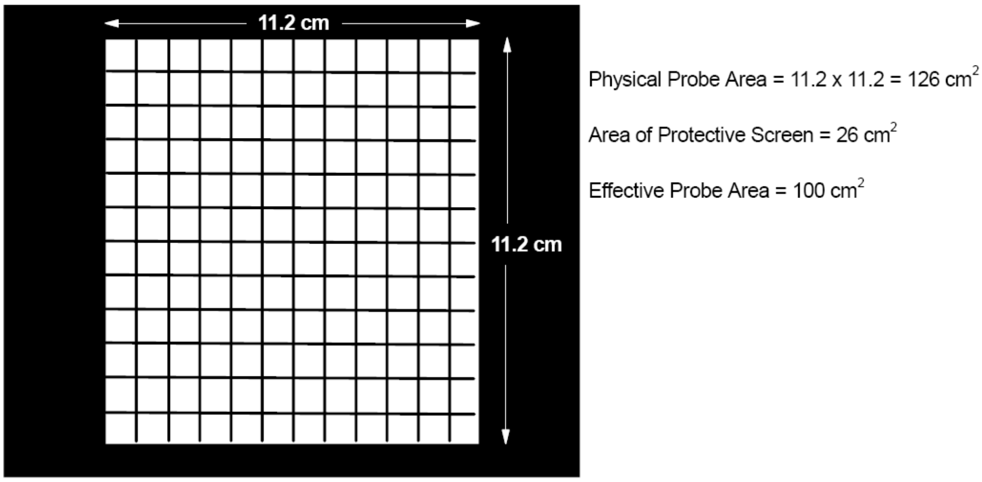
where:

C_s = integrated counts recorded by the instrument;

T_s = time period over which the counts were recorded in seconds;

ε_T = total efficiency of the instrument in counts per disintegration, effectively the product of the instrument efficiency (ε_i) and the source efficiency (ε_s);

A = physical probe area in m^2.



Gas Flow Proportional Detector with Physical Probe Area of 126 cm^2

Figure 3.13 The physical probe area of a detector

To convert instrument counts to conventional surface activity units, Equation 3-26 can be modified as shown in Equation 3-27:

$$\frac{dpm}{100\ cm^2} = \frac{C_s/T_s}{(\varepsilon_T) \times (A/100)} \tag{3-27}$$

Where:

T_s is recorded in minutes instead of seconds, and A is recorded in cm² instead of m².

Some instruments have background counts associated with the operation of the instrument. A correction for instrument background can be included in the data conversion calculation as shown in Equation 3-28. Note that the instrument background is not the same as the measurements in the background reference area.

$$Bq/m^2 = \frac{C_s/T_s - C_b/T_b}{(\varepsilon_T \times A)} \tag{3-28}$$

where:

C_b = background counts recorded by the instrument;

T_b = time period over which the background counts were recorded in seconds.

Equation 3-28 can be modified to provide conventional surface activity units as shown in Equation 3-29.

$$\frac{dpm}{100\ cm^2} = \frac{C_s/T_s - C_b/T_b}{(\varepsilon_T) \times (A/100)} \tag{3-29}$$

where T_s and T_b are recorded in minutes instead of seconds and A is recorded in cm² instead of m².

The presence of multiple radio-nuclides at a site requires additional considerations for demonstrating compliance with a dose- or risk-based regulation. As demonstrated in Section 3.3.6.2 , a gross activity DCGL should be determined.

Example 3.20: Calculation of a Derived Concentration Guideline Level for a an area contaminated by multiple radio-nuclides

Consider a site contaminated with ^{60}Co and ^{63}Ni, with ^{60}Co representing 60% of the total activity. The relative fractions are 0.6 for ^{60}Co and 0.4 for ^{63}Ni. If the DCGL for ^{60}Co is 8,300 Bq/m² (5,000 dpm/100 cm²) and the DCGL for ^{63}Ni is 12,000 Bq/m² (7,200 dpm/100 cm²), the gross activity DCGL is 9,500 Bq/m² (5,700 dpm/100 cm²) calculated using Equation 3-29.

When using the gross activity DCGL, it is important to use an appropriately weighted total efficiency to convert from instrument counts to surface activity units using Equations 3-26 through 3-29. In the above example, the individual efficiencies for ^{60}Co and ^{63}Ni should be independently evaluated. The overall efficiency is then determined by weighting each individual efficiency by the relative fraction of each radionuclide.

3.10.1.2 Soil activity: Conversion of radionuclide concentration and exposure rates to DCGL's

Analytical procedures, such as alpha and gamma spectrometry, are typically used to determine the radionuclide concentration in soil in units of Bq/kg. Net counts are converted to soil DCGL units by dividing by the time, detector or counter efficiency, mass or volume of the sample, and by the fractional recovery or yield of the chemistry procedure (if applicable).

Instruments, such as a PIC or micro-R meter, used to measure exposure rate typically read directly in mSv/h. A gamma scintillation detector (*e.g.*, NaI(Tl)) provides data in counts per minute and conversion to mSv/h is accomplished by using site-specific calibration factors developed for the specific instrument.

In-situ gamma spectrometry data may require special analysis routines before the spectral data can be converted to soil concentration units or exposure rates.

3.10.2 Statistical tests

The statistical tests are only applied to measurements made at discrete locations. Specific details for conducting the statistical tests are given in Section 3.10. When the data clearly show that a survey unit meets or exceeds the release criterion, the result is often obvious without performing the formal statistical analysis. Table 3.52 describes examples of circumstances leading to specific conclusions based on a simple examination of the data.

Table 3.52 Summary of statistical tests

Radionuclide not in background and radionuclide-specific measurements made:	
Survey result	**Conclusion**
All measurements less than $DCGL_W$	Survey unit meets release criterion
Average greater than $DCGL_W$	Survey unit does not meet release criterion
Any measurement greater than $DCGL_W$ and the average less than $DCGL_W$	Conduct Sign test and elevated measurement comparison
Radionuclide in background or radionuclide non-specific (gross) measurements made:	
Survey result	**Conclusion**
Difference between largest survey unit measurement and smallest reference area measurement is less than $DCGL_W$	Survey unit meets release criterion
Difference of survey unit average and reference area average is greater than $DCGL_W$	Survey unit does not meet release criterion
Difference between any survey unit measurement and any reference area measurement greater than $DCGL_W$ and the difference of survey unit average and reference area average is less than $DCGL_W$	Conduct WRS test and elevated measurement comparison

Both the measurements at discrete locations and the scans are subject to the elevated measurement comparison (EMC). The result of the EMC is not conclusive as to whether the survey unit meets or exceeds the release criterion, but is a flag or trigger for further investigation. The investigation may involve taking further measurements to determine that the area and level of the elevated residual radioactivity are such that the resulting dose or risk meets the release criterion[22]. The investigation should also provide adequate assurance, using the DQO process, that there are no other undiscovered areas of elevated residual radioactivity in the survey unit that might otherwise result in a dose or risk exceeding the release criterion. In some cases, this may lead to re-classifying all or part of a survey unit - unless the results of the investigation indicate that reclassification is not necessary.

The objective of compliance demonstration is to provide some level of confidence that the release criterion is not exceeded. As previously stated, 100% confidence in a decision cannot be proven because the data always contain some uncertainty. The use of statistical methods is necessary to provide a quantitative estimate of the probability that the release criterion is not exceeded at a particular site. Statistical methods provide for specifying (controlling) the probability of making decision errors and for extrapolating from a set of measurements to the entire site in a scientifically valid fashion [2], [132], [133], [134].

Clearly stating the null hypothesis is necessary before a statistical test can be performed. The null hypothesis recommended for use in EURSSEM is: 'The residual radioactivity in the survey unit does not exceed the release criterion'. This statement directly addresses the issue of compliance demonstration for the regulator (and other stakeholders) and places the burden of proof for demonstrating compliance on the site owner or responsible party.

The statistical tests can be applied for all sites, but should be applied at sites that were subjected to a historical site assessment (HSA). At this point, the results of the historical site assessment have been reviewed and the site is determined to be impacted based on existing data and professional judgment as described in Section 2.4. An impacted site, by definition, is expected to contain areas of contamination, so this statement of the null hypothesis is reasonable for these sites.

The information needed to perform a statistical test is determined by the assumptions used to develop the test. EURSSEM recommends like MARSSIM [2] the use of non-parametric statistical tests because these tests use fewer assumptions, and consequently require less information to verify these assumptions. The tests described in EURSSEM (see Section 3.10) are relatively easy to understand and to implement compared to other statistical tests.

Site conditions can also affect the selection of statistical tests. The distribution of contamination is of particular concern at sites with residual radioactivity. Is the contamination distributed uniformly, or is it located in small areas of elevated activity? Is the residual radioactivity present as surface, volumetric, or subsurface contamination?

To demonstrate the use of the Radiation Site Survey Investigation Process at radiation sites, EURSSEM addresses soil and groundwater. However, EURSSEM concentrates mainly on surface soil for the final status survey to demonstrate compliance. This represents a situation that is expected to commonly occur at sites with radioactive contamination, and allows the survey design to take into account the ability to directly measure surface radioactivity using scanning techniques. Other contaminated media may be identified during the historical site assessment (HAS) or preliminary surveys (*i.e.*, scoping, characterization, remedial action support). If other contaminated media (*e.g.*, subsurface contamination, volumetric contamination of building materials) are identified, methodologies for demonstrating compliance other than those described in this manual may need to be evaluated or developed.

The next sections are dealing with examples how statistical data processing can be performed in the following situations:

[22] Rather than, or in addition to, taking further measurements the investigation may involve assessing the adequacy of the exposure pathway model used to obtain the DCGLs and area factors, and the consistency of the results obtained with the historical site assessment and the scoping, characterization and remedial action support surveys.

- Contaminant not present in background;
- Contaminant present in background;
- Sites with a relatively uniform distribution of contamination;
- Small areas of elevated activity.

The examples are from final surveys as a final survey is in general the most complex and important one.

3.10.3 Example of statistical data processing: Contaminant not present in background

The one-sample statistical test (Sign test) described in Section 3.5.1.1 should only be used if the contaminant is not present in background and radionuclide-specific measurements are made. The one-sample test may also be used if the contaminant is present at such a small fraction of the derived concentration guideline levels ($DCGL_W$) value as to be considered insignificant. In this case, background concentrations of the radionuclide are included with the residual radioactivity (i.e., the entire amount is attributed to facility operations). Thus, the total concentration of the radionuclide is compared to the release criterion. This option should only be used if one expects that ignoring the background concentration will not affect the outcome of the statistical tests. The advantage of ignoring a small background contribution is that no reference area is needed. This can simplify the final status survey considerably.

The one-sample Sign test (see Section 3.10.3.2) evaluates whether the median of the data is above or below the $DCGL_W$. If the data distribution is symmetric, the median is equal to the mean. In cases where the data are severely skewed, the mean may be above the $DCGL_W$, while the median is below the $DCGL_W$. In such cases, the survey unit does *not* meet the release criterion regardless of the result of the statistical tests. On the other hand, if the largest measurement is below the $DCGL_W$, the Sign test will always show that the survey unit meets the release criterion.

3.10.3.1 Site and data description

To illustrate the data interpretation process, consider an example facility with 14 survey units consisting of interior concrete surfaces, one interior survey unit with drywall surfaces, and two exterior survey units. The contaminant of concern is ^{60}Co. The interior surfaces were measured with a gas-flow proportional counter (see 0) with an active surface area of 20 cm² to determine total beta-gamma activity. Because these measurements are not radionuclide specific, appropriate reference areas were chosen for comparison. The exterior soil was measured with a germanium spectrometer to provide radionuclide-specific results. A reference area is not needed because ^{60}Co does not have a significant background in soil.

The exterior Class 3 survey unit incorporates areas that are not expected to contain residual radioactivity. The exterior Class 2 survey unit is similar to the Class 3 survey unit, but is expected to contain residual radioactivity below the $DCGL_W$. The Class 1 interior concrete survey units are expected to contain small areas of elevated activity that may or may not exceed the $DCGL_W$. The Class 2 interior drywall survey unit is similar to the Class 1 interior concrete survey unit, but the drywall is expected to have a lower background, less measurement variability, and a more uniform distribution of contamination. The Class 2 survey unit is not expected to contain areas of activity above the $DCGL_W$. Section 3.10.3 describes the Sign test used to evaluate the survey units where the contaminant is not present in background. Section 3.10.4 describes the WRS test used to evaluate the survey units where the contaminant is present in background. Section 3.10.8 discusses the evaluation of the results of the statistical tests and the decision regarding compliance with the release criterion. The survey design parameters and DQOs developed for these survey units are summarized in Table 3.53.

Table 3.53 Final status survey parameters for example survey units

Survey unit	**Type**	**DQO**		**$DCGL_W$**	**Estimated standard deviation, σ**		**Test/section**
		α	**β**		**Survey**	**Reference**	
Interior Concrete	Class 1	0.05	0.05	5000 dpm per 100 cm²	625 dpm per 100 cm²	220 dpm per 100 cm²	WRS/App. A and App. D
Interior Drywall	Class 2	0.025	0.05	5000 dpm per 100 cm²	200 dpm per 100 cm²	200 dpm per 100 cm²	WRS/3.10.4.3
Exterior Lawn	Class 2	0.025	0.025	140 Bq/kg	3.8 Bq/kg	N/A	Sign/3.10.3.4
Exterior Lawn	Class 3	0.025	0.01	140 Bq/kg	3.8 Bq/kg	N/A	Sign/3.10.3.5

The statistical test discussed in this section is used to compare each survey unit directly with the applicable release criterion. A reference area is not included because the measurement technique is radionuclide-specific and the radionuclide of concern is not present in background. In this case the contaminant levels are compared directly with the $DCGL_W$. The method in this section should only be used if the contaminant is not present in background or is present at such a small fraction of the $DCGL_W$ value as to be considered insignificant. In addition, one-sample tests are applicable only if radionuclide-specific measurements are made to determine the concentrations. Otherwise, the method in Section 3.10.4 is recommended.

Reference areas and reference samples are not needed when there is sufficient information to indicate there is essentially no background concentration for the radionuclide being considered. With only a single set of survey unit samples, the statistical test used here is called a one-sample test. See Section 3.10.3.2 for further information appropriate to following the example and discussion presented here.

3.10.3.2 One-sample Sign test

The Sign test is designed to detect uniform failure of remedial action throughout the survey unit. This test does not assume that the data follow any particular distribution, such as normal or log-normal. In addition to the Sign test, the $DCGL_{EMC}$ (see Section 3.5.1.1) is compared to each measurement to ensure none exceeds the $DCGL_{EMC}$. If a measurement exceeds this DCGL, then additional investigation is recommended, at least locally, to determine the actual areal extent of the elevated concentration.

The hypothesis tested by the Sign test is:

Null Hypothesis

H_0: The median concentration of residual radioactivity in the survey unit is greater than the $DCGL_W$

versus

Alternative Hypothesis

H_a: The median concentration of residual radioactivity in the survey unit is less than the $DCGL_W$.

The null hypothesis is assumed to be true unless the statistical test indicates that it should be rejected in favour of the alternative. The null hypothesis states that the probability of a measurement less than the $DCGL_W$ is less than one-half, *i.e.*, the 50^{th} percentile (or median) is greater than the $DCGL_W$. Note that some individual survey unit measurements may exceed the $DCGL_W$ even when the survey unit as a whole meets the release criterion. In fact, a survey unit average that is close to the $DCGL_W$ might have almost half of its individual measurements greater than the $DCGL_W$. Such a survey unit may still not exceed the release criterion.

The assumption is that the survey unit measurements are independent random samples from a symmetric distribution. If the distribution of measurements is symmetric, the median and the mean are the same.

The hypothesis specifies a release criterion in terms of a $DCGL_W$. The test should have sufficient power (1-β, as specified in the DQOs) to detect residual radioactivity concentrations at the lower boundary of the gray region (LBGR). If σ is the standard deviation of the measurements in the survey unit, then Δ/σ expresses the size of the shift (*i.e.*, $\Delta = DCGL_W - LBGR$) as the number of standard deviations that would be considered 'large' for the distribution of measurements in the survey unit. The procedure for determining Δ/σ is given in Section 3.5.1.1.

3.10.3.3 Applying the Sign test

The Sign test is applied as outlined in the following five steps, and further illustrated by the examples in Section 3.10.3.4 and Section 3.10.3.5.

1. List the survey unit measurements, X_i, $i = 1, 2, 3..., N$.
2. Subtract each measurement, X_i, from the $DCGL_W$ to obtain the differences:

   $D_i = DCGL_W - X_i$, i = 1, 2, 3..., N.
3. Discard each difference that is exactly zero and reduce the sample size, *N*, by the number of such zero measurements.
4. Count the number of positive differences. The result is the test statistic S+. Note that a positive difference corresponds to a measurement below the $DCGL_W$ and contributes evidence that the survey unit meets the release criterion.
5. Large values of S+ indicate that the null hypothesis (that the survey unit exceeds the release criterion) is false. The value of S+ is compared to the critical values in Figure D.2 of 0. If S+ is greater than the critical value, *k*, in that table, the null hypothesis is rejected.

3.10.3.4 Sign test example: Class 2 exterior soil survey unit

For the Class 2 exterior soil survey unit, the one-sample non-parametric statistical test is appropriate since the radio-nuclide of concern does not appear in background and radio-nuclide-specific measurements were made.

Table 3.53 shows that the DQOs for this survey unit include α = 0.025 and β = 0.025. The $DCGL_W$ is 140 Bq/kg (3.8 pCi/g) and the estimated standard deviation of the measurements is σ = 3.8 Bq/kg (0.10 pCi/g). Since the estimated standard deviation is much smaller than the $DCGL_W$, the LBGR should be set so that Δ/σ is about 3.

If $\Delta/\sigma = (DCGL_W - LBGR)/\sigma$

$= 3$

then $LBGR = DCGL_W - 3\sigma$

$= 140 - (3 \times 3.8)$

= 128 Bq/kg (3.5 pCi/g).

Table 3.37 indicates the number of measurements estimated for the Sign test, N, is 20 (α = 0.025, β = 0.025, and Δ/σ = 3). (Table D.1 in 0 also lists the number of measurements estimated for the Sign test.) This survey unit is Class 2, so the 20 measurements needed were made on a random-start triangular grid. When laying out the grid, 22 measurement locations were identified.

Table 3.54 Example Sign analysis: Class 2 exterior soil survey unit

Data [Bq/kg]	**$DCGL_W$ – Data [Bq/kg]**	**Sign**
121	19	1
143	-3	-1
145	-5	-1
112	28	1
125	15	1
132	8	1
122	18	1
114	26	1
123	17	1
148	-8	-1
115	25	1
113	27	1
126	14	1
134	6	1
148	-8	-1
130	10	1
119	21	1
136	4	1
128	12	1
125	15	1
142	-2	-1
129	11	1
Number of positive differences S+ = 17		

The 22 measurements taken on the exterior lawn Class 2 survey unit are shown in the first column of Table 3.54. The mean of these data is 129 Bq/kg (3.5 pCi/g) and the standard deviation is 11 Bq/kg (0.30 pCi/g). Since the number of measurements is even, the median of the data is the average of the two middle values (126+128)/2 = 127 Bq/kg (3.4 pCi/g). A quantile plot of the data is shown in 0 Section D.3.3, Figure D.5.

There are five measurements that exceed the $DCGL_W$ value of 140 Bq/kg: 142, 143, 145, 148, and 148. However, none exceed the mean of the data plus three standard deviations: 127 + (3 × 11) = 160 Bq/kg (4.3 pCi/g). Thus, these values appear to reflect the overall variability of the concentration measurements rather than to indicate an area of elevated activity - *provided* that these measurements were scattered through the survey unit. However, if a posting plot demonstrates that the locations of these measurements are grouped together, then that portion of the survey unit containing these locations merits further investigation.

The middle column of Table 3.54 contains the differences, $DCGL_W$ - *Data*, and the last column contains the signs of the differences. The bottom row shows the number of measurements with positive differences, which is the test statistic S+. In this case, S+ = 17.

The value of S+ is compared to the appropriate critical value in Table D.2 of 0. In this case, for N = 22and $\alpha = 0.025$, the critical value is 16. Since S+ = 17 exceeds this value, the null hypothesis that the survey unit exceeds the release criterion is rejected.

3.10.3.5 Sign Test example: Class 3 exterior soil survey unit

For the Class 3 exterior soil survey unit, the one-sample non-parametric statistical test is again appropriate since the radio-nuclide of concern does not appear in background and radio-nuclide-specific measurements were made.

Table 3.53 shows that the DQOs for this survey unit include $\alpha = 0.025$ and $\beta = 0.01$. The $DCGL_W$ is 140 Bq/kg (3.8 pCi/g) and the estimated standard deviation of the measurements is $\sigma = 3.8$ Bq/kg (0.10 pCi/g). Since the estimated standard deviation is much smaller than the $DCGL_W$, the lower bound for the gray region should be set so that Δ/σ is about 3.

If $\Delta/\sigma = (DCGL_W - LBGR)/\sigma$

$= 3$

then $LBGR = DCGL_W - 3\sigma$

$= 140 - (3 \times 4)$

$= 128$ Bq/kg (3.5 pCi/g).

Table 3.37 indicates that the sample size estimated for the Sign test, N, is 23 ($\alpha = 0.025$, $\beta = 0.01$, and $\Delta/\sigma = 3$). This survey unit is Class 3, so the measurements were made at random locations within the survey unit.

The 23 measurements taken on the exterior lawn are shown in the first column of Table 3.55. Notice that some of these measurements are negative (-0.37 in cell A5). This might occur if an analysis background (*e.g.*, the Compton continuum under a spectrum peak) is subtracted to obtain the net concentration value. The data analysis is both easier and more accurate when numerical values are reported *as obtained* rather than reporting the results as 'less than' or not detected. The mean of these data is 2.1 Bq/kg (0.057 pCi/g) and the standard deviation is 3.3 Bq/kg (0.089 pCi/g). None of the data exceed $2.1 + (3 \times 3.3) = 12.0$ Bq/kg (0.32 pCi/g). Since N is odd, the median is the middle (12^{th} highest) value, namely 2.6 Bq/kg (0.070 pCi/g).

An initial review of the data reveals that every data point is below the $DCGL_W$, so the survey unit meets the release criterion specified in Table 3.53. For purely illustrative purposes, the Sign test analysis is performed. The middle column of Table 3.55 contains the quantity $DCGL_W$ - Data. Since every data point is below the $DCGL_W$, the sign of $DCGL_W$ - Data is always positive. The number of positive differences is equal to the number of measurements, N, and so the Sign test statistic S+ is 23. The null hypothesis will always be rejected at the maximum value of S+ (which in this case is 23) and the survey unit passes. Thus, the application of the Sign test in such cases requires no calculations and one need not consult a table for a critical value. If the survey is properly designed, the critical value must always be less than N.

Passing a survey unit without making a single calculation may seem an unconventional approach. However, the key is in the survey design which is intended to ensure that enough measurements are made to satisfy the DQOs. As in the previous example, after the data are collected the conclusions and power of the test can be checked by constructing a retrospective power curve as outlined in Appendix D, Section D.1.3.

One final consideration remains regarding the survey unit classification: 'Was any definite amount of residual radioactivity found in the survey unit?' This will depend on the MDC of the measurement method. Generally the MDC is at least 3 or 4 times the estimated measurement standard deviation. In the present case, the largest observation, 9.3 Bq/kg (0.25 pCi/g), is less than three times the estimated measurement standard deviation of 3.8 Bq/kg (0.10 pCi/g). Thus, it is unlikely that any of the measurements could be considered indicative of positive contamination. This means that the Class 3 survey unit classification was appropriate.

Table 3.55 Sign test example data for Class 3 exterior survey unit

	A Data	B $DCGL_W$ – Data	C Sign
1	3.0	137.0	1
2	3.0	137.0	1
3	1.9	138.1	1
4	0.37	139.6	1
5	-0.37	140.4	1
6	6.3	133.7	1
7	-3.7	143.7	1
8	2.6	137.4	1
9	3.0	137	1
10	-4.1	144.1	1
11	3.0	137	1
12	3.7	136.3	1
13	2.6	137.4	1
14	4.4	135.6	1
15	-3.3	143.3	1
16	2.1	137.9	1
17	6.3	133.7	1
18	4.4	135.6	1
19	-0.37	140.4	1
20	4.1	135.9	1
21	-1.1	141.1	1
22	1.1	138.9	1
23	9.3	130.7	1
Number of positive differences S+ = 23			

If one determines that residual radioactivity is definitely present, this would indicate that the survey unit was initially mis-classified. Ordinarily, EURSSEM recommends a resurvey using a Class 1 or Class 2 design. If one determines that the survey unit is a Class 2, a resurvey might be avoided if the survey unit does not exceed the maximum size for such a classification. In this case, the only difference in survey design would be whether the measurements were obtained on a random or on a triangular grid. Provided that the initial survey's scanning methodology is sufficiently sensitive to detect areas at $DCGL_W$ without the use of an area factor, this difference in the survey grids alone would not affect the outcome of the statistical analysis. Therefore, if the above conditions were met, a resurvey might not be necessary.

3.10.4 Example of statistical data processing: Contaminant present in background

The two-sample statistical test (Wilcoxon Rank Sum test, discussed in Section 3.5.1.1) should be used when the radio-nuclide of concern appears in background or if measurements are used that are not radio-nuclide specific, e.g., as at a final status survey. The two-sample Wilcoxon Rank Sum (WRS) test (Section 3.10.4.1) assumes the reference area and survey unit data distributions are similar except for a possible shift in the medians. When the data are severely skewed, the value for the mean difference may be above the $DCGL_W$, while the median difference is below the $DCGL_W$. In such cases, the survey unit does *not* meet the release criterion regardless of the result of the statistical test. On the other hand, if the difference between the largest survey unit measurement and the smallest reference area measurement is less than the $DCGL_W$, the WRS test will always show that the survey unit meets the release criterion.

The statistical tests discussed in this section will be used to compare each survey unit with an appropriately chosen, site-specific reference area. Each reference area should be selected on the basis of its similarity to the survey unit, as discussed in Section 3.3.5.

3.10.4.1 Two-Sample statistical test

The comparison of measurements from the reference area and survey unit is made using the Wilcoxon Rank Sum (WRS) test (also called the Mann-Whitney test). The WRS test should be conducted for each survey unit. In addition, the elevated measurement comparison (EMC) is performed against each measurement to ensure that it does not exceed a specified investigation level. If any measurement in the re-mediated survey unit exceeds the specified investigation level, then additional investigation is recommended, at least locally, regardless of the outcome of the WRS test.

The WRS test is most effective when residual radioactivity is uniformly present throughout a survey unit. The test is designed to detect whether or not this activity exceeds the $DCGL_W$. The advantage of the non-parametric WRS test is that it does not assume that the data are normally or log-normally distributed. The WRS test also allows for 'less than' measurements to be present in the reference area and the survey units. As a general rule, the WRS test can be used with up to 40 percent 'less than' measurements in either the reference area or the survey unit. However, the use of 'less than' values in data reporting is not recommended as discussed in Section 3.11. When possible, report the actual result of a measurement together with its uncertainty.

The hypothesis tested by the WRS test is:

Null Hypothesis

H_0: The median concentration in the survey unit exceeds that in the reference area by more than the $DCGL_W$

versus

Alternative Hypothesis

H_a: The median concentration in the survey unit exceeds that in the reference area by less than the $DCGL_W$.

The null hypothesis is assumed to be true unless the statistical test indicates that it should be rejected in favour of the alternative. One assumes that any difference between the reference area and survey unit concentration distributions is due to a shift in the survey unit concentrations to higher values (*i.e.*, due to the presence of residual radioactivity in addition to background). Note that some or all of the survey unit measurements may be larger than some reference area measurements, while still meeting the release criterion. Indeed, some survey unit measurements may exceed some reference area measurements by more than the $DCGL_W$. The result of the hypothesis test determines whether or not the survey unit as a whole is deemed to meet the release criterion. The elevated measurement comparison (EMC) is used to screen individual measurements.

Two assumptions underlying this test are: 1) samples from the reference area and survey unit are independent, identically distributed random samples, and 2) each measurement is independent of every other measurement, regardless of the set of samples from which it came.

3.10.4.2 Applying the Wilcoxon Rank Sum Test

The WRS test is applied as outlined in the following six steps and further illustrated by the examples in Section 3.10.4.3:

1. Obtain the adjusted reference area measurements, Z_i, by adding the $DCGL_W$ to each reference area measurement, X_i. $Z_i = X_i + DCGL_W$

2. The m adjusted reference sample measurements, Z_i, from the reference area and the n sample measurements, Y_i, from the survey unit are pooled and ranked in order of increasing size from 1 to N, where $N = m+n$.

3. If several measurements are tied (*i.e.*, have the same value), they are all assigned the average rank of that group of tied measurements.

4. If there are t 'less than' values, they are all given the average of the ranks from 1 to t. Therefore, they are all assigned the rank t(t+1)/(2t) = (t+1)/2, which is the average of the first t integers. If there is more than one detection limit, all observations below the largest detection limit should be treated as 'less than' values[23].

5. Sum the ranks of the adjusted measurements from the reference area, W_r. Note that since the sum of the first N integers is $N(N+1)/2$, one can equivalently sum the ranks of the measurements from the survey unit, W_s, and compute $W_r = N(N+1)/2 - W_s$.

6. Compare W_r with the critical value given in 0 Table D.4 for the appropriate values of n, m, and α. If W_r is greater than the tabulated value, reject the hypothesis that the survey unit exceeds the release criterion.

3.10.4.3 Wilcoxon Rank Sum test example: Class 2 interior drywall survey unit

In this example, the gas-flow proportional counter measures total beta-gamma activity (see 0) and the measurements are not radio-nuclide-specific. The two-sample non-parametric test is appropriate for the Class 2 interior drywall survey unit because gross beta-gamma activity contributes to background even though the radio-nuclide of interest does not appear in background.

Table 3.53 shows that the DQOs for this survey unit include $\alpha = 0.025$ and $\beta = 0.05$. The $DCGL_W$ is 8,300 Bq/m² (5,000 dpm per 100 cm²) and the estimated standard deviation of the measurements is about $\sigma = 1{,}040$ Bq/m² (625 dpm per 100 cm²). The estimated standard deviation is 8 times less than the $DCGL_W$. With this level of precision, the width of the gray region can be made fairly narrow. As noted earlier, sample sizes do not decrease very much once Δ/σ exceeds 3 or 4. In this example, the lower bound for the gray region was set so that Δ/σ is about 4.

If $\Delta/\sigma = (DCGL_W - LBGR)/\sigma$

$= 4$

then $LBGR = DCGL_W - 4\sigma$

$= 8{,}300 - (4 \times 1{,}040)$

$= 4{,}100$ Bq/m² (2,500 dpm per 100 cm²).

23 If more than 40 percent of the data from either the reference area or survey unit are 'less than', the WRS test *cannot* be used. Such a large proportion of non-detects suggest that the DQO process be re-visited for this survey to determine if the survey unit was properly classified or the appropriate measurement method was used. As stated previously, the use of 'less than' values in data reporting is not recommended. Wherever possible, the actual result of a measurement, together with its uncertainty, should be reported.

In Table 3.35, one finds that the number of measurements estimated for the WRS test is 11 in each survey unit and 11 in each reference area ($\alpha = 0.025$, $\beta = 0.05$, and $\Delta/\sigma = 4$). (Table D.3 in 0 also lists the number of measurements estimated for the WRS test.) This survey unit was classified as Class 2, so the 11 measurements needed in the survey unit and the 11 measurements needed in the reference area were made using a random-start triangular grid[24].

Table 3.56 lists the data obtained from the gas-flow proportional counter in units of counts per minute. A reading of 160 cpm with this instrument corresponds to the $DCGL_W$ of 8,300 Bq/m^2 (5,000 dpm per 100 cm^2). Column A lists the measurement results as they were obtained. The average and standard deviation of the reference area measurements are 44 and 4.4 cpm, respectively. The average and standard deviation of the survey unit measurements are 98 and 5.3 cpm, respectively.

Table 3.56 WRS test for Class 2 interior drywall survey unit

	A Data (cpm)	B Area	C Adjusted data	D Ranks	E Reference area ranks
1	49	R	209	22	22
2	35	R	195	12	12
3	45	R	205	17.5	17.5
4	45	R	205	17.5	17.5
5	41	R	201	14	14
6	44	R	204	16	16
7	48	R	208	21	21
8	37	R	197	13	13
9	46	R	206	19	19
10	42	R	202	15	15
11	47	R	207	20	20
12	104	S	104	9.5	0
13	94	S	94	4	0
14	98	S	98	6	0
15	99	S	99	7	0
16	90	S	90	1	0
17	104	S	104	9.5	0
18	95	S	95	5	0
19	105	S	105	11	0
20	93	S	93	3	0
21	101	S	101	8	0
22	92	S	92	2	0
	Sum =			253	187

In column B, the code 'R' denotes a reference area measurement, and 'S' denotes a survey unit measurement. Column C contains the adjusted data. The adjusted data are obtained by adding the $DCGL_W$ to the reference area measurements (see Section 3.10.4.2, Step 1). The ranks of the adjusted data appear in Column D. They range from 1 to 22, since there is a total of 11+11 measurements (see Section 3.10.4.2, Step 2).

[24] A random start systematic grid is used in Class 2 and 3 survey units primarily to limit the size of any potential elevated areas. Since areas of elevated activity are not an issue in the reference areas, the measurement locations can be either random or on a random start systematic grid (see Section 3.5.1.2).

Note that there were two cases of measurements tied with the same value, at 104 and 209. Each tied measurement is always assigned the average of the ranks. Therefore, both measurements at 104, are assigned rank (9+10)/2 = 9.5 (see Section 3.10.4.2, Step 3). Also note that the sum of *all* of the ranks is still 22(22+1)/2 = 253. Checking this value with the formula in Step 5 of Section 3.10.4.2 is recommended to guard against errors in the rankings.

Column E contains only the ranks belonging to the reference area measurements. The total is 187. This is compared with the entry for the critical value of 156 in Table D.4 of 0 for α = 0.025, with n = 11 and m =11. Since the sum of the reference area ranks is greater than the critical value, the null hypothesis (*i.e.*, that the average survey unit concentration exceeds the $DCGL_W$) is rejected.

The analysis for the WRS test is very well suited to the use of a computer spreadsheet. The spreadsheet formulas used for the example above are given in 0.4, Table D.10.

3.10.4.4 Class 1 interior concrete survey unit

As in the previous example, the gas-flow proportional counter measures total beta-gamma activity (see 0) and the measurements are not radionuclide specific. The two-sample non-parametric test is appropriate for the Class 1 interior concrete survey unit because gross beta-gamma activity contributes to background even though the radionuclide of interest does not appear in background.

3.10.4.5 Multiple radionuclides

The use of the unity rule when there is more than one radionuclide to be considered is discussed in 0.4. An example application appears in Section D.4.4.

3.10.5 Example of statistical data processing: Sites with a relatively uniform distribution of contamination

As discussed previously, the development of a DCGL starts with the assumption of a relatively uniform distribution of contamination. Some variability in the measurements is expected. This is primarily due to a random spatial distribution of contamination and uncertainties in the measurement process. The arithmetic mean of the measurements taken from such a distribution would represent the parameter of interest for demonstrating compliance.

Whether or not the radionuclide of concern is present in background determines the form of the statistical test. The Wilcoxon Rank Sum (WRS) test is recommended for comparisons of survey unit radionuclide concentrations with background. When the radionuclide of concern is not present in background, the Sign test is recommended. Instructions on performing these tests are provided in Section 3.10.3 and Section 3.10.4.

The Wilcoxon Rank Sum and Sign tests are designed to determine whether or not the level of residual activity uniformly distributed throughout the survey unit does not exceed the $DCGL_W$. Since these methods are based on ranks, the results are generally expressed in terms of the median of the data set. When the underlying measurement distribution is symmetric, the mean is equal to the median. When the underlying distribution is not symmetric, these tests are still true tests of the median but only approximate tests of the mean. However, numerous studies show that this is a fairly good approximation. The assumption of symmetry is less restrictive than that of normality because the normal distribution is itself symmetric. If, however, the measurement distribution is skewed to the right, the average will generally be greater than the median. In severe cases, the average may exceed the $DCGL_W$ while the median does not. For this reason, EURSSEM recommends comparing the arithmetic mean of the survey unit data to the $DCGL_W$ as a first step in the interpretation of the data (see Section 3.10.8.4).

The Wilcoxon Rank Sum test is a two-sample test that compares the distribution of a set of measurements in a survey unit to that of a set of measurements in a reference area. The test is performed by first adding the value of the $DCGL_W$ to each measurement in the reference area. The combined set of survey unit data and adjusted reference area data are listed, or ranked, in increasing numerical order. If the ranks of the adjusted reference site measurements are significantly higher than the ranks of the survey unit measurements, the survey unit demonstrates compliance with the release criterion.

The Sign test is a one-sample test that compares the distribution of a set of measurements in a survey unit to a fixed value, namely the $DCGL_W$. First, the value for each measurement in the survey unit is subtracted from the $DCGL_W$. The resulting distribution is tested to determine if the centre of the distribution is greater than zero. If the adjusted distribution is significantly greater than zero, the survey unit demonstrates compliance with the release criterion.

Guidance on performing the statistical tests and presenting graphical representations of the data is provided in 0.

3.10.6 Example of statistical data processing: Small areas of elevated activity

The guidance for the development of release criteria (or Derived Concentration Guideline Level - DCGL) is presented in Section 3.3.6, and will use in general exposure pathway models which in turn assume a relatively uniform distribution of contamination. While this represents an ideal situation, small areas of elevated activity are a concern at many sites.

EURSSEM [2] addresses the concern for small areas of elevated activity by using a simple comparison to an investigation level as an alternative to statistical methods. Using the elevated measurement comparison (EMC), which represents a conservative approach, requires that every measurement needs to be below the specified action level. The investigation level for this comparison is called the $DCGL_{EMC}$, which is the $DCGL_W$ modified to account for the smaller area by an area factor.

This area factor correction (discussed in Section 3.5.1.1) is considered to be a defensible modification because the exposure assumptions (*e.g.*, exposure time and duration) are the same as those used to develop the $DCGL_W$. In the case of multiple areas of elevated activity in a survey unit, a posting plot (discussed in Section 3.10.8.3) or similar representation of the distribution of activity in the survey unit can be used to determine any pattern in the location of these areas.

If elevated levels of residual radioactivity are found in an isolated area, in addition to residual radioactivity distributed relatively uniformly across the survey unit, the unity rule (see Section 3.3.6.3) can be used to ensure that the total dose or risk meets the release criterion. If there is more than one of these areas, a separate term should be included in the calculation for each area of elevated activity. As an alternative to the unity rule, the dose or risk due to the actual residual radioactivity distribution can be calculated if there is an appropriate exposure pathway model available. Note that these considerations generally only apply to Class 1 survey units, since areas of elevated activity should not be present in Class 2 or Class 3 survey units.

3.10.7 Verify the assumptions of applied statistical tests

An evaluation to determine that the data are consistent with the underlying assumptions made for the statistical procedures helps to validate the use of a test. One may also determine that certain departures from these assumptions are acceptable when given the actual data and other information about the study. The non-parametric tests described in this assume that the data from the reference area or survey unit consist of independent samples from each distribution.

Spatial dependencies that potentially affect the assumptions can be assessed using posting plots (see Section 3.10.8.3). More sophisticated tools for determining the extent of spatial dependencies are also available (*e.g.*, EPA QA/G-9 [121]). These methods tend to be complex and are best used with guidance from a professional statistician.

Asymmetry in the data can be diagnosed with a stem and leaf display, a histogram, or a quantile plot. Data transformations can sometimes be used to minimize the effects of asymmetry.

One of the primary advantages of the non-parametric tests used in this guidance is that they involve fewer assumptions about the data than their parametric counterparts. If parametric tests are used, (*e.g.*, Student's *t* test), then any additional assumptions made in using them should be verified (*e.g.*, testing for normality). These issues are discussed in detail in [121].

One of the more important assumptions made in the survey design described in Section 3.3 is that the sample sizes determined for the tests are sufficient to achieve the data quality objectives set for the Type I (α) and Type II (β) error rates. Verification of the power of the tests (1-β) to detect adequate remediation may be of particular interest. Methods for assessing the power are discussed in 0.1.3. If the hypothesis that the survey unit residual radioactivity exceeds the release criterion is accepted, there should be reasonable assurance that the test is equally effective in determining that a survey unit has residual contamination less than the $DCGL_W$. Otherwise, unnecessary remediation may result. For this reason, it is better to plan the surveys cautiously - even to the point of:

- Overestimating the potential data variability;
- Taking too many samples;
- Overestimating minimum detectable concentrations (MDCs).

If one is unable to show that the DQOs were met with reasonable assurance, a resurvey may be needed. Examples of assumptions and possible methods for their assessment are summarized in Table 3.57.

Table 3.57 Methods for checking the assumptions of statistical tests

Assumption	Diagnostic
Spatial Independence	Posting Plot
Symmetry	Histogram, Quantile Plot
Data Variance	Sample Standard Deviation
Power is Adequate	Retrospective Power Chart

3.10.7.1 Alternate null hypothesis

The selection of the null hypothesis in EURSSEM is designed to be protective of human health and the environment as well as consistent with current methods used for demonstrating compliance with regulations. EURSSEM also acknowledges that site-specific conditions (e.g., high variability in background, lack of measurement techniques with appropriate detection sensitivity) may preclude the use of the null hypothesis that the survey unit is assumed to be contaminated. Similarly, a different null hypothesis and methodology could be used for different survey units (e.g., Class 3 survey units). NUREG 1505 provides guidance on determining when background variability might be an issue, designing surveys based on the null hypothesis that the survey unit concentration is indistinguishable from the concentration in the reference area, and performing statistical tests to demonstrate that the survey unit is indistinguishable from background [122].

3.10.8 Data quality assessment process

The strength of data quality assessment (DQA) is its design that progresses in a logical and efficient manner to promote an understanding of how well the collected site characterisation data meet the intended use.

3.10.8.1 Assessment phase

In the assessment phase collected site characterisation data is evaluated whether the data meet the objectives of the survey and whether the data are sufficient to determine compliance with the DCGL. The assessment phase of the data life cycle consists of three phases: data verification, data validation, and data quality assessment (DQA).

Data verification

Data verification is used to ensure that the requirements stated in the planning documents (*e.g.*, quality assurance project plan, standard operating procedures) are implemented as prescribed.This means that deficiencies or problems that occur during implementation should be documented and reported. This also means that activities performed during the implementation phase are assessed regularly with findings documented and reported to the management. Corrective actions undertaken should be reviewed for adequacy and appropriateness and documented in response to the findings. Data verification activities should be planned and documented in the quality assurance project plan (see Section 2.13). These assessments may include but are not limited to inspections, quality control checks, surveillance, technical reviews, performance evaluations, and audits.

To ensure that conditions requiring corrective actions are identified and addressed promptly, data verification activities should be initiated as part of data collection during the implementation phase of the survey. The performance of tasks by personnel is generally compared to a prescribed method documented in the standard operation procedures, and is generally assessed using inspections, surveillance, or audits. Self-assessments and independent assessments may be planned, scheduled, and performed as part of the survey. Self-assessment also means that personnel doing work should document and report deficiencies or problems that they encounter to their supervisors or management.

The performance of equipment such as radiation detectors or measurement systems such as instruments, and human operators can be monitored using control charts. Control charts are used to record the results of quantitative quality control checks such as background and daily calibration or performance checks. Control charts document instrument and measurement system performance on a regular basis and identify conditions requiring corrective actions on a real time basis. Control charts are especially useful for surveys that extend over a significant period of time (*e.g.*, weeks instead of days) and for equipment that is owned by a company that is frequently used to collect survey data. Surveys that are accomplished in one or two days and use rented instruments may not benefit significantly from the preparation and use of control charts. The use of control charts is usually documented in the standard operation procedures.

A technical review is an independent assessment that provides an in-depth analysis and evaluation of documents, activities, material, data, or items that require technical verification to ensure that established requirements are satisfied. A technical review typically requires a significant effort in time and resources and may not be necessary for all surveys. A complex survey using a combination of scanning, direct measurements, and sampling for multiple survey units is more likely to benefit from a detailed technical review than a simple survey design calling for relatively few measurements using one or two measurement techniques for a single survey unit.

Data validation

Data validation is used to ensure that the results of the data collection activities support the objectives of the survey as documented in the quality assurance project plan, or permit a determination that these objectives should be modified. Data usability is the process of ensuring or determining whether the quality of the data produced meets the intended use of the data. Data verification compares the collected data with the prescribed activities documented in the standard operation procedures; data validation compares the collected data to the data quality objectives documented in the quality assurance project plan. Corrective actions may improve data quality and reduce uncertainty, and may eliminate the need to qualify or reject data.

Qualified data are any data that have been modified or adjusted as part of statistical or mathematical evaluation, data validation, or data verification operations. Data may be qualified or rejected as a result of data validation or data verification activities. Data qualifier codes or flags are often used to identify data that has been qualified. Any scheme used should be fully explained in the quality assurance project plan and survey documentation. The following are examples of data qualifier codes or flags (see Table 3.58) derived from national qualifiers assigned to results in the contract laboratory program.

Table 3.58 Examples of data qualifier codes or flags

U or < MDC	The radionuclide of interest was analyzed for, but the radionuclide concentration was below the minimum detectable concentration (MDC). Section 3.11 recommends that the actual result of the analysis be reported, so this qualifier would inform the reader that the result reported is also below the MDC.
J	The associated value reported is a modified, adjusted, or estimated quantity. This qualifier might be used to identify results based on surrogate measurements (see Section 3.3.6.2) or gross activity measurements (*e.g.*, gross alpha, gross beta). The implication of this qualifier is that the estimate may be inaccurate or imprecise which might mean the result is inappropriate for the statistical evaluation of the results. Surrogate measurements that are not inaccurate or imprecise may or may not be associated with this qualifier. It is recommended that the potential uncertainties associated with surrogate or gross measurements be quantified and included with the results.
R	The associated value reported is unusable. The result is rejected due to serious analytical deficiencies or quality control results. These data would be rejected because they do not meet the data quality objectives of the survey.
O	The associated value reported was determined to be an outlier.

Data validation is often defined by six data descriptors. These six data descriptors are summarized in Table 3.59 and discussed in detail in Section 3.11.2. The decision maker or reviewer examines the data, documentation, and reports for each of the six data descriptors to determine if performance is within the limits specified in the data quality objectives during planning. The data validation process for each data descriptor should be conducted according to procedures documented in the quality assurance project plan.

Data collected should meet performance objectives for each data descriptor. If they do not, deviations should be noted and any necessary corrective action performed. Corrective action should be taken to improve data usability when performance fails to meet objectives.

Data quality assessment

Data quality assessment (DQA) is the scientific and statistical evaluation of data to determine if the data are of the right type, quality, and quantity to support their intended use.

There are five steps in the data quality assessment process:

- Review the data quality objectives (DQOs) and survey design.
- Conduct a preliminary data review.
- Select the statistical test.

- Verify the assumptions of the statistical test.
- Draw conclusions from the data.

These five steps are presented in a linear sequence, but the data quality assessment process is applied in an iterative fashion much like the data quality objectives process.

Table 3.59 Suggested content or consideration, impact if not met, and corrective actions for data descriptors

Data descriptor	Suggested content or consideration	Impact if not met	Corrective action
Reports to decision maker	- Site description - Survey design with measurement locations - Analytical method and detection limit - Detection limits (MDCs) - Background radiation data - Results on per measurement basis, qualified for analytical limitations - Field conditions for media and environment - Preliminary reports - Meteorological data, if indicated by DQOs - Field reports	- Unable to perform a quantitative radiation survey and site investigation	- Request missing information - Perform qualitative or semi-quantitative site investigation
Documentation	- Chain-of-custody records - Standard Operation Procedures - Field and analytical records - Measurement results related to geographic location	- Unable to identify appropriate concentration for survey unit measurements - Unable to have adequate assurance of measurement results	- Request that locations be identified - Resurveying or re-sampling - Correct deficiencies
Data sources	- Historical data used meets Data Quality Objectives	- Potential for Type I and Type II decision errors - Lower confidence of data quality	- Resurveying, re-sampling or re-analysis for unsuitable or questionable measurements
Analytical method and detection limit	- Routine methods used to analyse radio-nuclides of potential concern	- Unquantified precision and accuracy - Potential for Type I and Type II decision errors	- Re-analysis - Resurveying, re-sampling or reanalysis - Documented statements of limitation
Data review	- Defined level of data review for all data	- Potential for Type I and Type II decision errors - Increased variability and bias due to analytical process, calculation errors or transcription errors	- Perform data review
Data quality indicators	- Surveying and sampling variability identified for each radio-nuclide - QC measurements to identify and quantify precision and accuracy - Surveying, sampling and analytical precision and accuracy quantified	- Unable to quantify levels for uncertainty - Potential for Type I and Type II decision errors	- Resurveying or re-sampling - Perform qualitative site investigation - Documented discussion of potential limitations

3.10.8.2 Review the data quality objectives of the site characterisation survey and sampling design

The following activities are associated with this step in the DQA process:

- The first step in the data quality assessment evaluation is a review of the data quality objective outputs to ensure that they are still applicable. For example, if the data suggest the survey unit was misclassified as Class 3 instead of Class 1, then the original data quality objectives should be redeveloped for the correct classification.
- Review of the translating of the data user's objectives into a statement of the hypotheses to be tested using collected site characterisation data. These objectives should be documented as part of the DQO Process, and this activity is reduced to translating these objectives into the statement of hypotheses.
- Translating the objectives into limits on the probability of committing Type I or Type II decision errors.
- Reviewing the survey design and noting any special features or potential problems. The goal of this activity is to familiarize the analyst with the main features of the survey design used to generate the site characterisation data. Review the survey design documentation with the data user's objectives in mind. Look for design features that support or contradict these objectives.
- Review the sampling design and data collection documentation. This documentation should be reviewed for consistency with the data quality objectives. For example, the review should check that the appropriate number of samples was taken in the correct locations and that they were analyzed with measurement systems with appropriate sensitivity.

Determining that the sampling design provides adequate power is important to decision making particularly in cases where the levels of residual radioactivity are near the derived concentration guideline level ($DCGL_W$). This can be done both prospectively, during survey design to test the efficacy of a proposed design, and retrospectively, during interpretation of survey results to determine that the objectives of the design are met. The procedure for generating power curves for specific tests is discussed in Appendix D. Note that the accuracy of a prospective power curve depends on estimates of the data variability, σ, and the number of measurements. After the data are analyzed, a sample estimate of the data variability, namely the sample standard deviation (s) and the actual number of valid measurements will be known. The consequence of inadequate power is that a survey unit that actually meets the release criterion has a higher probability of being incorrectly deemed *not* to meet the release criterion.

3.10.8.3 Conduct a preliminary data review

In this step of the DQA process, the analyst conducts a preliminary evaluation of the data set, calculating some basic statistical quantities and looking at the data through graphical representations. By reviewing the data both numerically and graphically, the analyst can learn the ‘structure’ of the data and thereby identify appropriate approaches and limitations for their use.

This step includes the activities:

- Reviewing quality assurance reports.
- Calculating basic statistical quantities (*e.g.*, mean, standard deviation and median, relative standing, central tendency, dispersion, shape, and association).
- Graphical data review (*e.g.*, histograms, scatter plots, confidence intervals, ranked data plots, quantile plots, stem-and-leaf diagrams, spatial or temporal plots).

3.10.8.4 Calculation of the basic statistical quantities; mean, standard deviation and median

<u>Example 3.21: Calculation of the basic statistical quantities; mean, standard deviation and median</u>

Suppose the following 20 concentration values are from a survey unit:

- *90.7; 83.5; 86.4; 88.5; 84.4; 74.2; 84.1; 87.6; 78.2; 77.6;*
- *86.4; 76.3; 86.5; 77.4; 90.3; 90.1; 79.1; 92.4; 75.5; 80.5.*

First, the average of the data (83.5) and the sample standard deviation (5.7) should be calculated.

The average of the data can be compared to the reference area average and the derived concentration guideline level ($DCGL_W$) to get a preliminary indication of the survey unit status. Where remediation is inadequate, this comparison may readily reveal that a survey unit contains excess residual radioactivity - even before applying statistical tests. For example, if the average of the data exceeds the derived concentration guideline level ($DCGL_W$) and the radionuclide of interest does not appear in background, then the survey unit clearly does not meet the release criterion. On the other hand, if every measurement in the survey unit is below the derived concentration guideline level ($DCGL_W$), the survey unit clearly meets the release criterion[25].

The value of the sample standard deviation is especially important. If too large compared to that assumed during the survey design, this may indicate an insufficient number of samples were collected to achieve the desired power of the statistical test. Again, inadequate power can lead to unnecessary remediation.

The median is the middle value of the data set when the number of data points is odd, and is the average of the two middle values when the number of data points is even. Thus 50% of the data points are above the median, and 50% are below the median. Large differences between the mean and the median would be an early indication of skewness in the data. This would also be evident in a histogram of the data. For the example data above, the median is 84.25 (i.e., (84.1 + 84.4)/2). The difference between the median and the mean (i.e., 84.25 - 83.5 = 0.75) is a small fraction of the sample standard deviation (i.e., 5.7). Thus, in this instance, the mean and median would not be considered significantly different.

Examining the minimum, maximum, and range of the data may provide additional useful information. The minimum in this example is 74.2 and the maximum is 92.4, so the range is 92.4 - 74.2 = 18.2. This is only 3.2 standard deviations. Thus, the range is not unusually large. When there are 30 or fewer data points, values of the range much larger than about 4 to 5 standard deviations would be unusual. For larger data sets the range might be wider.

3.10.8.5 Data review by graphics

<u>Example 3.22: Data review by graphics</u>

At a minimum, a graphical data review should consist of a posting plot and a histogram. Quantile plots are also useful diagnostic tools, particularly in the two-sample case, to compare the survey unit and reference area. These are discussed in 0, Section D.3.3.

A *posting plot* is simply a map of the survey unit with the data values entered at the measurement locations. This potentially reveals heterogeneities in the data - especially possible patches of elevated residual radioactivity. Even in a reference area, a posting plot can reveal spatial trends in background data that might affect the results of the two-sample statistical tests.

[25] It can be verified that if every measurement is below the derived concentration guideline level ($DCGL_W$), the conclusion from the statistical tests will always be that the survey unit does not exceed the release criterion.

If the data above were obtained using a triangular grid in a rectangular survey unit, the posting plot might resemble the display in Figure 3.14. Figure 3.14a shows no unusual patterns in the data. Figure 3.14b shows a different plot of the same values, but with individual results associated with different locations within the survey unit. In this plot there is an obvious trend towards smaller values as one move from left to right across the survey unit. This trend is not apparent in the simple initial listing of the data. The trend may become more apparent if isopleths are added to the posting plot.

If the posting plot reveals systematic spatial trends in the survey unit, the cause of the trends would need to be investigated. In some cases, such trends could be due to residual radioactivity, but may also be due to in-homogeneities in the survey unit background. Other diagnostic tools for examining spatial data trends may be found in [121]. The use of geostatistical tools to evaluate spatial data trends may also be useful in some cases [123].

A *frequency plot* (or a histogram) is a useful tool for examining the general shape of a data distribution. This plot is a bar chart of the number of data points within a certain range of values. A frequency plot of the example data is shown in Figure 3.15. A simple method for generating a rough frequency plot is the stem and leaf display discussed in 0, Section D.3.2.The frequency plot will reveal any obvious departures from symmetry, such as skewness or bimodality (two peaks), in the data distributions for the survey unit or reference area. The presence of two peaks in the survey unit frequency plot may indicate the existence of isolated areas of residual radioactivity. In some cases it may be possible to determine an appropriate background for the survey unit using this information. The interpretation of the data for this purpose will generally be highly dependent on site-specific considerations and should only be pursued after a consultation with the responsible regulatory agency.

The presence of two peaks in the background reference area or survey unit frequency plot may indicate a mixture of background concentration distributions due to different soil types, construction materials, etc. The greater variability in the data due to the presence of such a mixture will reduce the power of the statistical tests to detect an adequately remediated survey unit. These situations should be avoided whenever possible by carefully matching the background reference areas to the survey units, and choosing survey units with homogeneous backgrounds.

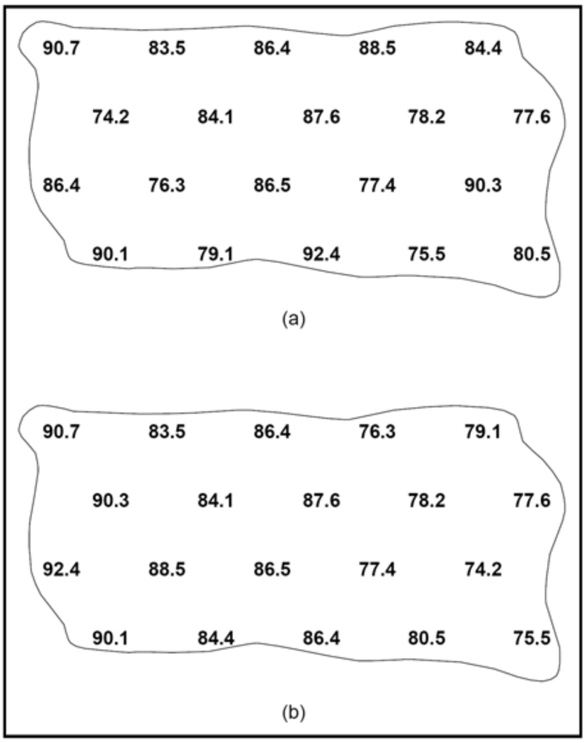


Figure 3.14 Examples of posting plots

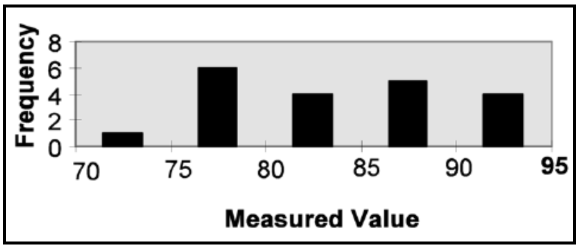


Figure 3.15 Example of a frequency plot

Skewness or other asymmetry can impact the accuracy of the statistical tests. A data transformation (e.g., taking the logarithms of the data) can sometimes be used to make the distribution more symmetric. The statistical tests would then be performed on the transformed data. When the underlying data distribution is highly skewed, it is often because there are a few high areas. Since the elevated measurement comparison (EMC) is used to detect such measurements, the difference between using the median and the mean as a measure for the degree to which uniform residual radioactivity remains in a survey unit tends to diminish in importance.

3.10.8.6 Review the selected statistical test

The statistical tests presented in Section 3.10.2 up to Section 3.10.7 are applicable for most sites contaminated with radioactive material and discuss also the rationale for selecting the statistical methods recommended for the different surveys in more detail. Additional guidance on selecting alternate statistical methods can be found in Section 3.3.9.9 in Table 3.26.

An appropriate procedure for summarizing and analyzing the data should be based on the preliminary data review.

3.10.8.7 Verify the assumptions of the statistical test

In this step, the analyst assesses the validity of the statistical test by examining the underlying assumptions in light of the collected site characterisation data. The key two questions to be resolved are:

- Do the data support the underlying assumptions of the test?
- Do the data suggest that modifications to the statistical analysis are warranted?

The underlying assumptions for the statistical tests are discussed in Section 3.10.2. Graphical representations of the data, such as those described in earlier in this Section and in 0, can provide important qualitative information about the validity of the assumptions. Documentation of this step is always important, especially when professional judgement plays a role in accepting the results of the analysis.

There are three activities included in this step:

- *Determining the approach for verifying assumptions*. For this activity, determine how the assumptions of the hypothesis test will be verified, including assumptions about distributional form, independence, dispersion, type, and quantity of data. In Sections 3.10.1 up to 3.10.7 methods are discussed for verifying assumptions for the final status survey statistical test during the preliminary data review.
- *Performing tests of the assumptions*. Perform the calculations selected in the previous activity for the statistical tests. Guidance on performing the tests recommended for the final status survey is included in Section 3.10.
- *Determining corrective actions (if any)*. Sometimes the assumptions underlying the hypothesis test will not be satisfied and some type of corrective action should be performed before proceeding. In some cases, the data for verifying some key

assumption may not be available and existing data may not support the assumption. In this situation, it may be necessary to collect new data, transform the data to correct a problem with the distributional assumptions, or select an alternate hypothesis test. Section 3.3.9.9 discusses potential corrective actions.

3.10.8.8 Verify the draw conclusions from the data

The final step of the DQA process is performing/verifying the statistical test and drawing conclusions that address the data user's objectives. The procedure for implementing the statistical test is described earlier in this Section 3.10.

There are three activities associated with this final step:

- Performing the calculations for the statistical hypothesis test (see Sections 3.10.1 up to 3.10.7).
- Evaluating the statistical test results and drawing the study conclusions. The results of the statistical test will be either accept the null hypothesis, or reject the null hypothesis.
- Evaluating the performance of the survey design if the design is to be used again. If the survey design is to be used again, either in a later phase of the current study or in a similar study, the analyst will be interested in evaluating the overall performance of the design. To evaluate the survey design, the analyst performs a statistical power analysis that describes the estimated power of the test over the full range of possible parameter values. This helps the analyst evaluate the adequacy of the sampling design when the true parameter value lies in the vicinity of the action level (which may not have been the outcome of the current study). It is recommended that a statistician be consulted when evaluating the performance of a survey design for future use.

Once the data and the results of the tests are obtained, the specific steps required to achieve site release depend on the procedures instituted by the governing regulatory agency and site-specific ALARA considerations. The following suggested considerations are for the interpretation of the test results with respect to the release limit established for the site or survey unit. Note that the tests need not be performed in any particular order.

Elevated Measurement Comparison

The elevated measurement comparison (EMC) consists of comparing each measurement from the survey unit with the *investigation levels* discussed in Section 3.3.2.7 and Section 3.10.2. The elevated measurement comparison is performed for both measurements obtained on the systematic-sampling grid and for locations flagged by scanning measurements. Any measurement from the survey unit that is equal to or greater than an *investigation level* indicates an area of relatively high concentrations that should be investigated - regardless of the outcome of the nonparametric statistical tests.

The statistical tests may not reject H_0 when only a very few high measurements are obtained in the survey unit. The use of the elevated measurement comparison against the investigation levels may be viewed as assurance that unusually large measurements will receive proper attention regardless of the outcome of those tests and that any area having the potential for significant dose contributions will be identified. The elevated measurement comparison is intended to flag potential failures in the remediation process. This should not be considered the primary means to identify whether or not a site meets the release criterion.

The derived concentration guideline level for the elevated measurement comparison is:

$$DCGL_{EMC} = A_m \text{ x } DCGL_W \tag{3-30}$$

where:

A_m = area factor for the area of the systematic grid area.

$DCGL_{EMC}$ = an *a priori* limit, established both by the $DCGL_W$ and by the survey design (*i.e.*, grid spacing and scanning MDC).

The true extent of an area of elevated activity can only be determined after performing the survey and taking additional measurements. Upon the completion of further investigation, the *a posteriori* limit, $DCGL_{EMC} = A_m \times DCGL_W$, can be established using the value of A_m appropriate for the *actual area of elevated concentration*. The area of elevated activity is generally bordered by concentration measurements below the $DCGL_W$. An individual elevated measurement on a systematic grid could conceivably represent an area four times as large as the systematic grid area used to define the $DCGL_{EMC}$. This is the area bounded by the nearest neighbours of the elevated measurement location. The results of the investigation should show that the appropriate $DCGL_{EMC}$ is not exceeded. Area factors are discussed in Section 3.5.1.1.

If measurements above the stated scanning maximum detection concentration (MDC) are found by sampling or by direct measurement at locations that were not flagged by the scanning survey, this may indicate that the scanning method did not meet the DQOs.

The preceding discussion primarily concerns Class 1 survey units. Measurements exceeding $DCGL_W$ in Class 2 or Class 3 areas may indicate survey unit mis-classification. Scanning coverage for Class 2 and Class 3 survey units is less stringent than for Class 1. If the investigation levels are exceeded, an investigation should:

- Ensure that the area of elevated activity discovered meets the release criterion;
- Provide reasonable assurance that other undiscovered areas of elevated activity do not exist.

If further investigation determines that the survey unit was mis-classified with regard to contamination potential, then a resurvey using the method appropriate for the new survey unit classification may be appropriate.

Interpretation of statistical test results

The result of the statistical test is the decision to reject or not to reject the null hypothesis. Provided that the results of investigations triggered by the elevated measurement comparison were resolved, a rejection of the null hypothesis leads to the decision that the survey unit meets the release criterion. However, estimating the average residual radioactivity in the survey unit may also be necessary so that dose or risk calculations can be made. This estimate is designated δ. The average concentration is generally the best estimator for δ [124]. However, only the unbiased measurements from the statistically designed survey should be used in the calculation of δ.

If residual radioactivity is found in an isolated area of elevated activity - in addition to residual radioactivity distributed relatively uniformly across the survey unit - the unity rule (Section 3.3.6.3) can be used to ensure that the total dose is within the release criterion:

$$\frac{\delta}{DCGL_W} + \frac{(\textit{average concentration in elevated area} - \delta)}{(\textit{area factor for elevated area})(DCGL_W)} < 1 \qquad (3\text{-}31)$$

If there is more than one elevated area, a separate term should be included for each. When calculating δ for use in this inequality, measurements falling within the elevated area may be excluded providing the overall average in the survey unit is less than the $DCGL_W$. As an alternative to the unity rule, the dose or risk due to the actual residual radioactivity distribution can be calculated if there is an appropriate exposure pathway model available. Note that these considerations generally apply only to Class 1 survey units, since areas of elevated activity should not exist in Class 2 or Class 3 survey units.

A retrospective power analysis for the test will often be useful, especially when the null hypothesis is not rejected (see 0, Section D.1.3). When the null hypothesis is not rejected, it may be because it is in fact true, or it may be because the test did not have sufficient power to detect that it is not true. The power of the test will be primarily affected by changes in the actual number of measurements obtained and their standard deviation. An effective survey design will slightly overestimate both the number of measurements and the standard deviation to ensure adequate power. This insures that a survey unit is not subjected to additional remediation simply because the final status survey is not sensitive enough to detect that residual radioactivity is below the guideline level. When the null hypothesis is rejected, the power of the test becomes a somewhat moot question. Nonetheless, even in this case, a retrospective power curve can be a useful diagnostic tool and an aid to designing future surveys.

If the survey unit fails

The guidance provided in EURSSEM is fairly explicit concerning the steps that should be taken to show that a survey unit meets release criteria. Less has been said about the procedures that should be used if at any point the survey unit fails. This is primarily because there are many different ways that a survey unit may fail the final status survey, e.g.:

- The overall level of residual radioactivity may not pass the non-parametric statistical tests.
- Further investigation following the elevated measurement comparison may show that there is a large enough area with a concentration too high to meet the release criterion.
- Investigation levels may have caused locations to be flagged during scanning that indicate unexpected levels of residual radioactivity for the survey unit classification.
- Site-specific information is needed to fully evaluate all of the possible reasons for failure, their causes, and their remedies.

When a survey unit fails to demonstrate compliance with the release criterion, the first step is to review and confirm the data that led to the decision and communicate with the stakeholders, e.g., regulators. Once this is done, the DQO Process (see Section 2.7) can be used to identify and evaluate potential solutions to the problem. The level of residual radioactivity in the survey unit should be determined to help define the problem. Once the problem has been stated, the decision concerning the survey unit should be developed into a decision rule. Next, determine the additional data, if any, needed to document that the survey unit demonstrates compliance with the release criterion. Alternatives to resolving the decision statement should be developed for each survey unit that fails the tests. These alternatives are evaluated against the DQOs, and a survey design that meets the objectives of the project is selected.

Example 3.23: A Class 2 survey unit passes Sign test but several measurements exceed $DCGL_W$

A Class 2 survey unit passes the non-parametric statistical tests, but has several measurements on the sampling grid that exceed the $DCGL_W$*. This is unexpected in a Class 2 area, and so these measurements are flagged for further investigation. Additional sampling confirms that there are several areas where the concentration exceeds the* $DCGL_W$*. This indicates that the survey unit was mis-classified. However, the scanning technique that was used was sufficient to detect residual radioactivity at the* $DCGL_{EMC}$ *calculated for the sample grid. No areas exceeding the* $DCGL_{EMC}$ *where found. Thus, the only difference between the final status survey actually done and that which would be required for a Class 1 area, is that the scanning may not have covered 100% of the survey unit area. In this case, one might simply increase the scan coverage to 100%. Reasons why the survey unit was mis-classified should be noted. If no areas exceeding the* $DCGL_{EMC}$ *are found, the survey unit essentially demonstrates compliance with the release criterion as a Class 1 survey unit.*

If, in the example above, the scanning technique was not sufficiently sensitive, it may be possible to re-classify as Class 1 only that portion of the survey unit containing the higher measurements. This portion would be re-sampled at the higher measurement density required for a Class 1 survey unit, with the rest of the survey unit remaining Class 2.

Example 3.24: A Class 1 survey unit passes Sign test but some areas were flagged

A Class 1 survey unit that passes the non-parametric statistical tests contains some areas that were flagged for investigation during scanning. Further investigation, sampling and analysis indicate that one area is truly elevated. This area has a concentration that exceeds the $DCGL_W$ *by a factor greater than the area factor calculated for its actual size. This area is then remediated. Remediation control sampling shows that the residual radioactivity was removed, and no other areas were contaminated with removed material. In this case one may simply document the original final status survey, the fact that remediation was performed, the results of the remedial action support survey, and the additional remediation data. In some cases, additional final status survey data may not be needed to demonstrate compliance with the release criterion.*

Example 3.25: A Class 1 survey unit fails the Sign test

Consider a Class 1 area which fails the non-parametric statistical tests. Confirmatory data indicate that the average concentration in the survey unit does exceed the $DCGL_W$ *over a majority of its area. This indicates remediation of the entire survey unit is necessary, followed by another final status survey. Reasons for performing a final status survey in a survey unit with significant levels of residual radioactivity should be noted.*

These examples are meant to illustrate the actions that may be necessary to secure the release of a survey unit that has failed to meet the release criterion. The DQO process should be revisited to plan how to attain the original objective that is to safely release the survey unit by showing that it meets the release criterion. Whatever data are necessary to meet this objective will be in addition to the final status survey data already in hand.

Removable activity

Some regulatory agencies may require that smear samples be taken at indoor grid locations as an indication of removable surface activity. The percentage of removable activity assumed in the exposure pathway models has a great impact on dose calculations. However, measurements of smears are very difficult to interpret quantitatively. Therefore, the results of smear samples should not be used for determining compliance. Rather, they should be used as a diagnostic tool to determine if further investigation is necessary.

3.11 Site characterisation: Reporting results

The process of reporting investigation results is an important consideration in planning the site characterization and should be developed during this planning phase. The process of reporting should also be clearly documented in the project plan and communicated with stakeholders. The documentation should provide a complete and unambiguous record of all actions, designs and radiological survey(s). In addition, sufficient data and information should be provided to enable an independent evaluation of the results of the survey including advises for repeating measurements at some time in the future and should comply at least with all applicable regulatory requirements.

Much of the information in the final status report will be available from other decommissioning documents. However, to the extent practicable, this report should be a stand-alone document with minimum information incorporated by reference.

This document should describe briefly:

- The instrumentation or analytical methods used.

- How the data were converted to DCGL units.
- The process of comparing the results to the DCGLs.
- The process of determining that the data quality objectives were met.
- The results of actions taken as a consequence of individual measurements or sample concentrations in excess of the investigation levels.
- Any additional data, remediation, or re-surveys performed to demonstrate that issues concerning potential areas of elevated activity were resolved.
- The results of the data evaluation using statistical methods to determine if release criteria were satisfied should be described.
- Criteria that were not met or if results indicate a need for additional data.

Appropriate further actions should be determined by the site management in consultation with the stakeholders, e.g., responsible regulatory agency.

Again, the level of effort for reporting should be based on the complexity of the survey and depends on the specific objectives of the survey. A simple survey with relatively few results may specify a single report, while a more complicated survey may specify several reports to meet the objectives of the survey. Reporting requirements for individual surveys should be developed during planning and clearly documented in the project plan. These requirements should be developed with cooperation from the stakeholders. (*e.g.*, regulators, the analytical laboratory should be consulted on reporting results for samples). The health physics society has developed several suggestions for reporting survey results and these are extended with other solutions from other sources. These suggestions include:

- The report should provide general information on the radiological status of the site. Survey results should include identification of the potential contaminants (including the methods used for radionuclide identification), general extent of contamination (*e.g.*, activity levels, area of contamination, and depth of contamination), and possibly even relative ratios of radio-nuclides to facilitate DCGL application.
- The report should also provide information about radioactive contaminants/materials that have never been present or no evidence about the presence could be established from analyses.
- Report the actual result of the analysis. Do not report data as ‘less than the detection limit’. Even negative results and results with large uncertainties can be used in the statistical tests to demonstrate compliance. Results reported only as ‘< MDC’ cannot be fully used and, for example, complicate even such simple analyses as calculating an average. While the non-parametric tests described in Sections 3.10.3 and 3.10.4, and in 0 can accommodate as much as 40% of the results as non-detects, it is better to report the actual results and avoid the possibility of exceeding this limit.
- Report results using the correct units and the correct number of significant digits. The choice of reporting results using SI units (*e.g.*, Bq/kg, Bq/m²) or conventional units (*e.g.*, pCi/g, dpm/100 cm²) is made on a site-specific basis. Generally, EURSSEM recommends that all results be reported in the same units as the DCGLs. Sometimes the results may be more convenient to work with as counts directly from the detector. In these cases the user should decide what the appropriate units are for a specific survey based on the survey objectives. The user should check the correct number of significant digits to report with the regulator.
- Report the measurement uncertainty for every analytical result or series of results, such as for a measurement system. This uncertainty, while not directly used for demonstrating compliance with the release criterion, is used for survey planning and data assessment throughout the radiation survey and site investigation process. In addition, the uncertainty is used for evaluating the performance of measurement

systems using quality control measurement results (as described in Section 3.3.9 for scans, direct measurements, and for laboratory analysis of samples). The uncertainty is also used for comparing individual measurements to the action level, which is especially important in the early stages of decommissioning (scoping, characterization, and remedial action support surveys described in Section 3.3.10.2) when decisions are made based on a limited number of measurements. Section 3.9.2.9 discusses methods for calculating the measurement uncertainty.

- Report the minimum detectable concentration (MDC) for the measurement system as well as the method used to calculate the minimum detectable concentration. The minimum detectable concentration is an *a priori* estimate of the capability for detecting an activity concentration with a specific measurement system. As such, this estimate is valuable for planning and designing radiation surveys. Optimistic estimates of the minimum detectable concentration (calculated using ideal conditions that may not apply to actual measurements) overestimate the ability of a technique to detect residual radioactivity, especially when scanning for alpha or low-energy beta radiations. This can invalidate survey results, especially for scanning surveys. Using a more realistic minimum detectable concentration, as described in Section 3.3.7, during scoping and characterization surveys helps in the proper classification of survey units for final status surveys and minimizes the possibility of designing and performing subsequent surveys because of errors in classification. Estimates of the minimum detectable concentration that minimize potential decision errors should be used for planning surveys.

  If the DCGL is less than or equal to the minimum detectable concentration of the applied instrument, and the radio-nuclide is not detected, report the actual result of the analysis. Do not report data as ‘less than the detection limit’. Even negative results and results with large uncertainties can be used in the statistical tests described in Section 3.3.2.7 and 3.3.2.8 and 0. Results reported as “< MDC” cannot be fully used and, for example, complicate even such simple analyses as calculating an average. When the minimum detectable concentration reported for a radionuclide is near the DCGL, the confidence in both identification and quantisation may be low. Information concerning non-detects or detections at or near minimum detectable concentration should be qualified according to the degree of acceptable uncertainty.

3.11.1 Reporting to decision maker or reviewer

Data and documentation supplied to the decision maker or reviewer should be evaluated for completeness and appropriateness and to determine if any changes were made to the survey plan during the course of work. The survey plan discusses the surveying, sampling, and analytical design and contains the quality assurance project plan (QAPP) and DQOs. The decision maker should receive all data as collected plus preliminary and final data reports. The final decision on qualifying or rejecting data will be made during the assessment of environmental data. The data validation process should be conducted according to procedures documented in the quality assurance project plan (QAPP). All data, including qualified or rejected data, should be documented and recorded even if the data are not included in the final report.

The use of preliminary analytical data reports allows the decision maker or reviewer to begin the assessment process as soon as the surveying effort has begun. These initial reports have three functions:

1. For scoping or characterization survey data, they allow the decision maker to begin to characterize the site on the basis of actual data. Radio-nuclides of interest will be identified and the variability in concentration can be estimated.
2. They allow potential measurement problems to be identified and the need for corrective action can be assessed.

3. Schedules are more likely to be met if the planning of subsequent survey activities can begin before the final data reports are produced.

3.11.2 Types of documentation

Three types of documentation should be assessed:

1. Field operation records;
2. Laboratory records;
3. Data handling records [125].

3.11.2.1 Field operation records

The information contained in these records documents overall field operations and generally consists of the following:

- *Field measurement records*. These records show that the proper measurement protocol was performed in the field. At a minimum, this documentation should include the names of the persons conducting the activity, measurement identification, measurement locations, measurement results, maps and diagrams, equipment and standard operation procedures used, and unusual observations. Bound field notebooks are generally used to record raw data and make references to prescribed procedures and changes in planned activities. Data recording forms might also be used. A document control system should be used for these records to control attributes such as formatting to include pre-numbered pages with date and signature lines.
- *Sample tracking records*. Sample tracking records (*e.g.*, chain-of-custody) document the progression of samples as they travel from the original sampling location to the laboratory and finally to disposal.
- *Quality control measurement records*. Quality control measurement records document the performance of quality control measurements in the field. These records should include calibration and standards' traceability documentation that can be used to provide a reproducible reference point to which all similar measurements can be correlated. Quality control measurement records should contain information on the frequency, conditions, level of standards, and instrument calibration history.
- *Personnel files*. Personnel files record the names and training certificates of the staff collecting the data.
- *General field procedures*. General field procedures (*e.g.*, standard operation procedures) record the procedures used in the field to collect data and outline potential areas of difficulty in performing measurements.
- *Deficiency and problem identification reports*. These reports document problems and deficiencies encountered as well as suggestions for process improvement.
- *Corrective action reports*. Corrective action reports show what methods were used in cases where general field practices or other standard procedures were violated and include the methods used to resolve non-compliance.

3.11.2.2 Laboratory records

The following list describes some of the laboratory-specific records that should be compiled if available and appropriate:

- *Laboratory measurement results and sample data*. These records contain information on the sample analysis used to verify that prescribed analytical methods were followed. The overall number of samples, sample identification, sample measurement results, any deviations from the standard operation procedures, time of day, and date should be included. Sample location information might also be provided.

- *Sample management records*. Sample management records should document sample receipt, handling and storage, and scheduling of analyses. The records will verify that sample tracking requirements were maintained, reflect any anomalies in the samples (*e.g*., receipt of damaged samples), and note proper log-in of samples into the laboratory.
- *Test methods*. Unless analyses were performed exactly as prescribed by standard operation procedures, this documentation will describe how the analyses were carried out in the laboratory. This documentation includes sample preparation and analysis, instrument standardization, detection and reporting limits, and method-specific quality control requirements. Documentation demonstrating laboratory proficiency with each method used could also be a part of the data reporting package, particularly for subcontracted work.
- *Quality control measurement records*. These include the general quality control records, such as initial demonstration of capability, instrument calibration, routine monitoring of analytical performance, calibration verification, etc., for selecting a radio-analytical laboratory. Project-specific information from the quality control checks such as blanks, spikes, calibration check samples, replicates, splits, and so on should be included in these reports to facilitate data quality analysis.
- *Deficiency and problem identification reports*. These reports document problems and deficiencies encountered as well as suggestions for process improvement.
- *Corrective action reports*. Corrective action reports show what methods were used in cases where general laboratory practices or other standard procedures were violated and include the methods used to resolve non-compliance. Corrective action procedures to replace samples violating the standard operation procedures also should be noted.

3.11.2.3 Data Handling Records

Data handling records document protocols used in data reduction, verification, and validation. Data reduction addresses data transformation operations such as converting raw data into reportable quantities and units, using significant figures, calculating measurement uncertainties, etc. The records document procedures for handling data corrections.

3.12 Common mistakes

3.12.1 Lack of clear specifications of the objectives and strategy

Clear specifications of the objectives and strategies for the characterisation are important. Often characterisation activities are begun with only vague notions of these objectives and strategies, and the problems that have commonly resulted include:

- Wrong variables were measured.
- Some variables that were needed were not measured.
- Wrong set of samples was taken.
- Data are compromised by interfering factors.
- Funds were wasted on unnecessarily sophisticated instrumentation and analytical techniques, realised accuracy and precision are inadequate.
- More samples were collected and analyzed than needed, and/or there are too few samples collected to answer the question.
- Methods were not approved by regulators.

3.12.2 Soil shielding

The most common mistake made during the interpretation of radiological survey data is to assume that if the survey does not highlight any areas of elevated radioactivity, the site is ‘clean’. However, the shielding afforded by the soil can significantly attenuate all types of radioactivity, including gamma activity. The ability to detect buried radioactivity will depend on the type of detector used, the type and specific activity of the buried material, the depth of burial and the quantity of the buried material. In many circumstances, gamma-emitting radionuclides buried at greater than a few tens of centimetres below ground surface cannot be detected at surface.

3.12.3 Lack of background measures

Another common mistake is to carry out a survey of radioactively contaminated land, but not to have made any background measurements in uncontaminated areas. Background activities must be known if a sensible determination of the extent of contamination is to be made, see Sections 3.3.3 and 3.3.4.

3.12.4 Unsuitable equipment

If surveys are carried out using equipment that is not fit for the aim of the survey, e.g., not sensitive enough to detect required radiation levels or levels or radioactivity. This may lead to the incorrect conclusion that the site is not contaminated.

3.12.5 Methods were not approved by regulators

Regulatory agencies (part of the stakeholders) responsible for the site often have to confirm whether the site is acceptable for release. This confirmation may be accomplished by the agency or an impartial party. Although some actual measurements may be performed, much of the work required for confirmation and verification will involve evaluation and review of documentation and data from survey activities. The evaluation may include site visits to observe survey and measurement procedures or split-sample analyses by the regulatory agency’s laboratory. Therefore, accounting for confirmation and verification activities during the planning stages is important to each type of survey. In some cases, post-remedial sampling and analysis may be performed by an impartial party. The review of survey results should include verifying that the data quality objectives are met, reviewing the analytical data used to demonstrate compliance, and verifying that the statistical test results support the decision to release the site. Confirmation and verification are generally ongoing processes throughout the Radiation Survey and Site Investigation Process.

4 Environmental remediation of radioactively contaminated sites

4.1 Introduction

This section of EURSSEM provides detailed guidance on the remediation of radioactively contaminated sites and/or groundwater and is intended for a technical as well as a non-technical audience.

It is recommended that notice should be taken of the information presented in Section 2 and Section 3 of this document. Section 2, "Development of a contaminated land strategy" comprises important information about planning of site characterisation, remediation and reuse activities at a high generic level, while Section 3 gives detailed guidance about "Characterisation of radioactively contaminated sites".

This Section 4 presents information and guidance on the development of a plan for the environmental remediation of a radioactively contaminated site by addressing the major factors involved.

In addition, an extensive overview is given of existing remediation techniques followed by information on how to implement or organise these remediation techniques and how to conduct post-remediation activities.

4.2 Design of an environmental remediation plan

After a decision has been taken to remediate a contaminated site, a remediation plan should be prepared and should show that the environmental remediation can be performed safely. Such a plan should be prepared for each contaminated site, unless otherwise required by the regulatory body, and should be subject to the approval of the regulatory body prior to its implementation and execution [12].

The first steps in the development of this plan should be to determine and evaluate possible remediation options. These options can range from complete remediation and unrestricted release of the site to more limited remediation with some subsequent uses of the site being restricted [12].

The degree of complexity of a given remediation process may vary depending on site specific situations. However, there are several components of the remediation process that should be considered essential for any site area being considered for remediation.

The goal of environmental remediation activities is the timely and progressive reduction of hazard and eventually, if possible, the removal without restrictions of regulatory control from the site. However, there are situations in which the removal of control from the site cannot practicably be achieved. In such cases, at least the unacceptable risks to human health and the environment should be removed. In these cases, any restrictions on access to or use of the site and any other restrictions should be established on the basis of an optimization process so as to maximize the net benefit to society. In the choice of the optimized remediation option, a wide variety of factors should be considered, and impacts on health, safety and the environment should be considered together with technical, social and financial factors. Non-radiological hazards should be considered in conjunction with the radiological hazards. Remediation should be aimed at reducing existing exposures and averting the potential for prolonged exposures to occur in the future. Remediation should [14]:

- Reduce the doses to individuals or groups of individuals being exposed;
- Avert doses to individuals or groups of individuals that are likely to arise in the future;
- Prevent or reduce environmental impacts from the radionuclides present in the contaminated site.

Reductions in the doses to individuals and reduced environmental impacts should be achieved by means of interventions to remove the existing sources of contamination, to modify the pathways of exposure or to reduce the numbers of individuals or other receptors exposed to radiation from the source [14].

The level of effort associated with planning an environmental remediation is based on the complexity of the remediation(s) to be performed. Large, complicated sites generally receive a significant amount of effort during the planning phase, while smaller sites may not require as much planning. This graded approach defines remedial requirements according to the type of environmental remediation action(s) being designed, the risk of making a decision error based on the data collected, and the consequences of making such an error. This approach provides a more effective environmental remediation design combined with a basis for judging the usability of the data collected.

4.2.1 Environmental remediation objectives and criteria

An environmental remediation programme should have clearly expressed objectives. The initial environmental remediation objectives should be established on the basis of the nature and extent of the contamination, the water resources that are currently or potentially threatened, and the potential for human and environmental exposure. These quantitative goals should define the extent of clean-up that is required to satisfy the established objectives. They include the required clean-up levels and the restoration time frame.

Past practices around the world have used extremely conservative scenarios for determining the risks of ionizing radiation to human health. As a result, environmental remedial activities have become extremely costly. Recently, a philosophy of using more realistic risk scenarios appears to becoming acceptable. In some cases, environmental remediation has been avoided altogether, with only the cost of monitoring remaining. This strategy has reduced the cost while continuing to adequately protect human health. It is recommended that when selecting and analysing the risk scenarios, the expected land use, the impacts on affected parties and environment, and the future groundwater needs should all be evaluated. A realistic scenario can then be developed which would allow for a more cost effective environmental remediation while still ensuring the safety of the public. Obviously, the effectiveness and the reliability of institutional controls may affect these decisions.

Risk assessment methods may be used, coupled with regulatory requirements, to determine achievable remediation goals. The beneficial use of an aquifer should also be considered. Water which does not meet the required standards for domestic use may still be useful for agricultural or industrial purposes. Finally, the potential effects on environmental receptors such as plant and animal species at or near the site may also affect the remediation goals.

If the environmental remediation is justified and any clean-up action optimized, criteria are needed to target environmental remediation activities, to assess performance as the work proceeds, and to verify that the environmental remediation has been achieved at its conclusion. These criteria may be expressed in terms of reference levels of residual dose, i.e., the projected dose from the future use of the remediated site, or in terms of concentration limits from which the residual dose, through a pathway analysis, can be calculated. Where necessary, re-entry criteria may be established by which it can be decided whether to allow the return of the population and/or reuse of the land for agriculture, and so on [3].

The term ‘reference levels’ (see also Section 2) includes reference levels, intervention levels, investigation levels and recording levels as defined in the IAEA Basic Safety Standards [12]. The reference level (often expressed in terms of annual effective dose) indicates a level below which remediation is normally unlikely to be justified, and it serves as a criterion for the unrestricted release of a site. A generic reference level for aiding decisions on remediation is an existing annual effective dose of 10 mSv from all sources, including the natural background radiation. This will normally be assessed as the mean dose for an appropriately defined critical group. Remedial measures would often be justified below the generic reference level and national authorities may define a lower reference level for identifying site areas that might need remediation.

4.2.2 Major factors in environmental remediation

A significant element for the success of any remediation strategy is to decouple/cut-off the source term from the groundwater pathway. In some contamination scenarios, the source may have only occurred over a short time period, such as a onetime leak. However, other scenarios may involve continued contaminant source contribution, such as the seepage from an uranium mill tailings or mine debris pile. In scenarios with continued source term contribution to the groundwater pathway, one of the first remedial actions is to remove or decouple the contaminant source. The clean-up of a site will be extended indefinitely if the source to the groundwater is not fully stopped [9].

In the context of intervention situations, the term 'remediation' has a meaning that is similar to rehabilitation, reclamation and clean-up. It does not include decommissioning, as decommissioning refers to the full range of activities leading to the termination of an authorized activity [12].

Major factors to be taken into account in an environmental remediation plan may be:

- future land use;
- public acceptability and perception and response to the problem;
- regulatory aspects;
- technical and institutional considerations;
- available environmental remediation techniques and resources;
- issues and conditions influencing the decision making process [9]:
  - potential human health and ecological impacts;
  - likely permanence of adverse effects of contamination;
  - potential for spread of contamination;
  - established radiological and other criteria;
  - potential for trans-boundary effects;
  - radioactive waste management and waste transportation;
  - post-remediation state;
- financial capability.

4.2.3 General environmental remediation design aspects

The application of environmental remediation operations consists of a phased strategy to allow flexible decision making for the most cost-effective and environmentally sound remedial approach. Its application allows all of the decisions and choices made during the management and selection process to be clearly seen and examined. This is an essential part of the process, and it can be particularly important, for example, when communicating with affected parties such as members of the public and regulators.

In the developed environmental remediation plan, due consideration should be given to:

- *Sound principles and ALARA*. Implementation of environmental remediation activities should be based on sound principles of project management and the ALARA (As Low As Reasonably Achievable) radiation protection principles formulated in the IAEA

Basic Safety Standards [3]. Only following the completion of all necessary measures, a remediation programme can be considered.

- *Applicable environmental remediation options*. For all the environmental remediation options identified as applicable, a study should be performed to determine the option that is best for the site. The study should factor in both justification and optimization. This study should include estimates of the costs and other resources associated with the treatment, removal, transport and disposal of contaminated material for each option; the estimated doses to workers and the public due to exposure before, during and after the remediation; the overall safety issues during remediation; the available technologies; the considerations for monitoring and sampling; the amount of waste that will be generated; and the institutional controls required after implementation of the option, if applicable.
- *Optimisation of protection*. For the set of options under consideration, optimization of protection should be performed for the justified options, to determine the option that has the highest net benefit. On the basis of this optimization, a preferred option should be selected that also takes into account non-quantitative considerations such as social and political aspects.
- *Selected environmental remediation option*. For the selected option, a detailed "environmental remediation plan showing that remediation can be accomplished safely should be prepared for each contaminated site, unless otherwise required by the regulatory body" and the "environmental remediation plan should be subject to the approval of the regulatory body prior to its implementation".
- *Post-remediation*. Plans should be provided for both the environmental remediation work and the possible necessary measures for post-remediation, such as maintenance, monitoring and institutional controls to enforce restrictions on land use and buildings, if applicable. Although institutional controls (long-term stewardship as indicated in Section 5) may last for a long period of time, they are part of the post-remediation as defined in this context and should thus be covered in the environmental remediation plan.
- *Approved plans*. Once the environmental remediation plan including post-remediation has been approved, it should be implemented as soon as possible. If it is decided not to remediate the site, decisions should be made on imposing restrictions on its use or access prior to release. If remedial actions are required, they should be implemented as soon as possible.
- *Regulatory control*. After the approved environmental remedial actions have been completed, the regulatory body should evaluate the effectiveness of the implementation.

Further, three basic planning approaches in environmental remedial actions are possible:

- *Monitored non-intervention*. This planning approach relies on natural processes to prevent significant exposure, meaning that the site will be undisturbed, while establishing a monitoring scheme for determining the evolution of the exposure of the site in time. The entire process needs to be carefully monitored so that alternative action can be initiated if required, and may be based on:
  - *Natural attenuation*. Natural attenuation is the least invasive of the four technical remediation principles. The concept is based on geochemical processes to retard radionuclide migration to the biosphere.
  - *Physical processes*. Physical processes are based on physical phenomena, e. g., volatilisation, dispersion, retention mechanisms, etc.
  - *Chemical processes*. Chemical processes are based on a chemical treatment of the radioactively contaminated materials.

- *Biological processes*. Biological processes are based on bio-degradation. Bio-degradation is a process or a collection of processes (e. g., bio-mineralization, 'bio-sorption' and microbially mediated phase transfer) in which naturally occurring micro-organisms such as yeast, fungi and bacteria, effect the fixation or mobilization of metals, including radionuclides, in various types of soil ecosystems.
- *Alternative land uses*. When extensive areas have been contaminated, many of the discussed remediation methods may be too expensive to carry out or too intrusive. In particular, when the land was used for agricultural purposes, alternative uses may need to be considered. Such alternative uses may range from switching to different crops to turning to completely different uses, such as parkland [43].

- *Containment of blocking pathway(s)*. This planning approach restricts the mobility of the radioactive contaminants: this involves immobilizing the contaminants inside the area in which they already exist, reducing the potential for further migration or entry into active pathways of exposure.
- *Source removal*. This planning approach relies on the removal of the radioactive contaminants from the site, using an appropriate treatment scheme: this involves extracting, concentrating and then safely disposing of the contaminants at another location.

The above mentioned planning approaches and principals are discussed in detail in Section 4.3.

If the established environmental remediation criteria have been met after source removal actions, the site should be possibly released without further restrictions. If the criteria have been met after pathway change actions, the site should be possibly released with appropriate restrictions (e. g., the radioactive source is still present). These restrictions could be in the form of institutional control on the use of the site and/or groundwater, for example, to ensure that restrictions on grazing are followed.

If, after the environmental remedial actions have been carried out, the criteria have not been met, the responsible party should determine whether further environmental remediation is feasible or whether the site should be released with restrictions, and should submit a proposal accordingly to the regulatory body for approval.

In the following paragraphs, the main issues regarding the remediation process are described in more detail.

4.2.4 Future land use

The options for future land use can range from complete remediation and unrestricted release of the site to more limited remediation with some subsequent uses of the site being restricted [12].

4.2.5 Public acceptability and perception and response to the problem

Involvement of affected parties and the general public is one of the factors to consider when evaluating technologies or screening for remedial alternatives. The public's perception of risk due to radiation exposure may be substantial enough to warrant a more stringent remedial goal for a contaminant in groundwater. It is important to involve the public and all affected parties in the decision making process [9]. Early interaction with relevant stakeholders, including for example, regulators, local and regional government, the public and special interest groups, to identify long term management goals, acceptable management strategies, remediation targets and long term uses of the site, is generally considered to facilitate the process [7]. Stakeholder participation was discussed in detail in Section 2.

4.2.6 Regulatory aspects

4.2.6.1 National and European regulations

National laws and regulations on environmental protection, human health, radiation safety and occupational safety will need to be considered and adhered within strategies for the remediation of contaminated sites. It is unlikely that any remediation strategy that does not fit within the regulatory framework will be acceptable to either the regulatory bodies or the general public, even if all other assessment factors, for example, health impact assessment, technical feasibility, waste acceptance criteria and disposal routes, are acceptable [7].

Most countries do not have specific regulatory regimes to deal with, e. g., mixed radioactive and non-radioactive contamination. In many cases, separate regulatory regimes operate for the two types of contaminant. The lead regulator is either the one responsible for radioactive materials or is selected on the basis of the judged or perceived dominant source of risk or hazard. As a result, the regulatory approach is often to assess and deal separately with the two types of constituent within any mixed contamination on any site. One of the two classes of contaminant may, in practice, dominate, dependent upon the controlling acceptable limits on soil, water and air from releases. However, the regulatory problems can sometimes be simplified by subdividing the site into areas where one or the other type of contaminant dominates the risks and hence controls the remedial strategy.

The degree of regulation, regulatory control and guidance for environmental remediation projects for sites with mixed contamination varies markedly from country to country. The variations frequently reflect the status and the scale of any nuclear power and weapons development, the significance of radioactivity issues, the size of the country and the degree of autonomy exercised by regional governments over environmental issues. Protection of the public, operational safety and environmental protection are key areas for regulation. In many European Union (EU) countries, there are regulatory bodies, with specific responsibilities for overseeing the operational safety of all works, including remediation activities, at major commercial nuclear sites, for example, power reactors and nuclear fuel fabrication and reprocessing facilities. Their remit may extend to nuclear weapons development and production facilities. For other facilities, which are not primarily nuclear facilities and where the use of radioactive materials is secondary to that of chemicals or other hazardous substances, the prime regulatory authority for safety in all operational works is frequently the one with responsibility for general workplace safety. For protection of the environment, which includes any discharges from sites to the air, water or land, waste disposals, etc. with potential impacts on the off-site public, flora and fauna, other regulatory bodies may be involved in environmental remediation. Local regulatory authorities, for example individual state or district environmental protection departments or agencies, may also have significant roles.

The boundaries between the responsibilities of the different regulators may not always be clear where environmental remediation projects involving mixed waste sites are to be considered. In addition, the level of input and the importance of the different regulators may often vary over the project life. These issues may frequently be resolved by agreements between the different regulators to work in unison or delegate the lead at particular sites or projects to one another, dependent upon the nature of the problems prevailing at the specific site. However, it is often beneficial at the start of any project to have the full involvement of all potentially interested regulatory bodies to ensure a common understanding of the problems, the proposed solutions and the constraints from different regulators.

4.2.6.2 Regulations affecting the implementation of a remediation plan

Implementation of remediation projects can potentially result in environmental impacts additional to those associated with mixed contamination alone. As a result various other regulatory permits and authorizations may be required [7].

Some techniques involving the re-injection of treated water into the geological formation may need a water disposal permit or licence. Any operation that typically can or will result in emission is likely to attract regulatory oversight. Permits, authorization or licences related to the remediation process could be needed for operations such as:

- Construction of wells;
- Extraction of water and also discharge of treated water;
- Re-injection of treated water into a geological formation;
- Introduction of materials to aid remediation; the materials may need to be of an approved standard, for example, food quality;
- Gaseous discharges; supplementary assessments including air plume modelling, environmental impact assessments and the need for off-gas treatments;
- All types of excavations (checks for underground services in utility company records and physical surveys for underground services);
- On-site treatment of contaminated soil;
- For remediation operations in sites of historical interest, archaeological permits may be needed.

Remediation work normally would be organized and carried out according to locally or internationally recognized best practice. This should help to ensure that environmental impacts accord with the as low as reasonably practicable (ALARP) principle [7].

4.2.6.3 Environmental impact assessment

A degree of broader regulatory control is exercised over major projects, including remediation of sites, through national requirements for assessments of environmental impacts before any new project is undertaken. In countries of the European Union, there are European Directive requirements for environmental impact assessments (EIA). Such environmental impact assessments may not only assess and quantify environmental impacts but may also justify the selection of the chosen remedial strategy through critical review of the potential options and quantification of their potential impacts. The environmental impact assessments can also identify measures to be taken to mitigate impacts and reduce them to the lowest practicable levels. Regulatory bodies are often statutory consultees to the environmental impact assessments and may, therefore, also influence the proposed remedial works through this route. In some countries, major remedial projects are treated as new developments on land and are also covered by land use planning regulations. The requirements for environmental impact assessments form part of these regulations, as do controls on potential public nuisances [7].

4.2.6.4 Assessment of worker and public exposures

Remediation of sites contaminated with hazardous and radioactive substances can result in the exposure of workers and potentially the public to physiological and possibly physical harm. Radiological, chemical, biological and some hazardous materials, for example asbestos, can give rise to the former, while corrosive, flammable and explosive constituents can give rise to the latter. At sites with ongoing activities, the exposure of workers directly involved in the remediation work and elsewhere on the site is frequently controlled through workplace regulations. Relevant national regulations often cover chemical and toxic substances hazardous to health, ionizing radiation, environmental nuisances, for example odours, noise and traffic, and construction type risks. All of these factors need to be considered in operational safety and require full assessment as in a safety case. When planning and licensing a remediation strategy, reductions in public exposures may be balanced against the exposures incurred by workers as a result of the remediation action [7].

Assessments of workers and public exposures are often necessary for regulatory approvals during the period work is carried out and finally for acceptable residual levels of contamination. These are usually determined by safety and risk assessments that address in separate parts the impacts of the radioactive and non-radioactive hazardous components. Some regulators may also prescribe methodologies and computer codes for undertaking assessments of acceptable residual levels of chemical or radioactive contamination. The acceptable residual levels often depend on scenarios for future site use and are subject to optimization. In addition, in some cases regulators and site liability owners/operators have been working together to develop guidance on agreed best practice on the characterization, assessment and remediation of contaminated sites. Synergistic effects between radioactive and chemical contaminants are not generally considered in these assessments unless specific data are available. The risk assessment methodologies used for assessing operational safety during remedial work and environmental impacts before, during and after such work employ very similar exposure pathway models for both types of contaminant. They also use the same risk basis for acceptability, i. e., 10^{-4} - 10^{-6} lifetime risk.

Information about safety and health risks and associated guidance can be obtained from standard reference sources, regulatory standards, medical surveillance, safety studies, toxicological data and epidemiological studies. Most of the guidance is national, with the exception perhaps of the European Union, where an internationally agreed body of regulations is being developed. In a similar way, existing international standards and guidance are usually focused on either radioactive or hazardous materials.

An IAEA Safety Requirements publication provides radiological criteria for aiding decision making on the remediation of areas contaminated by past practices and accidents [12]. In some countries remediation objectives for contaminants in soils have been implemented. There are international standards for acceptable levels of some radionuclides and toxic chemicals in drinking water. Databases have been established for chemical and hazardous substances, which relate their toxicity to acceptable levels in soils and water.

An IAEA Basic Safety Standards and its derivative publications is valuable reference for radiological risks [13]. There are international recommendations on exposure limits for workers and the public to radioactive substances.

There are also similar national standards in many countries controlling such exposures to toxic substances. Given similarities in the latter, these are effectively internationally accepted standards.

4.2.6.5 Regulatory controls

Institutional controls may be implemented to reduce or eliminate potential threat of exposure to human health. The following kinds of institutional controls have been established in some countries and may be considered to prevent exposure to contaminated groundwater [9]:

- Regulatory restrictions on construction and use of private water wells, such as well construction permits and water quality certifications;
- Acquisition of property by the government from private entities;
- Exercise of regulatory and police powers by governments, such as zoning and issuance of administrative orders;
- Restrictions on property transactions, including negative covenants and easements;
- Non-enforceable controls, such as well use advisories and deed notices;
- Relocation of affected populations (in extreme cases).

The effectiveness and reliability of these controls should be evaluated when determining whether rapid remediation is warranted. If there is adequate certainty that institutional controls will be effective and reliable, there is more flexibility to select a response action that has a longer restoration time frame or a determination that no remedial action is required.

4.2.7 Technical and institutional considerations

4.2.7.1 Justification and optimisation of remedial measures

Interventions in the form of remedial measures should be intended to decrease existing and potential annual exposures, by removing existing sources, modifying pathways or reducing the number of exposed people. For contamination resulting from past activities and accidents, the required level of remediation should be established on a site specific basis and in accordance with the radiation protection principles that apply to intervention situations [12].

These principles include the justification of remedial measures and the selection of the optimum measures among those justified. In applying these two principles to derive an optimized option for protection, all relevant advantages and disadvantages should be taken into account. These include avertable doses (individual and collective), radiological and non-radiological risks, environmental effects, risks to the workers implementing the remedial measures, economic costs, improvement of the economic situation, the generation of secondary waste, increased or reduced anxiety on the part of interested parties and social disruption arising during and after the implementation of the remedial measures.

- *Justification of remedial measures*

  The remedial measures should be justified by means of a decision aiding process requiring a positive balance of all relevant attributes relating to the contamination [12]. The justification principle should be implemented by means of an assessment of the overall radiological impacts from the contaminated sites in question, identification of options for reducing these impacts, evaluation of the reductions achievable in doses and in other harmful impacts and assessment of the harm and costs associated with these remediation options. Decisions taken on this basis should involve balancing benefits from the reductions in impacts and costs and other factors of influence. An informed decision should be taken on the basis of a full integration of all the advantageous and disadvantageous attributes for society resulting from the proposed remediation options.

  Situations giving rise to potential exposures as well as actual exposures should be considered during the assessment.

- *Optimization of remedial measures*

  The remedial measures should be optimized following the general approach to the optimization of protection in the context of practices. The optimum nature, scale and duration of the remedial measures should be selected from a set of justified options for remediation [12]. The aim is to obtain not only a positive benefit but also optimized protection. The decision aiding techniques for deciding on the optimum remediation option are independent of the nature of the situation causing the exposure. Normally, there would be a range of justified remediation options for which the net benefit would be positive.

  Some remediation options could involve restrictions on the use of the site, even when the remediation end criteria have been met. Such an option would, however, require institutional control as long as the restrictions are deemed necessary. Options that lead to unrestricted release of the site after the remediation criteria have been met have the additional benefit of not requiring institutional control or other regulatory burdens, and so should be favoured. It is recognized, however, that site specific features such as topography, size of the site and lack of waste management facilities might limit the feasibility of a remediation option that leads to unrestricted release.

In some circumstances, remediation may be required to protect the present population and may be justified on the basis of attributable health effects among people in future generations. While in most cases the cost of remediation, in terms of aspects such as disruption and inconvenience, will be borne by the present population, remedial measures taken to protect the present generation should be designed in such a way that predicted impacts on the health of future generations will not be greater than the levels of impact that are acceptable today.

When the performance and the costs of all remediation options have been assessed, a comparison should be performed to determine the optimum option. If this optimum is not obvious, the comparison should be performed using a quantitative decision aiding technique. The result of the application of quantitative techniques is termed the analytical solution. If, in addition, there are non-quantifiable, non-radiological factors to be taken into account, the analytical solution may not be the optimum solution. These qualitative factors should be combined with the analytical solution to determine a true optimum solution, after consultation with interested parties.

The optimization of remedial measures should result in reference levels expressed in terms of a residual activity concentration or dose criteria for the remediated site.

Remedial measures may remove all of the contamination, or remove only part of it, or may only alter the exposure pathways or the number of people exposed without removing the contamination itself. Depending on the expected residual dose, which can be derived from the expected effectiveness of the proposed remedial measures, associated restrictions should be defined as part of the remediation option, if necessary. The residual dose, as well as the advantages and disadvantages of the associated restrictions, should be integrated into the optimization process. If the option includes on-site disposal of radioactive waste, the resulting exposure from this disposal option should also be taken into account.

Owing to time or resource constraints, general sources of information or default parameters may have to be used for modelling calculations. Sensitivity analyses should be performed within the optimization procedure to assist in determining when and where generic input parameters should be replaced by site specific values.

4.2.7.2 Remedial performance evaluations

Performance evaluations of the full scale remedial action, based on monitoring data, should be conducted periodically to compare actual performance to expected performance. The performance monitoring should be designed to provide information as such, but not limited to the following [9]:

- Horizontal and vertical extent of the plume and contaminant concentration gradients, including a mass balance calculation;
- Rate and direction of contaminant migration;
- Changes in contaminant concentrations or distribution over time;
- Rates of contaminant mass removal and transition from advective removal to diffusion rate limited removal;
- Effects of hydrological events, such as above average rainfall, on contaminant mass;
- Removal and changes to groundwater flow;
- Calibration of model based on actual results and effects of changes of operational parameters to model predictions;
- Effects on regional groundwater levels and the resulting impacts;
- Effects of reducing or limiting surface recharge (if applicable);

- Effects of re-injection (if applicable);
- Effects of any modifications to the original remedial action;
- Other environmental effects of remedial action, such as saltwater intrusion, land subsidence, and effects on wetlands or other sensitive habitats.

The frequency and duration of performance evaluations should be determined by site specific conditions. Conducting performance evaluations and modifying remedial actions is part of a flexible approach to attaining remedial action goals. Decisions should be verified or modified during remediation to improve a remedy's performance and ensure protection of human health and the environment.

The performance assessment may provide information that can be used to determine whether the remediation goals are being met, have been achieved or, in some cases, are technically impracticable to achieve in a reasonable time.

4.2.7.3 Decisions regarding further action(s)

After all or most of the existing data and information on the contaminated site have been collected and analysed, a determination for further action should be made. The alternatives to be considered may include:

1. No further action needed

   A decision of no further action can be made if it is determined that there is no radiological contamination present or that the extent of the radiological contamination is below an acceptable risk level and below the regulatory requirements of concentration or radiological dose.

2. Further monitoring of contaminant plume is required

   Although no further action (e. g., remedial action) may be required, it might still be necessary or advisable to continue to monitor the site to ensure that the initial assessment of the situation is correct. For example, this could be the outcome when it appears that natural processes such as dispersion and radioactive decay would result in the contamination having no significant impact on the receptors (i. e., affected population). Continued monitoring would allow the assumptions regarding movement of the groundwater contaminant to be routinely checked. In addition, continued monitoring could provide comforting reassurance to affected parties such as the local population.

3. Insufficient data exist to make a decision

   Following the assessment of existing data and information, it could develop that there are insufficient data to make an informed decision regarding the possibility or advisability of remedial action. Under such a circumstance, it is common that a site characterization programme be implemented to fill the identified gaps in information and data. If there is a decision to collect additional data, the data collection objectives should be clearly identified and used in designing the site characterization programme.

4. Direct environmental remedial action(s) is required

In some cases, there will be wholly sufficient data and information regarding a site and the groundwater contamination problem to conclude that remedial action is required. In such a case, the strategy will advance to the technologies evaluation and remedial design phases.

4.2.7.4 Post-remediation control and stewardship

For some sites, it may not be practicable to reduce the contamination, whether radioactive or hazardous, to such low levels that they are suitable for unrestricted use. This will result in the imposition of restrictions referred to as institutional controls. These could involve surveillance of the site and control access systems. Regulatory authorities are typically responsible for approving the design of the programme, its implementation, and the evaluation of the results with respect to the residual impact on the public and the environment. Maintenance of institutional control over extended periods of time is a concern. The collection of processes and provisions for this are generally referred to as stewardship [7]. Stewardship is further discussed in Section 5 of this document.

4.2.8 Available environmental remediation techniques and resources

The nature of the source, the size of the plume, and the transmissivity of an aquifer will directly affect the effectiveness of the remediation whether it will be an in-situ or an ex-situ treatment of the radioactive contamination. Most environmental remediation technologies currently available are expensive to implement and take long periods of time to complete. Continued research is ongoing worldwide to develop new techniques for in-situ and ex-situ remediation. A general list and description of these technologies can be found in Section 4.5 of this document. Care should be taken to evaluate the success or failure of the technologies which have been developed and to compare the site specific characteristics against the test site to determine the viability at a particular site. Critical parameters of the environmental remediation technology being evaluated should be identified for comparing the viability of success at each site. For example, a technology may work quite well at a site with alluvial sands, but not at all at a site with fractured rock [9].

Based on the analysis performed on the site characterization data, a list of alternatives and technologies may be compiled. A screening process should determine if active remediation is required or if a passive alternative (institutional controls, no action, monitoring, etc.) is desired. If an active remediation option is chosen, a detailed analysis of technologies should be performed.

During the detailed analysis, remedial alternatives that have been retained from the alternative development phase should be analysed against a number of evaluation criteria. The purpose of the detailed analysis should be to compare alternatives so that the remedy that offers the most favourable balance among a set of criteria can be selected.

As an example, the analysis of a remedial action for groundwater can be made on the basis of the following evaluation criteria [9]:

- Overall protection of human health and the environment;
- Compliance with applicable regulations;
- Long term effectiveness and permanence;
- Reduction of toxicity, mobility, or volume;
- Short term effectiveness;
- Implement ability;
- Cost;
- Community or government acceptance;
- Final disposal of residues.

Other criteria may also be established based on site specific conditions. A narrative discussion and summary table should be prepared for each part of the detailed analysis to provide a historical paper documenting the decision process.

4.2.9 Worker health and safety

Workers involved with site remediation may be exposed to conventional construction and operations hazards as well as to hazards coming from radioactive materials, toxic metals, organic compounds or bio-hazardous agents, respirable fibres, flammable and combustible materials, corrosive and reactive chemicals, and explosives.

Remediating a contaminated site requires a thorough and disciplined approach to evaluating the potential hazards to site workers, and taking the necessary steps to perform work in a safe manner. The results of the safety analysis should be incorporated into the site health and safety plan, along with remediation work plans and procedures. Safety measures resulting from these safety analysis and findings should be made in compliance with the ALARA principle and optimal measures should be put into practice. As new hazards are identified at the site, they should become incorporated into an update of the assessment.

Prior to initiating site remediation field activities, a health and safety plan should be developed for conducting the various types of field or laboratory activities that typically integrates an existing site-wide health and safety programme with worker protection requirements specific to the worksite. The possible elements of a health and safety plan involve the following:

- Establishment of a proper organisation;
- Training;
- Hazard characterisation and exposure assessment;
- Site access and hazard controls;
- Site and worker monitoring and medical surveillance schedules;
- Decontamination (personnel and equipment);
- Emergency action plan;
- Emergency response.

Detailed guidance on the development of a ‘Health physics, safety, security and environmental protection plan’ was discussed in Section 2.6 of this document.

4.2.9.1 Radioactive waste management and transport

Wastes may arise directly from the remediation activities, for example clean-up of contaminated soils, retrieval of buried wastes, treatment of groundwater and filtration of contaminated ventilation air.

The waste streams resulting from the environmental remediation should be identified as early as possible in the planning process. The quantities and types of waste that will be generated should be considered during the planning phase to ensure that the waste management system will be capable of accommodating the waste materials.

Waste acceptance and criteria are national issues and should be controlled. Many countries have established regulatory frameworks for dealing with radioactive wastes, for example dose limits, clearance limits, acceptable levels of contamination at the different stages of waste management, specific activity limits and criteria regarding hazardous contents. They may also have similar frameworks for chemical and hazardous wastes. Wastes with mixed contaminants, however, are generally considerably more difficult to condition, store and dispose of than radioactive or hazardous wastes alone. Their characteristics frequently do not comply with the waste acceptance criteria of disposal facilities managing radioactive wastes from more traditional origins, for example operational wastes from nuclear power plants, research reactors, fuel fabrication and reprocessing plants, research and development sources and small users of radioactive material. Conversely, many hazardous waste landfills are not normally licensed to accept radioactive materials, and those that are, may have very low limits. As a result, the remediation strategy should take account of the availability of disposal routes, including specific conditioning of mixed or separated wastes, in order to meet the waste acceptance criteria and long term safety of the disposal facilities [7].

Remediation strategies also need to meet requirements regarding regulations for transportation of radioactive materials and hazardous materials. Attention may need to be given to international shipments, where sites being remediated are close to national borders. There are separate international standards for the safe transport of radioactive materials and hazardous materials by road, rail, air and water. There are also standards and guidance within the European Union for determining hazardous waste categories through assessment of levels at which residues contaminated with selected substances should be treated as hazardous. National transports of radioactive waste can be subjected to special national regulations.

4.3 Remediation: planning approaches

The objective of any technique used in a remediation project should be either to remove or to reduce the source term or to block the exposure pathways. This can be achieved in a variety of ways and needs to be tailored to the contaminants and pathways of interest. It may be necessary to use a suite of techniques to achieve the remediation objectives, especially for source term isolation or removal.

In the case of dispersed contamination, a rigorous assessment of the actual and potential pathways is required to determine the optimal action. This assessment begins with the identification and consultation of records, if available. The historical assessment needs to be confirmed by a physical site characterization, for example by walk-over gamma ray measurements. Detailed sampling and analysis may be needed to more clearly identify hot spots and to delineate materials that do not require further attention. In recent years, a variety of strategies and techniques for efficient site characterization have been developed [43].

For sites with mixed contamination of radioactive and other hazardous substances, it is often necessary to use several remediation technologies, sometimes in series, i.e., treatment trains, to effectively address risk from the radioactive, chemical and physical hazards that could be present. In addition, sites may have contamination in different media. It is not uncommon, for example, on sites with extensive soil contamination, to also have groundwater contamination. Different technologies will probably be needed for remediating the different problems.

However, there are three basic planning approaches for any intended remedial actions. These are:

(1) *Monitored non-intervention*. This approach relies on natural processes to prevent significant exposure, meaning that the site will be undisturbed, while establishing a monitoring scheme for determining the evolution of the exposure of the site in time. The entire process needs to be carefully monitored so that alternative action can be initiated if required. Relating techniques of monitored non-intervention are in detail described in Section 4.3.1.

(2) *Source term removal*. This approach relies on the removal of the radioactive contaminants from the site, using an appropriate treatment scheme: this involves extracting, concentrating and then safely disposing of the contaminants at another location. Relating techniques of source term removal including in-situ as well as ex-situ treatments are described in Section 4.3.3.

(3) *Containment or blocking pathway(s)*. This approach restricts the mobility of the radioactive contaminants: this involves immobilizing the contaminants inside the area in which they already exist, reducing the potential for further migration or entry into

active pathways of exposure. Relating techniques of containment or a so-called blocking of pathways are in detail described in Section 4.3.2.

The three generic planning approaches that represent the fundamental technical choices for remediation can be summarized as monitored non-intervention, removal and containment. Each of these fundamental technical planning approaches will direct decision makers to follow substantially different paths with regard to their subsequent approaches, actions and potential results, making available significantly different technological options for application.

In addition, since a variety of remediation techniques exist for removing, reducing and containing contamination, the technologies illustrated in Figure 4.1 are grouped by the primary emphasis of the technology into separation, extraction or containment. The groupings are not necessarily mutually exclusive; for example, a barrier system may be used to contain and extract a contaminant, and, in some cases, the use of a particular technique may occur on or off the site.

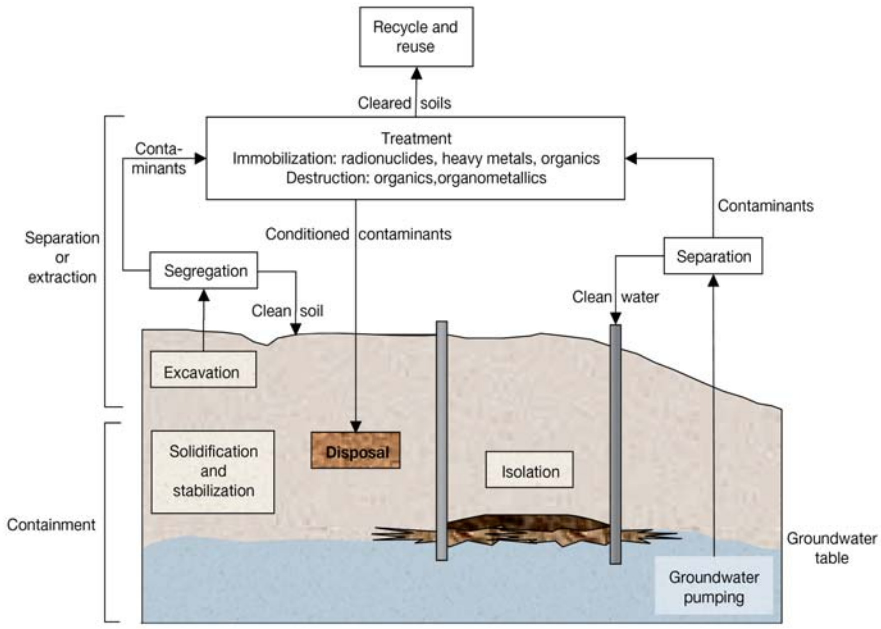


Figure 4.1 Classification of remediation planning approaches

The selection of a planning approach can not be made solely on the basis of scientific or engineering considerations. In addition to technical constraints, there may be a wide range of regulatory and socio-economic constraints on the selection of an appropriate remediation or disposal strategy [43]. National regulations may favour certain techniques and prohibit or discourage others.

International agreements may also preclude or restrict some strategies. The local population may want to participate in the remediation decision making process; public acceptability can be a major factor in selecting a particular remediation technique. Active inclusion of the public will increase their knowledge and awareness of the problem, increase acceptance of the remediation technique selected for deployment and increase acceptance of restrictions on land use that may result. Participation may also enhance the public's willingness to support the long term maintenance of remediation measures and related installations.

A wide variety of remediation techniques are now commercially available or at the demonstration stage. Although most of the techniques are of a generic nature, others use proprietary formulations of reactants and other agents, or applications that are protected by patents and similar means. Because the field is continuously developing, formal methods to assess the applicability and effectiveness of technologies have been developed. Approaches to selecting technologies vary from country to country. Some countries regularly undertake technology assessments to help ensure that proposed projects are effective and efficient. The findings are typically made accessible in technology directories or bibliographies. There are also international, semi-governmental, and industrial or research community sponsored initiatives. Technology and technology supplier directories are also available. Other states and organizations rely on informal approaches, for instance on the basis of personal judgement by experts and managers, to select technologies [7].

4.3.1 Planning approach: monitored non-intervention

A variety of naturally occurring physical, chemical and biological processes in the subsurface can reduce contaminant concentrations at a given point in space and time without human intervention [7]. The combination of these processes is known as natural attenuation or “non-intervention” approach. This depends on the natural processes of retention (sorption), retardation (physical, chemical and biological), and radioactive decay.

Consideration of this option requires modelling and evaluation of contaminant degradation rates and pathways to demonstrate that natural processes will reduce contaminant concentrations below regulatory standards before exposure through various pathways can occur [3].

A decision not to intervene in site clean-up implies reliance on the capacity of natural media (rocks, soils, sediments and groundwater) to retard contaminant migration (i.e., natural attenuation) or on physical, chemical and biological processes to reduce activity levels to below those of concern (i.e., dilute and disperse). In either case, environmental monitoring will be required to verify that such an approach is effective for the system under investigation. It should be noted that, ultimately, all remediation options that do not entail complete removal of the contaminant source would de facto revert to this solution if the half-lives of the radioactive species exceed a few hundred years [43].

It is also important to draw a distinction between those radionuclides that occur naturally and those that do not, such as caesium, technetium and the transuranics. In the case of the former, reference may be made to the known geochemistry of the element in a given environmental medium (see Section 3.2.4). This provides a degree of confidence in predicting future migration behaviour. For artificial radionuclides, experience can be limited to laboratory data or small scale field trials.

In general, natural attenuation is considered a viable option when it can be determined that contaminants are degrading or becoming immobilized at a rate faster than the rate of migration and are not expected to reach human or ecological receptors. Doing ‘nothing’ may be considered the baseline option in any remediation case. In terms of expenditure on actual remediation activities, this is certainly the cheapest option. Nevertheless, it may entail a variety of other costs, including social and economic, at a later stage. Most notably cost for monitoring would arise. The cost efficiency of active remediation would be compared with this baseline option, taking all cost elements into account for all possible remediation options. The advantages of natural attenuation include reduced generation of remediation waste and possible reductions in the cross-media transfer of contaminants. The disadvantages include slower clean-up, the creation of transformation products that may be more toxic than the original contaminants, more costly site characterization, a reliance on uncertain institutional controls to ensure long term monitoring, and the chance that subsurface conditions will not support natural attenuation as long as necessary [7]. Also from the point of influence on workers health and safety non-intervention is it the best approach.

When natural attenuation is considered as a remediation option, monitoring is performed to assess contaminant migration, degradation and retardation. This is often referred to as monitored non-intervention. The purpose of monitoring is to ascertain compliance with regulatory requirements and to recognize emerging problems well in advance and thus to be able to implement contingency plans in good time. An approach relying on monitored natural attenuation consists of the following three main elements: a site assessment and monitoring programme, a model to predict the site development and a contingency plan. These three elements are developed interactively, whereby modelling results are used to optimize the monitoring programme while the model in turn is refined using the monitoring and site assessment data. The contingency plan is periodically revised on the basis of conclusions from the other two elements. Mathematical methods to deal with spatial and temporal parameter uncertainty in this context have been developed.

The physical, chemical and biological processes as well as the rate and extent to which these natural attenuation processes occur depend on the contaminant and site hydro-geological and geochemical conditions. These processes are typically categorized as either destructive or non-destructive. Destructive processes reduce the potential risk from a contaminant by converting it to a less toxic form and include bio-degradation and hydrolysis. Bio-degradation is by far the most prevalent destructive mechanism. Non-destructive processes reduce potential risk from a contaminant by reducing its concentration and thus its bio-availability in groundwater or surface water.

Non-destructive processes include hydrodynamic dispersion and dilution, and adsorption, which reduce the mobility and solution concentration by binding to soil minerals and organic matter.

Each contaminant tends to be unique in the way different environmental processes affect its fate, so making generalizations that apply to all contaminants is inappropriate. Especially significant is the difference between organic and inorganic contaminants. The fate of organic and inorganic contaminants is controlled by a combination of physical, chemical and biological processes. The physical processes control the rate and direction of travel as contaminants migrate through soil away from the source. The chemical and biological processes determine the extent to which the initial compounds will be transformed in the soil. Although organic contaminants may be completely degraded to carbon dioxide and water, some intermediate degradation products may pose a greater risk than the original contaminant. For example, vinyl chloride is more persistent, more mobile and more toxic than its parent chlorinated compounds. Some inorganic contaminants are amenable to destructive attenuation, for example, oxy-anions, nitrate, sulphate, chromate and arsenate. The resulting products, however, may or may not be of lesser concern: for instance, nitrogen gas, ammonia and Cr^{3+}. In general, inorganic contaminants may be transformed by non-destructive processes to forms that have lower mobilities or bio-availabilities.

It is important to note that inorganic contaminants persist in the environment because chemical elements are not amenable to attenuation by destructive processes, except for radioactive decay.

The presence of a contaminant mixture can enhance or inhibit natural attenuation of any one component of the mixture. In some cases the presence of co-contaminants may be aiding natural attenuation reactions to occur, but in other cases co-contaminants can interfere with these processes. For example, the presence of fuels can enhance the bio-degradation of chlorinated solvents, whereas the degradation reactions that reduce pH can mobilize radionuclides and metals. Conversely, the presence of metals, including radionuclides, can inhibit bio-degradation.

The non-intervention does not need to mean only a “to do nothing” approach. It can also include some human activities to facilitate the natural mechanisms and processes of retardation, retention and decay of contaminants, especially when large areas of landscape are treated.

4.3.1.1 Natural attenuation

The concept of natural attenuation has received a great deal of attention in recent years. It constitutes the least invasive approach to environmental restoration. The concept is not new; for example, it forms an integral component of the design criteria for geological repositories that depend on geochemical processes to retard radionuclide migration to the biosphere. It is not entirely without financial cost. Reliance on natural attenuation requires adequate monitoring, owing to the evolution of natural systems with time and the incomplete understanding of the processes operating. The effects of any change in land use or in water abstraction would also need to be assessed, hence the increased use of the term 'monitored natural attenuation' in the literature [43].

A large number of processes can contribute to natural attenuation, as discussed below. Figure 4.2 illustrates the effect of some of these processes on the migration and concentration distribution of radionuclides. In order to be effective, they must prevent or delay the arrival of a radionuclide at a receptor until such time that it will have decayed to an insignificant level.

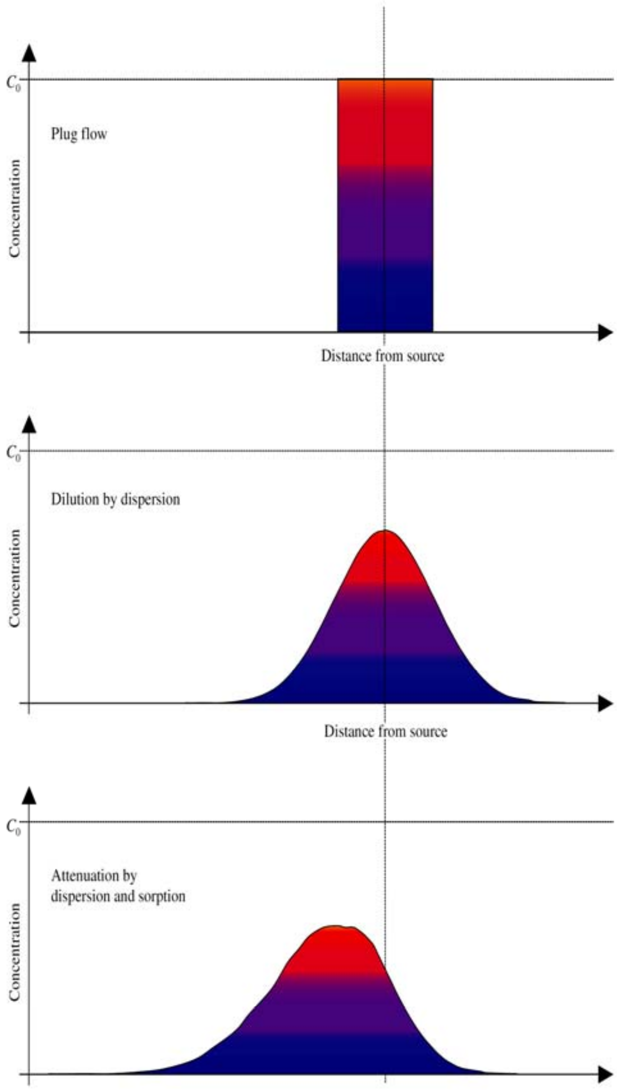


Figure 4.2 Transport mechanisms effecting dilution and attenuation

Whether to intervene or to rely on natural attenuation can only be determined on a site by site basis [43]. Factors militating against intervention include:

- The areal extent of the contamination;

- The accessibility of the site;
- The proximity to sensitive receptors;
- The radionuclide inventory;
- The time frame;
- The presence or absence of co-contaminants;
- The chemical and mineralogical characteristics of the material;
- In the case of surface deposits, the geotechnical stability;
- The transmissivity of the host medium.

A comprehensive site investigation programme is essential to determine these factors.

The degree of confidence that can be ascribed to natural attenuation in preventing harmful exposure or environmental damage is proportional to the level of characterization of that site. Developing an understanding of the physical, chemical and biological processes operating is more crucial in the case of natural attenuation than if the contamination were to be removed physically from the site.

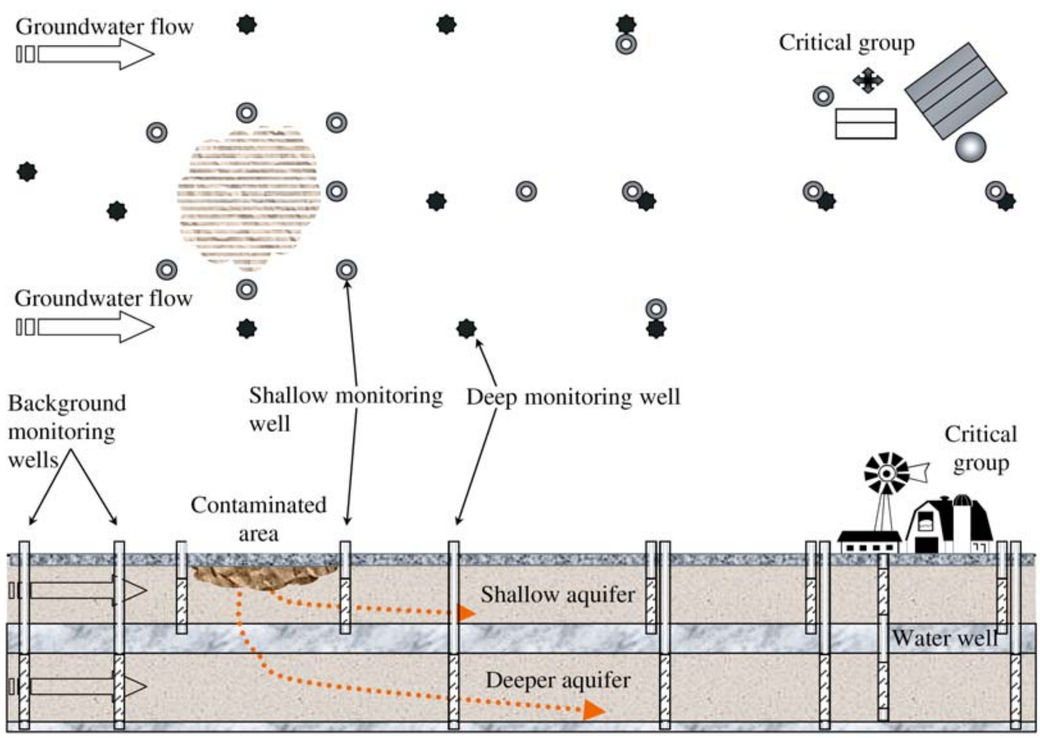


Figure 4.3 Schematic presentation of the principle of natural attenuation

A decision to apply monitored natural attenuation (Figure 4.3) as the preferred management strategy will invariably be made by considering a combination of scientific, economic and political criteria. Ideally it should be based on a prior risk analysis of the specific site and follow an established technical protocol. Given a backdrop of scarce resources, various initiatives are under way to promote the acceptance of natural attenuation as a part of a cost effective and environmentally sound solution for radioactively contaminated sites worldwide [43].

4.3.1.2 Physical processes

Physical processes, such as volatilization and dispersion may also contribute to natural attenuation. The transport and retention mechanisms for dissolved organic contaminants are largely the same as for inorganic constituents.

In some instances of contamination, concentrations of non-miscible organic compounds may be so high that they form a three phase system together with the solid substrate and the groundwater, often referred to as non-aqueous phase liquids (NAPL). In cases where the vapour pressure is high at ambient temperatures, even a four phase system may develop, with a separate gas phase. In the unsaturated zone a four phase system may be present in the sense that in-phase polar liquids fill some of the pore space.

Volatilization removes contaminants from groundwater or soil by transfer to a gaseous phase, eventually reaching the unsaturated zone. For highly volatile organic compounds such as benzene, volatilization may account for 5 – 10 % of the total mass loss at a site, with most of the remaining mass loss due to bio-degradation. For less volatile organic compounds, the expected mass loss due to volatilization would be lower, of course. Volatilization and transfer into the unsaturated zone may actually enhance bio-degradation of certain organic compounds [7].

Where a separate phase of non-miscible organic compounds exists, two cases can be distinguished:

(1) The density of the organic liquid is lower than the density of water. In this case the contaminant will float on the groundwater table.

(2) The density of the organic liquid is higher than the density of water. In this case the organic liquids will collect at the bottom of an aquifer, often referred to as dense non-aqueous phase liquids (DNAPL).

The potential for attenuation by physico-chemical processes is lower for those lighter, and also more volatile, organic phases. They may readily migrate as liquid or gas phase. Conversely, the denser liquids collect in depressions at the bottom of the aquifers and remain rather stationary, also due to the typically rather higher viscosity. This, indeed, makes them rather inaccessible to pump and treat remediation techniques. While the bulk of the contaminant may remain stationary, a small fraction may dissolve in the water and thus lead to a persistent source term. Natural bio-degradation processes may give rise to a continuing source term of degradation products that may be of concern. It is further possible that such dense non-aqueous phase liquids act as an in-situ solvent extraction process, concentrating heavy metals, including radionuclides. On the other hand, lighter organic phases are often more amenable to bio-degradation.

Lighter-than-water organic liquids floating on the water table may become entrapped in the capillary fringe due to a fluctuating groundwater table. The migration and retention processes in the four phase system of the type soil solids - pore water - soil gas - liquid organic are rather complex and controlled inter alia by the surface tension of the organic liquid and its vapour pressure.

The dispersion of dense non-aqueous phase liquids is initially driven by gravity and controlled by the capillary forces in the unsaturated zone. Once they reach the saturated zone, a three phase system develops. The further downward movement is controlled by the surface tension of the organic phase and the hydrodynamics in the aqueous phase. These factors may result in dispersion of the organic phase. If the amount of dense non-aqueous phase liquids is not sufficient for a complete in-phase flow, droplets of the organic phase may become trapped and isolated in pores due to their surface tension. This in turn will reduce the permeability of the aquifer concerned. The trapped droplets can act as a long term source for small releases of organic contaminants and are not amenable to removal by techniques such as pump and treat.

- Radioactive decay
  The half-lives of radionuclides now present in the environment range from microseconds to many millions of years. For higher members of the natural series (^{234}U, ^{235}U, ^{238}U, ^{232}Th), together with some transuranics (e.g., ^{239}Pu) and fission products (e.g., ^{99}Tc, ^{129}I), no substantial decay will have occurred even on the longest assessment timescale. However, many other isotopes produced by nuclear fission (e.g., ^{60}Co, ^{90}Sr, ^{137}Cs) will not persist beyond a few hundred years. Clearly, it is therefore essential that a detailed radionuclide inventory be compiled before deciding to adopt natural attenuation as a management policy at any given site. The extreme fractionation between members of a decay series caused by chemical processing precludes the assumption of secular equilibrium in the majority of cases [43].

- Dilution and dispersion
  Radioactive materials are discharged routinely into the air and into surface waters, both fresh and marine, from nuclear facilities worldwide.

  The effectiveness of dilution in aqueous media is critically dependent on the speciation of the radioelement under the prevailing environmental conditions This will control factors such as solubility, adsorption to surfaces, bio-availability and toxicity. Many radiologically important elements may be concentrated by geochemical and/or biological processes, leading to secondary sources of potential contamination. Similarly, physical dispersion of solids may not always be effective if the size and density of the particles differ significantly from the ambient environment [43].

  There is no doubt that, even where not proscribed by legislation, the dilute and disperse option is opposed by regulators, environmental groups and the public at large.

- Filtration
  In most situations the dominant exposure pathway is via flowing water. Resistate minerals (e.g., monazite, zircon and barite), other insoluble materials, for example cement, or particulate matter on to which radionuclides have become bound may be retarded by filtration. This will depend on the relative size of the particles and the pore distribution of the host medium, although even small colloids may be removed by fine grained clay matrices or fibrous peat. In the case of aquifer transport, adequate characterization of the hydro-geological flow regime (permeability, hydraulic conductivity, heterogeneity, fracture distribution) is a prerequisite for a quantitative assessment. Variably saturated conditions and geotechnical issues also have to be taken into account for surface deposits.

- Volatilization
  Radon produced by decay of parent radium isotopes will escape from well ventilated soils or heaps, and hence the progeny will be subject to atmospheric dispersion. Methylated and permethylated forms of bismuth, lead, polonium and selenium microbially generated in the subsurface can also be volatilized [43].

4.3.1.3 Chemical processes

Examples of naturally occurring chemical processes in the subsurface that might reduce contaminant concentrations at a given point in space and in time without human intervention are:

- Precipitation
  Relatively few natural series radio-elements and no artificial isotopes will exist in sufficient mass concentrations to precipitate as a pure phase from surface, pore or groundwaters: the exceptions are uranium, lead and thorium.

  Uranium is a relatively mobile element in the near surface zone, owing to the stability of U(VI) aqueous complexes. However, it may be precipitated by reduction to U(IV) or in the form of uranyl minerals, principally phosphates, silicates, arsenates, vanadates and oxy-hydroxides, several of which may occur simultaneously at the same locality. It follows that the amount of uranium released to groundwaters or surface waters from these secondary sources will depend on the solubility and dissolution rate of the phases as a function of pH and water composition. Unfortunately, too few quantitative data exist at present to allow predictive modelling an issue that needs to be addressed [43].

Lead, for example, may precipitate as the insoluble sulphide galena (PbS) that will incorporate ^{210}Pb by isotopic substitution.

Thorium occurs only in the tetravalent state and is substantially insoluble except at very low pH. Where mobilized, for example in acid mine drainage (AMD), fixation occurs rapidly, often within a few micrometres, via the formation of silicates or, in the absence of silica, oxy-hydroxides.

- Co-precipitation
  Radionuclides present at very low mass concentrations can nevertheless form solid phases by co-precipitation in mineral lattices. An important example is the high selectivity shown by radium for barite, a mineral that has been very well characterized and is also exploited in a remediation context. It is likely that transuranic isotopes would be similarly incorporated in uranium and lanthanide bearing minerals. Establishing the geochemical controls on migration of artificial radio-elements is the major challenge to workers involved in the remediation of legacy nuclear sites [43].

  Co-precipitation on ferric oxy-hydroxide flocs is an extremely efficient removal mechanism for a large number of radio-elements in solution. As the contaminants tend to be released upon crystallization to goethite, the process is often classified under the more general heading of sorption.

- Sorption
  Sorption, the process by which particles such as clay and organic matter ‘hold onto’ liquids or solids, retards migration of some organic compounds. This increases the time for bio-degradation to occur before contaminants can migrate to a potential receptor. Sorption is controlled by the organic content of soil, soil mineralogy and grain size.

  In its strictest sense, sorption refers to the non-specific and reversible uptake of ionic species at charged surface sites. Used loosely, it has come to encompass aspects of co-precipitation, ion exchange and a number of ion specific interactions that are more appropriately termed complexation. The distinction is not made here other than in the case of co-precipitation, described above, as the latter clearly extends beyond the surface, resulting in the formation of a defined mineral phase.

  Certain functional groups, notably the carboxylic or phenolic groups, on organic molecules will dissociate to a certain degree when the substance is dissolved in water. Such substances are termed ‘polar’. These groups, being anionic in nature, will give the molecules an overall negative charge and thus in general disfavour attenuation by hydrolysed mineral surfaces that are also negatively charged. There may be, however, more complex interaction mechanisms via hydrogen bonds or whereby metal ions act as bridges between the hydrolysed mineral surfaces and the charged molecule. In addition, complex soil organic constituents that are attached to the mineral surfaces can act as intermediates [7].

  The interaction between non-polar organic molecules, i.e., those that do not dissociate in water, and solid mineral surfaces is much more complex. Such molecules may form surface coatings on clays, for example, and hence become immobile.

  Clay minerals typically show a strong affinity for radionuclides in the cationic form. Geological media with high clay mineral content are therefore more likely to affect attenuation. Adsorption and ion exchange would be expected to play an important role in retarding the migration of soluble monovalent and divalent ions. Examples include the pronounced retention of caesium on zeolites (e.g., clinoptilolite) and the substitution of strontium for interlayer cations in smectites. Surface sorption is an important transient for multivalent ions in the formation of new mineral phases [43].

- Complexation by organics
  A number of radionuclides exhibit significant migration potential in the presence of aqueous, low molecular weight organic compounds. Equally, however, immobile organic matter in the form of peat or organic rich horizons in soils and sediments may provide an excellent substrate for radionuclide retention. These phenomena have been studied extensively in the context of 'natural analogue' studies for the performance assessment of radioactive waste repositories. Uranium approaching percentage levels has been reported in peat from Canada and northern Europe, whereas iodine, often considered to be a conservative tracer in such assessments, has been shown to be fixed in organic rich lacustrine deposits [43].

4.3.1.4 Biological processes

Bio-degradation is a process or collection of processes (e.g., bio-mineralization, 'bio-sorption' and microbially mediated phase transfer) in which naturally occurring micro-organisms such as yeast, fungi and bacteria break down organic substances into less toxic or non-toxic compounds. The ability of micro-organisms to metabolize nutrients depends on the chemical composition of the environment. In most organisms, the metabolic process requires the exchange of oxygen and carbon. Bio-degradation can occur in the presence or absence of oxygen. Nutrients and essential trace elements must be available in sufficient quantity in order for the micro-organisms to break down all of the organic contaminant mass. The complex bio-geochemical processes effecting the fixation or mobilization of metals, including radionuclides, in various types of soil ecosystems have been studied with increased intensity in the aftermath of the Chernobyl accident and in other remediation contexts [43].

In general there are three bio-degradation processes:

- Those where the contaminant is used by the microbes as the primary food source;
- Those where the contaminant is used to transfer energy;
- Those where the bio-degradation occurs in response to a chain reaction between the contaminant and an enzyme produced during an unrelated reaction (termed co-metabolism).

For fuel hydrocarbons, the first process is dominant. The full degradation of chlorinated solvents requires all three processes. Until recently, scientists believed that chlorinated organic compounds were generally highly resistant to bio-degradation in the environment, but in the past two decades a variety of biological processes have been discovered that can transform these compounds in nature [7]. It is worth noting that many microbial communities are very adaptable to the local circumstances and in the absence of other readily available energy sources may evolve to utilize highly resilient organic compounds. These processes are extremely complex and not yet fully understood, but are a topic of a significant body of research:

(1) *The contaminant is used as the primary food source.* In the presence of oxygen, bacteria are able to use the carbon in organic contaminants as their primary food source. This relatively rapid process has greater potential for fuels and chlorinated solvents with few chlorine atoms per molecule. Highly chlorinated organic compounds are less susceptible to this type of degradation. In the absence of oxygen, micro-organisms can sometimes still use contaminants as their primary food supply. This form of degradation under anaerobic conditions depends not only on the compound but also on temperature, pH and salinity. In breaking down chlorinated solvents, bacteria use nitrate, iron, sulphate and carbon dioxide to help metabolize the

carbon in the organic contaminants. If degradation is complete, the products are usually carbon dioxide, water and chlorine.

(2) *The contaminant is used to transfer energy.* All living organisms respire in that they use organic substances and other nutrients by breaking them down into simpler products. In the absence of oxygen, micro-organisms may use chlorinated compounds as an aid to respiration rather than as a food source. This is accomplished through an electron transfer process. Where carbon in a contaminant is the food source, the contaminant is an electron donor. In the case where food is obtained from a different source, the contaminant sometimes aids this transfer by accepting electrons that are released during respiration. The most common anaerobic process for degrading chlorinated compounds is an electron transfer process termed reductive de-chlorination. In this process, hydrogen atoms are sequentially substituted for chlorine atoms in the contaminant molecule. The major requirement for reductive de-chlorination is the presence of other organic compounds that can serve as the food source.

(3) *Co-metabolism.* In co-metabolism microbes do not degrade the contaminant directly, but the contaminant degrades by enzymatic reactions that occur during metabolism of other substrates. Reductive de-halogenation occurs only under anaerobic conditions, although some chlorinated compounds can be biologically degraded by other mechanisms in aerobic environments. Aerobic co-metabolism requires the presence of electron donor compounds, such as methane, toluene, phenol or other organic compounds, that leads to production of the enzymes.

The bio-degradation process most frequently observed at sites where natural degradation of chlorinated solvents occurs is reductive de-halogenation, where microbes use the chlorinated compounds for energy metabolism and remove a chlorine atom. For example, reductive de-halogenation can transform tetra-chloro-ethene (PCE), which has four chlorine atoms, to tri-chloro-ethylene (TCE), which has three, and then transform tri-chloro-ethylene to cis-dichloro-ethene (cis-DCE), with two chlorine atoms. Cis-dichloro-ethene can then be reduced to vinyl-chloride, which can be further reduced to ethylene, an essentially harmless compound. A potential risk of this process is a build-up of intermediate transformation products, such as vinyl-chloride, that are more toxic than the parent compound.

Natural attenuation of chlorinated compounds is a slow process and may not occur at all at a given site. Thus it is not likely to be an appropriate strategy at sites where rapid and sure clean-up of contamination is required. Monitoring for natural attenuation can also be costly. Nevertheless, the presence of intermediate and final degradation products indicates that at some sites natural degradation processes do take place. A primary advantage, however, is that it can eliminate the need for an engineered solution that may disrupt the site or it can reduce the size of an area requiring treatment with an engineered system. Engineering intervention, such as supplying nutrients to stimulate the natural degradation processes, can greatly enhance the attenuation [7].

4.3.1.5 Alternative land uses and agricultural countermeasures

When extensive areas have been contaminated, many of the discussed remediation methods may be too expensive to carry out or too intrusive. In particular, when the land was used for agricultural purposes, alternative uses may need to be considered. Such alternative uses may range from switching to different crops to turning to completely different uses, such as parkland [43].

Many studies have been targeting possible agricultural countermeasures in response to concentration levels in food and agricultural crops exceeding the applicable standards. Most studies have been conducted to test the effect of different physical and chemical countermeasures. However, information on the long term effect of countermeasures, and especially of a change to non-food crops, is still scarce.

When investigating alternative crops, the principal questions to be addressed are:

- Can an alternative crop be found that is suited to the climate and soil conditions prevailing in the contaminated area?
- What is the fate of the radionuclide in the cultivation system and along conversion routes?
- How does the radionuclide in question behave during biomass processing and what is the expected radionuclide concentration in the end products?
- What is the exposure during biomass cultivation and processing?
- Would production and utilization of the alternative crop be economically feasible?
- What are the overall prospects for the chosen alternative crop as an alternative land use for large contaminated areas?

In order to understand the fate of the various radionuclides and their distribution in products, residues and waste, one needs to know the various radionuclide fluxes. These depend on the initial deposition levels, crop accumulation factors, which in turn depend on plant and soil characteristics, and the radionuclide accumulation in the produce (e.g., wood, rape or beetroot). Whether residues and waste need to be treated as radioactive waste depends on the radionuclide concentration and the applicable exemption limits.

Crops used for liquid bio-fuel (oils, alcohol) production, such as rape, wheat, sugar beet, barley, potatoes and winter rye, may be suitable alternative crops.

The data in Table 4.1 indicate that crops with a low transfer factor (TF) to the useable product can be found and that the resulting liquid bio-fuels are almost free from activity, and that ^{137}Cs levels in the waste and residues are generally of no concern.

Table 4.1 Caesium transfer factors to different plant parts of some potential bio-fuel crops [43]

Crop	Plant component	Caesium TF (10^{-3} m^2/kg)
Spring wheat	Straw Grain	0.23–0.36 0.13–0.16
Winter wheat	Straw Grain	0.27–0.44 0.08–0.18
Rye	Straw Grain	0.43–0.60 0.17–0.29
Spring rape	Green mass Straw Seeds	0.33–0.81 0.38–0.92 0.27–0.66
Brassicaceae	Seeds	0.037–3.4
Peas	Seeds Straw	0.69–1.25 0.82–1.45
Leguminosae	Seeds	94 (12–750)
Sugar beet	Root	0.43
Root crops	Root	0.025–11 (1.1–110)
Green vegetables	Leaves Leaves (peaty)	0.07–4.86 260 (25–2700)
Sunflowers	Straw Seeds	1.48–2.88 0.43–0.82

Examples from Belarus, however, show that caesium levels in oil cake from rapeseed oil (~2000 t/ha) and the pulp and vines from sugar beet (~4000 t/ha) may be too high for use as animal fodder and for incineration and that they may have to be disposed of as radioactive waste. On the other hand, the production of rapeseed and processing to edible rapeseed oil are profitable technologies and the levels of caesium and strontium in the rapeseed oil after three filtrations and bleaching are below the detection limit [43].

The valorization of contaminated land by willow short rotation coppice (SRC) for energy production has been addressed is another possibility. Coppicing is a method of vegetative forest regeneration by cutting trees at the base of their trunk at regular time intervals. Fast growing species of the Salix genus (willows) are frequently used in a coppice system because of the ease of their vegetative reproduction and the large biomass produced. The harvested biomass is converted into heat or power (with an appropriate off-gas treatment). As such, this non-food industrial crop is a potential candidate for the valorisation of contaminated land that has use restrictions. Short rotation coppice may be preferred over traditional forestry since revenues come sooner after establishment and more regularly (every 3 - 5 years). Short rotation coppice yields are also high on good agricultural soils, and its use is not a drastic change in land use; short rotation coppice is easy to introduce and it is easy to return the land to the production of food crops. Short rotation coppice may also be considered as complementary to forestry, given the different culture requirements of both vegetation systems. Forests perform well on sandy soils, whereas short rotation coppice requires soils with a sufficient water retention capacity. Short rotation coppice has additional potential advantages in a contamination scenario: since it is a perennial crop, dispersion of radionuclides will be limited. Harvest can be in winter, when the soil may be covered by snow, resulting in radiation protection of the workers. Finally, short rotation coppice cultivation is not too labour intensive, which is also an advantage with respect to exposure.

Willow short rotation coppice may be a suitable rehabilitation tool for highly contaminated land, but only if the radionuclide levels in the wood are below the exemption limits for fuel wood, if the average yearly dose received during coppice cultivation and coppice wood conversion is acceptable, if short rotation coppice can be grown successfully in the contaminated territories (soils, climate), if the cultivation of short rotation coppice is technically feasible and if short rotation coppice production and conversion are economically profitable.

For soils with a medium to high fixation (finer textured soils) and sufficient potassium availability, the transfer ratio of concentration in plant biomass to concentration in soil is $< 10^{-5}$ m^2/kg, and wood can be safely burnt and the ashes can be disposed of without concern [43]. For light textured soils, however, with a low radio-caesium fixation and low soil potassium, the transfer to wood is around 10^{-3} m^2/kg, and concentrations in wood may be elevated enough that the prevailing exemption limits are reached. Given that transfers for common forestry and for straw of winter wheat and rape are comparable, the same applies for burning wood or straw for energy.

Short rotation coppice has generally a high annual yield of about 12 t/ha, but sandy soils are only suitable for short rotation coppice production if well fertilized and irrigated. Only during the conversion phase and when burning highly contaminated wood (3000 Bq/kg) do doses in the vicinity of ash collectors exceed the level of 1 mSv/a for a member of the general public [43]. Contributions from other possible exposure pathways are negligible (external exposure during cultivation and transport, inhalation dose in the combustion plant and doses to the public following wood burning).

Crop yield and the capital cost of the conversion units are among the most important parameters affecting system profitability. At the production site, a minimum yield of 6 t/ha/a is required for Belarus production conditions and of 12 t/ha/a for western European conditions, if all other parameters are optimal [43]. Heating schemes may be a viable option for wood conversion in Belarus, whereas electricity generation schemes are not.

Subsidies would be required in Europe to make wood conversion economically feasible. It has also been concluded that the existence of a contamination scenario does not necessarily hamper the economic viability of the energy production schemes studied. The cost associated with the disposal of contaminated ashes was estimated as less than 1 % of the bio-fuel cost and will not affect economic feasibility.

Forestry can also be considered to be an adequate alternative land use [43]. Soil to wood transfers to coniferous and deciduous wood are around 10^{-3} m²/kg and are hence comparable with the transfers to willow wood observed for low fertile soils with limited caesium fixation. They are high compared with the transfers observed for willow in finer textured soils and soils with an adequate potassium status. Moreover, the annual biomass increase is only 6 t/ha for forests and may attain 12 t/ha for short rotation coppice grown on soils with an adequate water reserve and fertility status. Short rotation coppice may hence be a more promising land use option on these types of soil than traditional forestry. On soils with a low water reserve (e.g., sandy soil), however, willow yield without irrigation is too low to be economically feasible, and forestry may hence be the preferred option [43].

Fibre crops are also potential alternative crops for agricultural land with restricted use. Potentially suitable crops are the annual fibre crops hemp (Cannabis sativa L.) and flax (Linum usitatissimum L.). Hemp and flax are well known arable crops that have been cultivated for centuries. Ukraine has a legacy of flax and fibre hemp cultivation, but in Belarus there is only some flax production. Since the early 1990s the acreage for production of flax and hemp has declined dramatically in Ukraine. Establishment of fibre crops on contaminated arable land is generally of no radiological concern. The transfers observed to hemp fibres are a factor of 4 to 50 higher than the transfers observed to flax. Cultivation is hence generally restricted to not too contaminated areas (< 1000 kBq/m²). For both crops it holds that contamination levels in the waste products (oil seed cake, chaff, ash after burning of straw) may, however, be high enough that they should be considered as radioactive waste. The economics of this land use has not, however, been investigated [43].

The introduction of alternative crops in a contamination scenario may be a feasible and adequate remedial option. Although there are some scenarios in which energy production from short rotation coppice and potentially other alternative crops on contaminated arable land is radiologically safe and economically feasible, installing this cultivation system on a large scale requires extensive logistics, infrastructure and initial investment. Implementation is likely only to be successful with adequate political support.

There are a number of additional types of alternative land use, such as the creation of parkland. Such measures, however, would largely be administrative and would amount to ‘institutional control’.

Many studies have been concerned with possible agricultural countermeasures in response to concentration levels in foodstuffs and agricultural crops exceeding the permissible levels in the wake of the Chernobyl. To this end, a database of 5261 experiments carried out during 1987-1999 and their respective results was compiled by participants from Belarus, the Russian Federation and Ukraine [43]. The main evaluation criterion was the efficiency of experimental treatments in reducing radionuclide concentrations in final products as compared with untreated controls. It is important to note, however, that the majority of countermeasures do not intend to influence soil or groundwater concentrations, but aim to break exposure pathways.

Countermeasures can be based on a selection of crops that exhibit smaller radionuclide uptake than crops used previously, on food processing to reduce radionuclide contents or on choosing non-food crops, resulting in either case in a produce from the contaminated land that is radiologically acceptable [43].

Assessments have shown that substituting crops and fertilization are the most effective countermeasures in plant production. The efficiency of countermeasures, expressed by the reduction factor of radionuclide concentration in final products, was found to be of the order of 3 to 9, depending on the soil and individual crops. Substituting crops may not be expensive, but its viability depends on a variety of economic conditions [43].

Fertilizer application will suppress the uptake of certain radionuclides, mainly due to competitive effects. Thus potassium dosages will generally decrease the soil to plant transfer of ^{137}Cs, certainly when the soil is low in potassium. Reported reduction factors have varied between studies, but overall reduction factors ranging between 1.1 and 5.0 have been obtained. The efficiency of potassium additions strongly depends on the exchangeable potassium content in the soil. For soils with a low to optimal potassium content, high dosages of potassium fertilizer are very effective and profitable. For soils with a high potassium content, only moderate dosages of potassium fertilizer are recommended to replace the potassium removed with crop yields [43].

The behaviour of ^{90}Sr and its uptake by plants are controlled by its similarity to calcium. Many investigators have found a significant correlation between strontium transfers and the reciprocal of the exchangeable calcium content [43]. Consequently, much of the research and actions to reduce strontium uptake by plants has centred on the use of lime as a soil based countermeasure. The use of lime has reduced strontium uptake by up to 40 %, the use of limed compost by up to 60 %. Generally, the reduction factor of radionuclide uptake by agricultural crops varies widely, from 1.1 to 3, depending strongly on the initial soil pH. The liming effect is most pronounced for acid soils [43].

Countermeasures that aim to provide the optimum (from the plant production point of view) rates of fertilizer application are the most viable, since the investment on fertilizer is paid back in the form of additional crop yields, and frequently profits are made. It has to be noted that the addition of nitrogen fertilizer should be moderate, as high dosages appear to stimulate the accumulation of ^{137}Cs and ^{90}Sr in plants. Phosphorus dosages should be in accordance with crop responses and the phosphorus content of the treated soil, and should be crop specific [43].

4.3.2 Planning approach: containment or blocking pathways

4.3.2.1 Enhanced attenuation

Although contaminated media sometimes provide sufficient attenuation capacity, normally these attenuation mechanisms must be enhanced through technical measures. Methods of enhancement can consist of stimulating bio-degradation of organic compounds, improving soil retention capacities, for example improving the sorption capacity, or changing the geochemical environment, for example changing the bulk redox state, such that migration of metals is hindered. Enhancement of attenuation may be targeted at particular exposure pathways; for example, plant uptake may be minimized or blocked to prevent contaminants from entering the food chain [43].

Simple ploughing or deep soil mixing is not an efficient means of reducing direct surface gamma exposure as such an approach will result in a dispersal of radionuclides over a larger area, thereby increasing the volume of contaminated soil [43].

Studies subsequent to the Chernobyl accident found that deep ploughing with digging, combined with liming and potassium fertilizer application, can decrease caesium and strontium transfer from soil to plants by a factor of 3 to 4. The objective of deep ploughing is to skim off the upper 0 - 5 cm contaminated soil layer and burrow it beneath the turned over arable layer (30 - 50 cm), thereby preserving most of the soil fertility. Subsequent cultivation practices have to be limited to shallower depths to prevent the contaminated soil layer from being dug up or roots from reaching this layer. This quite cost effective countermeasure had only limited application after the Chernobyl accident because of the thin humus horizon of the predominantly light textured soils in the region [43].

Changing the pH and redox conditions in contaminated zones can enhance attenuation, particularly in situations in which treatment is otherwise difficult, such as the presence of fractured rock. Oxidation or reduction can be achieved by injecting aqueous solutions of appropriate agents, or by bubbling gases through the contaminated zone. Long term sustainability is uncertain, and competing geochemical processes need to be evaluated carefully. Environments with relatively low redox potential and high organic matter content (e.g., wetlands) tend to trap metals naturally, a property that can be utilized (see Section 4.5.1.18) [43].

The number of sorption sites may be increased by adding clay or zeolites to soils. The addition of reactive minerals, such as lime, apatite and its derivatives, such as bone meal, may lead to immobilization through the formation of sparingly soluble mineral phases incorporating the contaminating radionuclides [43].

4.3.2.2 Physical barriers and liners

Applicable to radiological, non-radiological and mixed contamination, one of the most straightforward means of dealing with contaminated sites appears to be to isolate them from human and other receptors by constructing physical barriers [7]:

- *Surface barriers*, which are intended to minimize surface water infiltration into the contaminated soil of the site, to provide a barrier inhibiting direct contact and intrusion by plants and animals, and to inhibit inadvertent human intrusion. There are several general types of surface barrier, such as single layer covers, engineered multi-layer covers and biotic barriers.
- *In-situ barriers*, which are constructed vertically or horizontally below ground level to contain contaminated material. Vertical barriers are comprised of low permeability trenches, walls or membranes to impede lateral migration, usually keyed into a naturally occurring low permeability basal stratum. Horizontal barriers are installed beneath contaminated soil of the site using in-situ techniques such as grouting or soil mixing.

Surface containment systems are fully accessible during construction, allowing checking and testing, i.e., comprehensive quality control. They may be constructed on an uncontaminated surface to act as a liner on to which contaminated material is placed or they may be constructed above contaminated material to act as a cover. Liners form the basis of a dedicated landfill or 'containment cell' and invariably are used in combination with covers, for total encapsulation.

A surface barrier alone may not provide sufficient containment or isolation of contaminants so that a combination of technologies may be required to control contaminant migration and/or exposure to contaminants. A cover system and active hydraulic control, i.e., a drainage system, will be needed to limit groundwater rise within the containment.

Physical containment can be used in an integrated fashion with other remedial methods. Excavation of hot spots may precede the construction of a covering system in order to reduce the size of the soil of the site to be contained. In-situ stabilization may be employed as a pre-treatment step to enhance immobilization of contaminants and to provide a stronger base to support a final cover, thus reducing the maintenance needs caused by subsidence. Alternatively, physical barriers can aid other forms of remediation by limiting the volume of contaminated material to be treated when using methods such as groundwater pump and treat.

Forming barriers in-situ by injection (see Figure 4.9) from the surface can reduce construction and waste disposal costs and can be useful for replenishing barriers that have lost their effectiveness over time. Development of barrier emplacement methods that do not involve soil excavation is a significant advantage of this technology.

4.3.2.3 Surface barriers

Surface barriers, often referred to as (landfill) caps, are a common form of remediation for many types of contamination because they are a conceptually easy to understand and fairly inexpensive way to manage some of the risks associated with a contaminated site, such as direct exposure of humans and release of contaminants. They usually also enjoy a high public acceptance, as they seem to indicate visibly that something 'is being done'. Surface barriers or caps can be used to:

- Minimize direct exposure on the surface of the contamination from both radioactive and other hazardous substances;
- Prevent vertical infiltration of water into contaminated zones and wastes that would produce contaminated leachate;
- Contain waste while treatment is being applied;
- Control gas emissions from underlying contaminated materials that might be hazardous by themselves (e.g., radon and volatile organic compounds) or act as a carrier for contaminants, for example, ^{210}Pb and ^{210}Po;
- Create a land surface that can support vegetation and/or be used for other purposes.

The design of surface barriers is site specific and depends on the intended functions of the system. Surface barriers can range from a one layer system of vegetated soil to a complex multilayer system of soils and geo-synthetic products (Figure 4.4). In general, less complex systems are required in dry climates and more complex systems are required in humid climates. The materials used in the construction of surface barriers include low permeability and high permeability soils and low permeability geo-synthetic products. The low permeability materials divert water and prevent its passage into the contaminated zone. The high permeability materials carry away water that percolates into the barrier. Other materials may be used to increase slope stability.

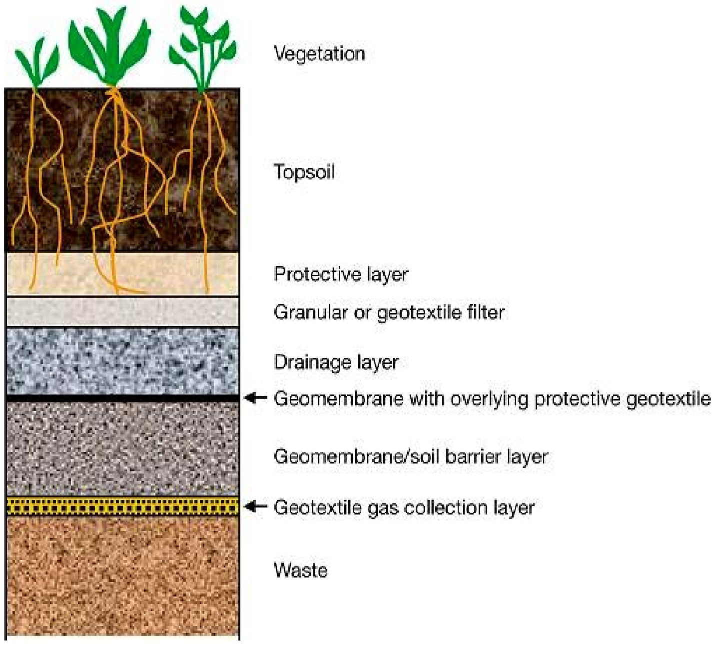


Figure 4.4 Generic layout of surface capping [7]

Low permeability barrier layers are either natural clays and other low permeability soils or geo-synthetic clay liners. Soils used as barrier materials are generally clays that are compacted to a hydraulic conductivity no greater than 1×10^{-8} m.s^{-1}. Compacted soil barriers are generally installed in lifts of at least 15 cm to achieve a thickness of 0.5 m or more. A flexible synthetic geo-membrane (plastics) liner is placed on the top of this layer. The candidate list of polymers commonly used is lengthy, and includes polyvinyl-chloride, poly-ethylenes of various densities, reinforced chloro-sulphonated polyethylene, polypropylene, ethylene interpolymer alloy (EIA) and many new materials. Geo-membranes are usually supplied in large rolls and are available in several thicknesses (0.5 - 3.6 mm), widths (3 - 30 m) and lengths (60 - 275 m). A composite barrier uses both soil and a geo-membrane, taking advantage of the properties of each. The geo-membrane is essentially impermeable, but, if a leak develops, the soil component prevents significant leakage into the underlying waste. Inspections of existing geo-membranes have, however, shown that their functionality cannot be guaranteed even a few years after their installation. Differential settlement and imperfect seams during installation are the main causes [7]. In addition, there is no experience with the really long term stability of synthetic materials, as these have been in existence for generally less than 50 years.

For barriers placed over degradable contaminants, the collection and control of methane and carbon dioxide, which are potent greenhouse gases, must be part of the design and operation of the surface barrier. It is, however, generally accepted wisdom that degradable materials should not be emplaced into engineered landfills.

Surface barriers may be temporary or final. Temporary barriers can be installed before final closure to minimize generation of leachate until a better/the final remedy is selected and implemented. They are usually used to minimize infiltration when the underlying contaminant mass is undergoing settling. A more stable base will thus be provided for the final cover, reducing the cost of post-closure maintenance. Surface barriers may also be applied to residue and waste masses that are so large that other treatments are impractical. At mining sites, for example, surface barriers can be used to minimize the infiltration of water to contaminated tailings piles and to provide a suitable base for the establishment of vegetation. In conjunction with water diversion and retention structures, surface barriers may be designed to route surface water away from the waste area while minimizing erosion [7].

Land filling does not lessen toxicity, mobility or volume of mixed contamination but does mitigate migration. Surface barriers are most effective where most of the underlying contamination or waste materials are above the water table. A surface barrier, by itself, cannot prevent the horizontal flow of groundwater through the contaminated material, only the vertical entry of water into it. In many cases, surface barriers are used in conjunction with subsurface barriers, such as vertical walls, to minimize horizontal flow and migration. The effective life of physical barrier components can be extended by long term inspection and maintenance. In addition, precautions must be taken to ensure that the integrity of the cap is not compromised by land use activities [7].

As indicated in Table 4.2 individual criteria of a remediation technique may be evaluated, if data for the technique are available.

Table 4.2 Evaluation of remediation criteria for given technique

Criteria	Quality
Effectiveness in remediating the contamination	
Ease of implementation	
Cost associated with the remediation programme	
Occupational safety and health risks associated with the technology	
Potential secondary environmental impacts (collateral damage)	
Prior experience with the application of the technology	
Socio-economic considerations	

Legend: * low
** medium
*** high

The humus content of a soil is important because of its tendency to form co-ordinate bonds with calcium and strontium, which are stronger than the binding by ion exchange sites on soil minerals. Organic matter addition has resulted in strontium transfer reductions by a factor of 1.2 to 7. The latter value was obtained after the addition of 15 % organic matter to a sandy soil. Field experiments on a podzoluvisol (loamy sand) soil in Belarus that increased humus content from 1.5 % to 3.5 % resulted in a reduction of ^{137}Cs and ^{90}Sr activity in perennial grass by a factor of 2 [43].

Chemical amendments, such as zeolites, ammonium hexa-cyanoferrate (AFCF) or clay minerals, also reduce radionuclide uptake by plants, since the radionuclides are trapped and so rendered less available for plants. A reduction factor of 4.6 in ^{90}Sr transfer has been obtained for a sandy soil after the addition of 1 % zeolites, and a factor of 25 by applying 10 g ammonium hexa-cyanoferrate per square metre. However, the investigation of zeolites and clay amendments in field trials on a loamy sand soil in Belarus resulted in only a rather low reduction of activity in cereals [43].

A more radical improvement of private hay land and meadows in all Chernobyl affected rural settlements of Belarus, the Russian Federation and Ukraine has been recommended. This countermeasure combines the liming of acid soils, fertilization (including the basic application of organic fertilizers), destruction of old turf, sowing of new grass stand and regulation of soil water (drainage), if needed; for example, radical meadow improvement has resulted in a reduction of grass activity by a factor of 1.7 to 3.5, but other applications have achieved reduction factors for ^{137}Cs of up to 16 - 20. The reduction factor of surface meadow improvement is lower, and is 3.5 on average [43].

Although strictly speaking not remediation techniques, certain livestock management measures are effective in reducing public exposures. Such measures include feeding complexants, such as Prussian blue, to dairy animals to prevent ^{137}Cs transfer into the milk, or changes in pasture or fodder at critical times to reduce uptake. Achieved reduction factors vary widely between 2 and 15 [43].

Food processing can significantly reduce radionuclide concentrations in products. The efficiency depends on the type of processing and varies widely, removing 50 - 98% of the ^{137}Cs or ^{90}Sr during the production of butter or casein from milk [43].

Table 4.3 Effects of various countermeasures on rape radioactivity [43]

	Activity reduction in rape products	
	^{137}Cs	^{90}Sr
Liming to 6 t/ha	14 %	42 %
Application of N90P90K180 fertilizer	42 %	27 %
Liming to 6 t/ha + N90P90K180 fertilizer	45 %	59 %
Variety selection	2.5 times	3.0 times
Rapeseed oil processing (crude oil)	250 times	600 times

The relative efficiency of different agricultural countermeasures can be seen from the experiments in which rape was grown on radioactively contaminated land in Belarus (Table 4.3). The effect of liming is mainly due to a rise of the soil pH and hence the increased availability of exchangeable calcium. Choosing a rape variety with less uptake offers activity reductions of up to three times. The most efficient removal of activity is offered by oil processing, resulting in a reduction of up to 600 times. Concentrations of radionuclides after a three stage filtration and bleaching are below the limits of detection. The combination of oil seed processing with several agricultural countermeasures therefore allows the production of food grade oil practically free from radionuclides and produces a valuable protein by-product (cake as animal fodder) with permissible concentrations of radionuclides [43].

4.3.3 Planning approach: removal of source term

4.3.3.1 Excavation

It should be noted that in general any method relying on the removal of contaminated soil is likely to require the substitution of the removed material with clean soil. Therefore, in addition to considerations with respect to technical feasibility, an economic source of clean soil will be required to make this option viable. Conversely, a precondition for any removal option is the availability of a suitable disposal site for the excavated materials, whether they are left untreated or whether they are conditioned before emplacement.

Retrieval consists of excavating and removing buried wastes or subsurface contaminated soil or sediments. For buried wastes, retrieval could entail removal of overburden soil, interstitial soil and possibly impacted underlying soil as well. Retrieving low level radioactive and hazardous soil and buried wastes from a site is a proven and reliable approach. However, retrieval and waste management techniques for transuranic wastes have not been proven to the same extent and may require site specific and innovative design elements to ensure protection of human health and the environment. In addition, problems with the acceptance of wastes in disposal facilities might arise.

The removal of wastes from a site allows them to be treated to reduce the toxicity and mobility of the various contaminants with a view to making the wastes suitable for disposal in a licensed engineered facility. Retrieval removes or greatly reduces the risks associated with the site if the retrieved wastes are disposed of off-site or isolated from the environment. This typically results in significantly reduced long term site monitoring and maintenance requirements. Furthermore, with a complete removal of the contaminants, the site can be released for unrestricted use. However, it has to be borne in mind that the disposal site may now need such monitoring and maintenance. Nevertheless, some advantage would be gained by concentrating contaminants at a smaller number of sites requiring supervision.

The retrieval and disposal of waste materials is time consuming and expensive. One of the greatest concerns in retrieving buried radioactive and hazardous wastes and contaminated soil is increased potential for worker exposure, contamination spread and off-site release.

Two categories of technology are usually implemented during retrieval of contaminated materials and wastes from sites with mixed contamination:

1. *Contamination control* minimizes the spread of contamination and controls the source. Depending on site-specific conditions and materials present (e.g., soils, bulk debris, process sludges and containerized liquids), various controls may be used.
2. *Excavation*: various associated equipment are available on the market, including conventional heavy earth moving equipment, standard construction equipment with appropriate modifications (e.g., sealed and pressurized cabins with filtered intakes and extracts or supplied air) and remotely controlled equipment. Most equipment used for excavation of soil and buried wastes is standard heavy construction equipment proven for use at hazardous waste sites around the world. If the hazards at a site are particularly severe, remotely operated equipment and hermetically (airtight) sealed equipment with filtered or supplied air can also be used.

Most of the required equipment and techniques for excavation or retrieval have been proven in highly contaminated environments. For example, remote excavators have been proven successful in waste retrieval simulations and have been used throughout facilities for decontamination and demolition work. In addition, shielded excavators and hermetically sealed vehicles have been used successfully. In general, hermetically sealed retrieval equipment is less expensive, needs less maintenance, is capable of more precise digging and can be operated faster than remote equipment. In some environments, shielding (e.g., Lexan™ windows) of equipment is required to protect workers from potential explosions and radiation. Filtered or supplied air can be added to equipment to protect operators, as has been proven at many sites. Additional information can be found in [7].

It should be noted that where a medium, typically water, is being used, secondary mixed wastes or wastewater may arise that require treatment and disposal.

4.3.3.2 Contamination control methods

In general, controls are grouped into two categories - those used before retrieval and those used during retrieval. Both types can be effective at controlling contamination, thus decreasing the potential for exposure, the costs of operation and maintenance of equipment and the cost of decontamination. Process options for contamination control include the following [7]:

- *Confinement:* enclosures constructed from plastic, metal, fibreglass or other materials are used to prevent the spread of airborne contaminants by enclosure of a piece of equipment, work area or an entire site. Enclosures may be relatively lightweight and portable or they may be more substantial, sturdier and less portable. Enclosures are typically double walled to minimize the potential for contaminant releases.
- *Ventilation and vacuum systems:* ventilation systems use laminar airflow at the dig-face of an excavation and within enclosures to direct dust to high efficiency particulate air (HEPA) filter units. Vacuum systems are used to remove loose particles from equipment and structures and draw in dust and debris generated during excavation activities.
- *Foams, sprays, misters, fixatives and washes:* their application is intended to control odors, volatile organic compounds (VOC), dust and other emissions, creating a barrier between the work surface and the atmosphere, or to aid settling airborne particulates. They are also used in the decontamination of personnel and equipment. The materials selected are non-toxic, non-hazardous, non-flammable and bio-degradable.
- *Electrostatics:* electrically charged plastics and electrostatic curtains can be used to minimize the spread of contamination from enclosed areas. Curtains can be used upstream of emission filtering systems to neutralize charged dust particles.
- *In-situ stabilization:* in-situ stabilization can be performed before initiating excavation operations to control contamination in the soil and waste matrix. Grout, resins or polymers may be injected into wastes or soil to solidify material or sprayed onto the surface to suppress dust generation. Stabilization can also be achieved by in-situ vitrification or ground freezing technologies.

4.3.3.3 Excavation techniques

A number of hand-held tools of specialized designs have been developed to facilitate the retrieval of various waste forms. Designs include grappling devices for waste containers and debris, as well as water jets, magnets and vacuum systems. A summary of potentially available hand-held tools is presented in Table 4.4.

Table 4.4 Description of retrieval equipment

Technology	Description
Remote excavators	
Remotely controlled demolition robots	Remotely controlled excavators with a fully articulated telescopic arm. Available with several different end-tools that can be used for hammering, cutting and scooping wastes. The largest varieties can reach approximately 4 m below the ground surface.
Remotely controlled confined space demolition equipment	Remotely controlled excavators with a telescopic boom capable of moving in three dimensions. Available with several end-tools. The largest

Technology	Description
	Keibler Thompson machine can reach approximately 5 m below the ground surface.
Remotely operated excavator	The excavator is mounted on a wheeled undercarriage that was developed to retrieve unexploded ordnance. A television set provides images for remote control. The only such excavator in existence is currently used at an air force base.
T-Rex® front shovel excavators that require modification for use	Tele-operated, heavy lift, long reach excavators designed to retrieve boxes, drums and containers with a front shovel excavator. Controls can be operated from distances of up to 380 m (1250 ft) from the excavator.
Front end loaders with a bucket of 2 m^3 volume	Front end loaders developed for use by remote control. They provide a three dimensional colour video/audio feedback and can be controlled from distances of up to 500 m. These systems can be modified for use on excavators.
Tele-operated excavators using T-Rex® remote control kits	Remotely controlled excavators (bucket and thumb) adapted for hazardous environments, such as unexploded ordnance (UXO), through sensors, controllers and hydraulic components.
Remotely controlled excavator vehicle system experimental platforms based on excavators	Remotely controlled, tethered platforms for excavators. Attachments can grasp objects, sift soil and make an excavator act as a bulldozer. A clam shell and air jet vacuum system can also be attached.
Automated ordnance excavators	Remotely controlled excavators with extended reach capability, developed for unexploded ordnance (UXO) removal. Can grasp objects such as drums and boxes.
Small emplacement excavators	Military tractors with a front end loader and backhoe remote operation for retrieving buried wastes and soil. Systems can be controlled from distances of up to 800 m.
Remotely controlled excavators, Hitachi excavators, innovative end-effectors and self-guided transport vehicles. Standard excavators with end-effectors (such as buckets, rippers and breakers) used for buried waste retrieval. Systems can be controlled from inside a cab, via a remote tether or from distances of up to 750 m. Modified Bobcats®.	Remotely controlled skid steer loaders with a Bobcat® vehicle base with barrel grapple, sweeper and bucket attachments. Modified for use in hazardous environments, remote kit for other excavators.
Standard construction equipment with modifications	
Sealed and pressurized cabins, with filtered air intakes and extractors	Standard construction equipment with modifications made to the cabins. The sealed and pressurized cabins use filtered air (through high efficiency particulate air filtration).
Sealed and pressurized cabins, with supplied air	Standard construction equipment with modifications made to the cabins. The sealed and pressurized cabins use supplied air.
Remote end-tools	
Safe excavators	High pressure probes dislodge compacted soil, other hardened materials using an air jet/vacuum end-effector system. Vacuums up soil.
Two armed, tethered, hydraulically powered interstitial conveyance systems	Crane deployed with two excavators and vacuums designed for low level radiation fields. Maximum pick-up load of 320 kg.
Highly manipulative tentacles	Tele-operated manipulators and bellows actuators.
Hydraulic impact end-effectors	Water cannons for tank applications; attached to robotic manipulator arm and used to break up monolithic hard cake forming around risers in tanks.
Schilling Tital II®	Manipulators deployed by cranes for selective retrieval. Basic components include a hydraulic system, positioning system, electronics module and mechanical interface.
Mineclaw®	Manipulators with a strong electromagnet to pick up barrels. Custom grapple with a payload of several hundred kilograms and an

Technology	Description
	electromagnet to retrieve metals.
Confined sluicing end effectors	Water jets designed for waste tank clean-up. Use high pressure water jets to cut material into small pieces and evacuate with a vacuum jet pump. Captures slurry water.
Soil skimmers	Skimmers remove soil overburden, for example in 8, 10 or 15 cm increments. Adjustable depth controls determine the depth of cut without disturbing soil underneath.
Innovative end-effectors	These consist of three assemblies: a thumb, an attachable/detachable integrated transfer module and a shovel assembly capable of soil retrieval and dust-free waste dumping.
Quick-change couplers	These are available in manual and hydraulic versions. They are used on various buckets, rakes, clamps, rippers and other end-effectors.
Vacuum systems	Nuclear grade vacuum systems for contamination control and retrieval of soil with high efficiency particulate air (HEPA) filtration and waste containers safe from criticality.

As indicated in Table 4.5 individual criteria of a remediation technique may be evaluated, if data for the technique are available.

Table 4.5 Evaluation of remediation criteria for given technique

Criteria	Quality
Effectiveness in remediating the contamination	
Ease of implementation	
Cost associated with the remediation programme	
Occupational safety and health risks associated with the technology	
Potential secondary environmental impacts (collateral damage)	
Prior experience with the application of the technology	
Socio-economic considerations	

Legend: * low
** medium
*** high

4.3.3.4 Immobilisation and solidification (ex-situ)

A solidification of excavated materials comes usually after excavation. Often the objective is not only to immobilize the contaminants but to add value to the waste material by converting it into a useful product, for example for construction purposes. Use in general construction as a substitute for valuable raw materials requires special testing and licensing procedures to ensure environmental compatibility and compliance with quality criteria such as compressive strength, freeze-thaw cycle stability, leachability, etc. Solidified wastes may also be used in the construction of cappings, etc., for (hazardous waste) landfills. In cases where no further use is envisaged, minimization of the volume increase by the solidification agents is desirable to save valuable raw materials and repository space. If only small volumes arise, the material may be combined with material from other waste streams requiring a similar immobilization treatment. Combining waste streams can make the process more economically viable, as products in marketable quantities are produced [43].

The treatment may be undertaken on or off the site at dedicated facilities. In the case of off-site treatment, the material has to comply with the applicable transport regulations and must meet the appropriate safety criteria while being handled. The additional risk from transporting material must be worked into the respective safety and cost-benefit analyses.

The main conclusion of a recent report on the European perspective of naturally occurring radioactive material (NORM) waste treatment was that immobilization is not widely used or accepted as a treatment. Many companies regard this type of technology as less feasible for naturally occurring radioactive material (NORM) waste material and hence have not pursued the development of immobilization techniques as a waste treatment process. However, for treating the radioactive remainder of a separation step, immobilization is widely seen as a treatment with a high potential [43].

Into this latter classification would also fall ground freezing as a temporary measure to prevent the dispersal of contaminants. Either an impermeable screen around a contamination can be established or the contaminated material itself can be frozen in order to facilitate its handling. In either case, it is unlikely that in the present context of low level dispersed contamination this method would find a field of application [43].

The removal of a contaminated topsoil layer is, of course, the most effective measure, but generates large quantities of waste and is only applicable to small areas of land. Moreover, the most fertile layer of the soil is removed in the process. The overall efficiency of such a measure depends very much on the operating conditions and on the distribution of the contamination in the vicinity of a critical group. In Belarus, the Russian Federation and Ukraine the removal of contaminated topsoil was recommended for all settlements where the ^{137}Cs activity exceeded 555 kBq/m^2 and for 25 - 33 % of settlements where the ^{137}Cs activity was in the range of 370 to 555 kBq/m^2. It was estimated that it would incur costs of about €325 per inhabitant [43].

Containment technologies aim to prevent exposures by isolating contaminants at the site and obstructing migration to surrounding soils and groundwater. Containment technologies are considered when contaminated materials are to be permanently disposed at a site or as a temporary control measure to prevent the spread of contamination. Containment options are considered when extensive subsurface contamination precludes treatment or excavation of the waste [3]. In general, containment technologies are applicable to all forms and types of waste.

4.4 Remediation: evaluation criteria of approaches and techniques

Once measurable remediation objectives have been established, several factors have an impact on the decision making process. These basic evaluation criteria include engineering and non-engineering considerations [7]:

- Effectiveness in remediating the contamination;
- Ease of implementation
- Cost associated with the remediation programme;
- Occupational safety and health risks associated with the technology;
- Potential secondary environmental impacts (collateral damage);
- Prior experience with the application of the technology;
- Socio-economic considerations.

4.4.1 Effectiveness in remediating the contamination

The term ‘effectiveness’ is a measure of the ability of a technology to remove or reduce contaminants to prevent exposure or undue detriment to other properties of the site. There is often a preference amongst regulatory bodies for selecting remedial actions that employ treatment technologies that, as their principal element, permanently and significantly reduce the toxicity, mobility or volume of the hazardous contaminants. Permanent and significant reductions can be achieved through destroying toxic contaminants, reducing total mass, irreversibly reducing the contaminant mobility or reducing the total volume of contaminated media. This criterion focuses the evaluation of an alternative on a variety of specific factors [7]:

- Treatment processes used and materials they treat;
- Amount of hazardous materials destroyed or treated;
- Degree of expected reduction in toxicity, mobility or volume described as a percentage of reduction;
- Degree to which the treatment is irreversible;
- Type and quantity of treatment residuals that remain following treatment;
- Ability of the alternative to satisfy the statutory preference for treatment as a principal element.

Another key objective is often that the remediation should not only improve the situation by eliminating contaminant exposure pathways for health risk but also not be detrimental to the long term environmental qualities of the site. For example, the functionality of soils has to be retained to avoid unnecessary restrictions on future land use.

Another factor to consider in assessing long term effectiveness is the magnitude of the residual risk, i.e., the risk remaining from untreated wastes or treatment residuals remaining after remedial activities have been completed. The characteristics of the residual wastes need to be considered to the degree that they remain hazardous, taking into account their volume, toxicity, mobility and any propensity to bio-accumulate.

The adequacy and reliability of controls, for example, containment systems and institutional controls used to manage the residual risks need to be considered. These include the long term reliability of the management controls necessary for continued protection from residual risk and assessment of the potential needs for maintaining and replacing the technical components of the remedial solution.

Site specific considerations have an impact on the effectiveness and efficiency of the chosen remediation method. Because the mineralogical and geochemical characteristics of the contaminant vary among contaminated sites, remediation methods are not universally effective and efficient. Methods to model and predict the effectiveness of technologies under consideration have been developed. The anticipated performance of a given technique can be simulated and compared with similar results from other techniques to facilitate the selection. The remediation action will be complemented by a post-remediation assessment and monitoring programme to assure its efficacy and that may also be part of any institutional control required on residual contamination.

Steps have already been undertaken to incorporate remediation activities into the ISO 9000 quality management systems. Record keeping is an integral part of quality assurance and quality control. It is essential that records are kept of remedial actions undertaken, so that at any later point in time their performance can be evaluated against that of the original design. Having comprehensive documentation available also facilitates interventions in the case of unsatisfactory performance.

4.4.2 Ease of implementation

An assessment is required of the ease or difficulty of implementing the option. This will involve both technical and administrative/regulatory considerations. The former include difficulties in constructing and operating the process, the likelihood of technical problems during implementation that might lead to delays in schedule, the ease of undertaking additional remedial action, should it be necessary, and the ability to monitor the effectiveness of the remedy. The administrative considerations are in essence project risk factors. They include the ease with which the option can be coordinated with other on-site works, etc., and the potential for new regulatory constraints to develop, for example, uncovering buried historical remains or encountering endangered species. They also include the availability of any required off-site treatment, storage and disposal facilities with sufficient capacity, availability of necessary equipment and specialists as well as provisions to ensure any necessary additional resources, availability of services and materials, and availability of prospective technologies [7].

4.4.3 Cost associated with the remediation programme

The term 'cost' in this section is intended to cover the direct expenditure of funds associated with the remediation technology. This includes the costs for design, construction management, equipment, labour and materials to deploy the technology, licensing the technology, treatability studies, operations and maintenance, monitoring, and disposal of residual wastes. Standard engineering cost principles can be applied to develop cost estimates for remediation technologies [7].

Cost data for a wide variety of remediation techniques are available from various sources. For example, the appendix of a recent IAEA report [45] provides an overview of remediation cost, drawing on national directories, such as the Historical Cost Assessment System (HCAS) in the USA [46] that provide useful material for relative cost assessments of the techniques listed.

Long term monitoring, surveillance and maintenance can be a major cost element. Depending on the time for which institutional control is required, provisions have to be made for funding these activities over periods of decades or even centuries.

In any comparison of technologies, discounted lifetime costs can also be determined for each option using nationally approved procedures, for example, discounted cash flow or net present value calculations, and discount rates. Consideration may also be given to different cash flow-time options, for example, uniform cash flows and low capital costs. The cost of remediation should be commensurate with the added level of protection afforded to the public by its implementation.

The costs associated with remediating a mixed contaminant site are likely to be higher than those for 'simple' sites due to the added complexity and multiple waste streams.

4.4.4 Occupational safety and health risks associated with the technology

The term 'occupational safety and health' in this section is intended to cover the potential hazards and risks to workers involved in implementing the remediation technology [7]. Safety risks may result from accidents during deployment. Health risks may result from workers being exposed to radionuclides and other contaminants. Because the occupational risks of different technologies can vary substantially, these risks may be an important consideration in selecting a technology.

Worker and public health and safety is a critical component of any remediation project and is an essential consideration in developing characterization strategies and choosing a particular remediation option(s). The remediation of a mixed contaminant site is typically complex and requires a significant amount of evaluation. The costs of a remediation project can rise significantly as a result of establishing the necessary health and safety practices.

During a remediation programme at a mixed contaminant site, the health and safety programme will cover all phases where workers and the public are at risk, including site characterization. For example, during the characterization phase, workers may be exposed to toxic chemicals while taking samples and undertaking other field work. As another example, during extraction and treatment of organic contaminants, site workers could become exposed to vapours if working in confined spaces (e.g., in an excavation pit) or through leaks in a soil vapour extraction (SVE) system. Another possibility is that the remediation technique may be subject to an accident that results in a fire, with release of toxic emissions. The types of hazard that might be addressed in a mixed contaminant remediation project include, but are not limited to, radiological, chemical, biological, explosive, industrial, electrical and transportation hazards.

The following steps may be considered in ensuring a proper health and safety programme:

(1) Establish an effective multidisciplinary project team and conduct comprehensive work planning to avoid unsafe operations and work stoppages.

(2) Conduct a hazard characterization and exposure assessment to determine the breadth of the health and safety programme, and the associated cost and impact.

(3) Develop a site specific health and safety plan.

(4) Establish access and hazard controls during the characterization and remediation activities through the application of a hierarchy of access and hazard control methods; this may include, for example, using remote handling equipment, establishing special, enclosed, working areas, or using appropriate levels of personal protective clothing.

(5) Establish place and procedures for decontamination of personnel and equipment.

These elements are commonly accompanied by rigorous training and medical surveillance programmes for the site workers, as well as an emergency preparedness and response plan.

Remediation of a contaminated site involving the removal of large numbers of drums or other packaged wastes may give rise to specific safety concerns. Drums may be corroded and containment not assured. Special attention may need to be given to the risks associated with, for example, mechanical or manual handling, inhalation of contaminated vapour or dust, and fire and explosion hazards. In this respect, the risks associated with chemical, flammable and explosive materials may be greater than those associated with radiological hazards. The remediation of some chemically contaminated sites has already given rise to severe accidents and deaths.

Many remediation projects will involve a wide range of conventional civil engineering activities including:

- Decommissioning and decontamination of buildings;
- Stabilization of excavations;
- Transport and storage of excavated soils;
- Contouring and similar civil engineering activities;
- Excavations;
- Drainage of excavations;
- Sorting of contaminated soils.

These lead to typical building site exposures and hazards such as weather, draughts, dust, fumes, gases, noise and vibration, suspended loads and moving machinery. Some of these may be associated in addition with toxic or radioactive exposures. The toxicity or radioactivity of hazards may be known or unknown in quantity and intensity, and may vary over the project duration.

A variety of precautions can be taken, such as the establishment of safe procedures, technical measures and personal protective measures. Technical measures include, for instance, use of remote handling equipment and enclosed cabins on earth moving equipment, while personal protection measures largely consist of protective clothing and use of respirators. Monitoring of the concentrations of hazardous materials in the various workplace media is an integral part of health and safety measures.

Safe procedures are designed to minimize the handling of hazardous material and to handle it in such a way that a minimum of dispersion occurs. Such procedures also ensure that the organizations and people involved in the remediation project are adequately qualified for the project in hand.

4.4.5 Potential secondary environmental impacts (collateral damage)

The implementation of a remediation project may result in a variety of environmental impacts in addition to those resulting from the contamination itself. When a remediation strategy is selected, the impact of this strategy on the local environment may need to be evaluated (operational safety cases) to determine the net reduction in hazards, i.e., it will not be reasonable to cause more harm as a result of the remediation than by undertaking no remediation at the site. For instance, certain technologies, such as removal of topsoil or soil washing, may remove surface contamination at the cost of destroying the soil ecosystem [7].

Environmental risk involves adverse impacts on ecological receptors located on-site or off-site due to significant disturbance to the site ecosystem and its surroundings as a result of remediation. Impacts to be considered will be:

- Nuisances, for example noise, vibration, dust and traffic;
- Impacts on water resources, for example surface and groundwater contamination;
- Impacts on soils, for example, reduced fertility.

Depending on the size of the site, an area larger than the actual contamination may be required for installations, intermediate storage of wastes, etc. Removal, transport and disposal of residual wastes may result in environmental impacts and risks at locations other than those of the original contamination. There is, for example, little benefit in removing a contaminant that is well fixed on a low volume of soil, only to produce a high volume of aqueous wastes with the contaminant in a soluble or mobile form. In addition, the remediation techniques chosen may generate large quantities of secondary wastes and may pose risks of exposure to the public or operators that exceed the risks of quiescent contamination [7].

Environmental risk arising from the implementation of remedial actions may also extend to possible impacts on natural resources, such as surface water, groundwater, air, geological resources or biological resources. The potential for environmental risk may be an important factor in decision making because some remediation technologies are more likely than others to produce adverse impacts on ecological receptors, including habitat disruption, or to generate damage to natural resources.

4.4.6 Prior experience with the application of the technology

The term ‘prior experience’ in this section is intended to cover the track record associated with implementing the remediation technology at other sites. It can be very useful to know whether the technology has been used successfully in the past. Information about previous deployments is available from a number of sources including vendors, regulatory authorities, professional organizations, internet databases, trade associations and publications.

4.4.7 Socio-economic considerations

The term ‘socio-economic considerations’ in this section is intended to cover political, social and economic factors that may influence the selection of a remediation technology and its application to a site with dispersed radioactive contamination. The legal and institutional framework, prevailing socio-economic boundary conditions and public perceptions can influence the choice and deployment of technologies for remediation of sites with dispersed radioactive contamination. The level of public reassurance generally increases with the degree of intervention and, hence, with the cost of the operation [7].

4.5 Overview of available remediation techniques

In Table 4.6, Table 4.7 and Table 4.8, an overview of available containment and removal remediation techniques is given together with an indication of the groups of substances for which they are suitable. These tables are taken from [7] and combine both techniques for recovering contaminants from soils and groundwater, as well as techniques for concentrating and conditioning contaminants.

In Table 4.6 remediation techniques are sorted according to their planning approach or principle. Principles of removal remediation techniques are divided into 4 groups: physical, chemical, biological and thermal. In Table 4.7 remediation techniques are sorted according to media (groundwater, soil, sludge) the techniques are usable for. In Table 4.8 remediation techniques are sorted according to the radioactive contaminants the techniques are usable for.

It must be emphasized that almost certainly and for almost all practical cases any of the methods and technologies discussed will not 'remediate' a given contamination on its own. Owing to physicochemical properties, behaviour and initial conditions, any one technology will leave behind a certain residual level of contamination. Other remediation technologies, more appropriate and effective for this residual contamination level, will then have to be applied.

Table 4.9 provides an overview of the technologies discussed further in this document.

Table 4.6 Remediation techniques sorted by planning approach or principle

Technology	Medium	Contaminant	Brief characterization	Detailed description	Planning approach or principle
In-situ bioremediation	Soil	Organic compounds	Enzyme activity of natural soil microbes to break down contaminants is stimulated by the injection of nutrient, oxygen (for aerobic microbes) or surfactant containing solutions.	Section 4.5.2.6	Biological removal
Biodegradation	Soil	Organic compounds	The generic process utilized in composting, land farming and other bioremediation processes.	Section 4.5.2.11	Biological removal
Composting	Soil	Organic compounds	Contaminated soil is excavated and placed in specialized facilities. Cellulose, biomass, nutrients and sometimes additional indigenous microbes are added to promote degradation. Specialized bacteria may be added to break down a particular compound.	Section 4.5.2.12	Biological removal
Bioventing	Soil	Organic compounds	In-situ process of injecting air into contaminated soil at an optimal rate, increasing soil O_2 concentration and thereby stimulating the growth of indigenous aerobic bacteria. Low injection rates keep volatilization to a minimum.	Section 4.5.2.6	Biological removal
Ex-situ bioremediation	Soil	Organic compounds	The enzyme activity of natural soil microbes to break down contaminants is stimulated in bioreactors, treatment beds and lagoons by the addition of nutrients, oxygen (for aerobic microbes), surfactant, etc. to soils or surface water and groundwater. The process is similar to composting or sewage treatment.	Section 4.5.2.12	Biological removal
Land farming	Soil	Organic compounds	Once excavated, contaminated soils are spread over a clean area. The soil is aerated by regular turning or tilling to promote biodegradation.	Section 4.5.2.12	Biological removal
Slurry phase bioremediation	Soil and sludge	Organic compounds	An engineered process for treating contaminated soils or sludge that relies upon the mobilization of contaminants to the aqueous phase, where they are susceptible to microbial degradation.	Section 4.5.2.12	Biological removal
Biosorption	Surface water and groundwater	Radionuclides and heavy metals	Certain micro-organisms take up metal ions in their cell walls or on their surface, a process which can be used to concentrate these contaminants. Facilities can be designed as bioreactors or like sewage treatment plants (organic stationary phase).	Section 4.5.2.12	Biological removal
Constructed wetlands	Surface water and groundwater	Radionuclides and heavy metals	Contaminated waters are routed into artificial ‘swamps’, where the metals are taken up by plant tissue. The plants are harvested and incinerated. The resulting ashes are disposed off.	Section 4.5.1.18	Biological removal
Biological wastewater treatment	Surface water and groundwater	Organic compounds (radionuclides and heavy metals)	Biological sewage treatment plants will also destroy certain organic contaminants. Bacterial populations specialized for certain contaminants may be used. The resulting sludge will also contain the majority of radionuclides and heavy metals and can be collected for further treatment.	N/A	Biological removal
Reactive barriers	Groundwater	Organic compounds, heavy metals and radionuclides	This is an in situ method of funnelling the natural or enhanced groundwater flow through a physical barrier containing reactive chemicals (oxidation or precipitation), metal catalysts (redox reactions), bacteria (biodegradation) or adsorbents.	Section 4.5.1.9	Containment

Technology	Medium	Contaminant	Brief characterization	Detailed description	Planning approach or principle
Isolation	Soil	All types	Physical barriers, such as slurry walls or sheet piling, are installed to prevent movement of contaminants.	Sections 4.5.1.1 to 4.5.1.8	Containment
In-situ chemical oxidation	Soil and groundwater	Organic compounds (heavy metals and radionuclides)	The injection of ozone (O_3), hydrogen peroxide (H_2O_2) or chlorine compounds induces a redox reaction that chemically converts contaminants into less toxic compounds. This may reduce the mobility of contaminants throughout a plume.	Section 4.5.1.15	Containment
In-situ solidification	Soil and sludge	Radionuclides and heavy metals	The aim is to lower the mobility of contaminants by injecting binding materials (cement, organic or inorganic polymers) that react with the contaminant, the water and/or the soil to produce a low solubility solid.	Section 4.5.1.10	Containment
Vitrification	Soil and sludge	Radionuclides and heavy metals	The contaminated material is mixed with glass forming constituents and fluxes to produce solid glass blocks or slag-like products.	N/A	Containment
In-situ vitrification (ISV)	Soil and sludge	Radionuclides and heavy metals	Soil is vitrified in situ to immobilize contaminants by applying electrical resistance or inductive melting.	Sections 4.5.1.11 to 4.5.1.14	Containment
Ex-situ solidification	Soil or sludge	Radionuclides and heavy metals (organic compounds)	A low solubility solid is produced from contaminated soil by mixing it with a reactive binder (cement, gypsum, organic or inorganic polymer). The solid material may be disposed off in-situ or at a designated repository.	Section 4.3.3.4	Containment
Biosorption	Surface water and groundwater	Radionuclides and heavy metals	Certain microorganisms take up metal ions in their cell walls or on their surface; the processes involved can be used to concentrate these contaminants. Facilities can be designed as bioreactors or like sewage treatment plants (organic stationary phase).	Section 4.5.2.11	Containment
Ex-situ oxidation	Groundwater	Organic compounds	Organic contaminants are oxidatively destroyed in extracted groundwater by UV irradiation, ozone (O_3) sparging and/or hydrogen peroxide (H_2O_2). Off-gases are generally treated by ozonation.	Section 4.5.2.11	Chemical removal
Ex-situ chemical treatment	Groundwater	Radionuclides and heavy metals (organic compounds)	Ion exchange, precipitation, reverse osmosis, etc. are applied to concentrate contaminants for further conditioning.	Section 4.5.2.11	Chemical removal
Ex-situ dehalogenation	Soil	Halogenated volatile organic compounds	Contaminants in excavated soils are dehalogenated using one of two processes. Base catalysed dehalogenation involves mixing the soils with sodium hydroxide (NaOH) and a catalyst in a rotary kiln. In glycolate dehalogenation, an alkaline polyethylene glycol (APEG) reagent dehalogenates the volatile organic compounds in a batch reactor. The resulting compound from either reaction is either non-hazardous or less toxic.	N/A	Chemical removal
Pump and treat systems	Groundwater	All types	Groundwater is pumped to the surface and treated by a variety of methods. The efficiency depends on the type of contaminant and the concentration.	Section 4.5.2.1	Physical removal
Funnel and gate systems	Groundwater	All types	The pump and treat methods and reactive barriers can be improved by constructing impervious walls, funnelling the water flow towards the well or the reactive barrier.	Section 4.5.1.9	Physical removal

Technology	Medium	Contaminant	Brief characterization	Detailed description	Planning approach or principle
Ex-situ filtration	Groundwater	Radionuclides and heavy metals	Contaminated ground or surface water is passed through a filter column to remove contaminated suspended solids. The resulting filter cake requires further treatment and disposal.	N/A	Physical removal
Membrane separation	Groundwater	Volatile organic compounds	A vapour-air separation method is used that involves the diffusion of volatile organic compounds through a non-porous gas separation membrane.	Section 4.5.2.11	Physical removal
Ex-situ air stripping	Groundwater	Volatile organic compounds and organic compounds	Removes volatiles in pumped surface or groundwater. Stripping towers (e.g., packed columns) have a concurrent flow of gas and liquid. The waste airstream may undergo further treatment by, for example, activated carbon or incineration.	Section 4.5.2.11	Physical removal
Vacuum extraction	Groundwater	Volatile organic compounds	A vacuum created inside a well forces the groundwater to rise, allowing additional groundwater to flow in. Once in the well, the airflow causes some of the trapped volatile contaminants to vaporize, thus enabling the capture of volatile organic compounds through vapour extraction.	Section 4.5.2.10	Physical removal
Free product recovery	Groundwater	Organic compounds	A non-miscible, liquid phase organic compound, either lighter or heavier than the groundwater, is removed by pumping from a defined horizon.	N/A	Physical removal
Air sparging	Groundwater and soil	Volatile organic compounds and organic compounds	A method is used that promotes volatilization of organic compounds by air injection into the saturated zone; also promotes natural aerobic biodegradation.	Section 4.5.2.4	Physical removal
Vapour phase carbon adsorption	Off-gases	Volatile organic compounds and organic compounds	Off-gases collected from ex situ or in situ stripping methods are routed through canisters containing granular activated carbon.	N/A	Physical removal
Physical segregation	Soil	Radionuclides and heavy metals	Often contaminants (including radionuclides) adsorb to fine grain size fractions in the soil. Size fractionation by sieving or flotation may thus result in a much smaller volume of contaminated material to be treated.	Section 4.5.2.11	Physical removal
In-situ soil washing	Soil	All types	This technique consists of flushing contaminated material in situ. It entails the injection and extraction of acidic or basic solutions, with added surfactants, chelates, etc., to dissolve, desorb and remove contaminants.	N/A	Physical removal
Ex-situ soil washing	Soil	All types	This ex-situ technique uses pH controlled solutions with the addition of acids or bases, surfactants or chelates to dissolve, desorb and remove contaminants. Organic solvents may be used for organic contaminants. A preceding size fractionation improves efficiency and reduces the volumes of material to be treated.	Section 4.5.2.11	Physical removal
Soil vapour extraction (SVE)	Soil	Volatile organic compounds	Removes volatile organic compounds from the unsaturated zone by creating a zone of low vapour pressure. Soil vapour extraction is most effective in highly permeable soils.	Section 4.5.2.10	Physical removal
Excavation	Soil and sludge	All types	Contaminated materials are removed from the site and transferred to a designated disposal site. Conditioning may be required before disposal.	Section 4.3.3.1.2	Physical removal

Technology	Medium	Contaminant	Brief characterization	Detailed description	Planning approach or principle
Rhizo-filtration	Groundwater and surface water	Metals and radionuclides	Process goal: contaminant extraction and capture. Plants: sunflowers, Indian mustard and water hyacinth. Status: laboratory and pilot scales.	Section 4.5.2.9	Phyto-remediation
Hydraulic control (plume control)	Groundwater and surface water	Water soluble organic compounds and inorganic compounds	Process goal: contaminant degradation or containment. Plants: hybrid poplars, cottonwood and willow. Status: field demonstrations.	N/A	Phyto-remediation
Phyto-volatilization	Groundwater, soil, sediment and sludge	Chlorinated solvents, phyto-volatilization releases (some inorganic compounds (Se, As and Hg) to air)	Process goal: contaminant extraction from media and release to air. Plants: poplars, alfalfa black locust and Indian mustard. Status: laboratory and field applications.	N/A	Phyto-remediation
Phyto-stabilization	Soil and sediment	As, Cd, Cr, Cu, Hs, Pb and Zn	Process goal: contaminant containment. Plants: Indian mustard, hybrid poplars and grasses. Status: field applications.	Section 4.5.1.17	Phyto-remediation
Phyto-extraction	Soil, sediment and sludge	Metals: Ag, Gd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Zn; Radionuclides: Sr-90, Cs-137, Pu-239, U-238, U-234	Process goal: contaminant extraction and capture. Plants: Indian mustard, pennycress, alyssum, sunflowers and hybrid poplars. Status: laboratory, pilot and field applications.	Section 4.5.2.8	Phyto-remediation
Vegetative cover (evapo-transpiration cover)	Soil, sediment and sludge	Organic and inorganic compounds	Process goal: contaminant containment and erosion control. Plants: poplars and grasses. Status: field applications.	N/A	Phyto-remediation
Rhizo-degradation	Soil, sediment, sludge and groundwater	Organic compound degradation (TPH, PAHsa , pesticides, chlorinated solvents and PCBs)	Process goal: contaminant destruction. Plants: red mulberry, grasses, hybrid poplar, cat's tail and rice. Status: field applications.	N/A	Phyto-remediation
Phyto-degradation	Soil, sediment, sludge, groundwater and surface water	Organic compounds, sludge, chlorinated solvents, groundwater phenols, herbicides and munitions	Process goal: contaminant destruction. Plants: algae, stonewort, hybrid poplars, black willow and bald cypress. Status: field demonstrations.	N/A	Phyto-remediation
Riparian corridors (non-point source control)	Surface water and groundwater	Water soluble organic and inorganic compounds	Process goal: contaminant destruction. Plants: poplars. Status: field applications.	N/A	Phyto-remediation
Thermally enhanced soil vapour extraction	Soil	Volatile organic compounds and organic compounds	Contaminated soil is heated by the injection of hot air or steam, or by electrical resistance or microwave heating, thereby volatilizing contaminants. Off-gases are captured for further treatment.	Section 4.5.2.10	Thermal removal
Catalytic oxidation	Soil	Organic compounds	The use of a catalyst helps to lower the reaction temperature, and thus the	Section 4.5.2.11	Thermal removal

Technology	Medium	Contaminant	Brief characterization	Detailed description	Planning approach or principle
			energy input, for thermal treatment methods.		
Thermal desorption (ex-situ)	Soil and sludge	Volatile organic compounds and organic compounds	Excavated soils and sludges are heated to approximately 425°C (high temperature thermal desorption) or to approximately 200°C (low temperature thermal desorption) in an effort to volatilize organic contaminants. An off-gas treatment system is attached to capture and treat vapour phase contaminants.	Section 4.5.2.11	Thermal removal
Incineration	Soil and sludge	Organic compounds	This process involves the combustion of excavated soils and sludges in, for example, rotary kilns or fluidized bed incinerators for the thermal destruction of contaminants. Often conducted off-site, but also on-site in mobile facilities.	Section 4.5.2.11	Thermal removal
Pyrolysis	Soil and sludge	Organic compounds	This process involves anaerobic thermal decomposition of organic contaminants in excavated soil or sludge.	Section 4.5.2.11	Thermal removal

Table 4.7 Remediation techniques sorted by effective medium

Technology	Medium	Contaminant	Brief characterization	Detailed description	Type of technique
Reactive barriers	Groundwater	Organic compounds, heavy metals and radionuclides	This is an in situ method of funnelling the natural or enhanced groundwater flow through a physical barrier containing reactive chemicals (oxidation or precipitation), metal catalysts (redox reactions), bacteria (biodegradation) or adsorbents.	Section 4.5.1.9	Containment
Ex-situ oxidation	Groundwater	Organic compounds	Organic contaminants are oxidatively destroyed in extracted groundwater by UV irradiation, ozone (O_3) sparging and/or hydrogen peroxide (H_2O_2). Off-gases are generally treated by ozonation.	Section 4.5.2.11	Chemical removal
Ex-situ chemical treatment	Groundwater	Radionuclides and heavy metals (organic compounds)	Ion exchange, precipitation, reverse osmosis, etc. are applied to concentrate contaminants for further conditioning.	Section 4.5.2.11	Chemical removal
Pump and treat systems	Groundwater	All types	Groundwater is pumped to the surface and treated by a variety of methods. The efficiency depends on the type of contaminant and the concentration.	Section 4.5.2.1	Physical removal
Funnel and gate systems	Groundwater	All types	The pump and treat methods and reactive barriers can be improved by constructing impervious walls, funnelling the water flow towards the well or the reactive barrier.	Section 4.5.1.9	Physical removal
Ex-situ filtration	Groundwater	Radionuclides and heavy metals	Contaminated ground or surface water is passed through a filter column to remove contaminated suspended solids. The resulting filter cake requires further treatment and disposal.	N/A	Physical removal
Membrane separation	Groundwater	Volatile organic compounds	A vapour-air separation method is used that involves the diffusion of volatile organic compounds through a non-porous gas separation membrane.	Section 4.5.2.11	Physical removal
Ex-situ air stripping	Groundwater	Volatile organic compounds and organic compounds	Removes volatiles in pumped surface or groundwater. Stripping towers (e.g., packed columns) have a concurrent flow of gas and liquid. The waste airstream may undergo further treatment by, for example, activated carbon or incineration.	Section 4.5.2.11	Physical removal
Vacuum extraction	Groundwater	Volatile organic compounds	A vacuum created inside a well forces the groundwater to rise, allowing additional groundwater to flow in. Once in the well, the airflow causes some of the trapped volatile contaminants to vaporize, thus enabling the capture of volatile organic compounds through vapour extraction.	Section 4.5.2.10	Physical removal
Free product recovery	Groundwater	Organic compounds	A non-miscible, liquid phase organic compound, either lighter or heavier than the groundwater, is removed by pumping from a defined horizon.	N/A	Physical removal
Air sparging	Groundwater and soil	Volatile organic compounds and organic compounds	A method is used that promotes volatilization of organic compounds by air injection into the saturated zone; also promotes natural aerobic biodegradation.	Section 4.5.2.4	Physical removal
Rhizo-filtration	Groundwater and surface water	Metals and radionuclides	Process goal: contaminant extraction and capture. Plants: sunflowers, Indian mustard and water hyacinth. Status: laboratory and pilot scales.	Section 4.5.2.9	Phyto-remediation

Technology	Medium	Contaminant	Brief characterization	Detailed description	Type of technique
Hydraulic control (plume control)	Groundwater and surface water	Water soluble organic compounds and inorganic compounds	Process goal: contaminant degradation or containment. Plants: hybrid poplars, cottonwood and willow. Status: field demonstrations.	N/A	Phyto-remediation
Phyto-volatilization	Groundwater, soil, sediment and sludge	Chlorinated solvents, phyto-volatilization releases (some inorganic compounds (Se, As and Hg) to air)	Process goal: contaminant extraction from media and release to air. Plants: poplars, alfalfa black locust and Indian mustard. Status: laboratory and field applications.	N/A	Phyto-remediation
Vapour phase carbon adsorption	Off-gases	Volatile organic compounds and organic compounds	Off-gases collected from ex situ or in situ stripping methods are routed through canisters containing granular activated carbon.	N/A	Physical removal
In-situ bioremediation	Soil	Organic compounds	Enzyme activity of natural soil microbes to break down contaminants is stimulated by the injection of nutrient, oxygen (for aerobic microbes) or surfactant containing solutions.	Section 4.5.2.6	Biological removal
Biodegradation	Soil	Organic compounds	The generic process utilized in composting, landfarming and other bioremediation processes.	Section 4.5.2.11	Biological removal
Composting	Soil	Organic compounds	Contaminated soil is excavated and placed in specialized facilities. Cellulose, biomass, nutrients and sometimes additional indigenous microbes are added to promote degradation. Specialized bacteria may be added to break down a particular compound.	Section 4.5.2.12	Biological removal
Bioventing	Soil	Organic compounds	In-situ process of injecting air into contaminated soil at an optimal rate, increasing soil O_2 concentration and thereby stimulating the growth of indigenous aerobic bacteria. Low injection rates keep volatilization to a minimum.	Section 4.5.2.6	Biological removal
Ex-situ bioremediation	Soil	Organic compounds	The enzyme activity of natural soil microbes to break down contaminants is stimulated in bioreactors, treatment beds and lagoons by the addition of nutrients, oxygen (for aerobic microbes), surfactant, etc. to soils or surface water and groundwater. The process is similar to composting or sewage treatment.	Section 4.5.2.12	Biological removal
Land farming	Soil	Organic compounds	Once excavated, contaminated soils are spread over a clean area. The soil is aerated by regular turning or tilling to promote biodegradation.	Section 4.5.2.12	Biological removal
Isolation	Soil	All types	Physical barriers, such as slurry walls or sheet piling, are installed to prevent movement of contaminants.	Sections 4.5.11 to 4.5.1.8	Containment
Physical segregation	Soil	Radionuclides and heavy metals	Often contaminants (including radionuclides) adsorb to fine grain size fractions in the soil. Size fractionation by sieving or flotation may thus result in a much smaller volume of contaminated material to be treated.	Section 4.5.2.11	Physical removal
In-situ soil washing	Soil	All types	This technique consists of flushing contaminated material in situ. It entails the injection and extraction of acidic or basic solutions, with added surfactants, chelates, etc., to dissolve, desorb and remove contaminants.	N/A	Physical removal

Technology	Medium	Contaminant	Brief characterization	Detailed description	Type of technique
Ex-situ soil washing	Soil	All types	This ex-situ technique uses pH controlled solutions with the addition of acids or bases, surfactants or chelates to dissolve, desorb and remove contaminants. Organic solvents may be used for organic contaminants. A preceding size fractionation improves efficiency and reduces the volumes of material to be treated.	Section 4.5.2.11	Physical removal
Soil vapour extraction (SVE)	Soil	Volatile organic compounds	Removes volatile organic compounds from the unsaturated zone by creating a zone of low vapour pressure. Soil vapour extraction is most effective in highly permeable soils.	Section 4.5.2.10	Physical removal
Thermally enhanced soil vapour extraction	Soil	Volatile organic compounds and organic compounds	Contaminated soil is heated by the injection of hot air or steam, or by electrical resistance or microwave heating, thereby volatilizing contaminants. Off-gases are captured for further treatment.	Section 4.5.2.10	Thermal removal
Catalytic oxidation	Soil	Organic compounds	The use of a catalyst helps to lower the reaction temperature, and thus the energy input, for thermal treatment methods.	Section 4.5.2.11	Thermal removal
Ex-situ dehalogenation	Soil	Halogenated volatile organic compounds	Contaminants in excavated soils are dehalogenated using one of two processes. Base catalysed dehalogenation involves mixing the soils with sodium hydroxide (NaOH) and a catalyst in a rotary kiln. In glycolate dehalogenation, an alkaline polyethylene glycol (APEG) reagent dehalogenates the volatile organic compounds in a batch reactor. The resulting compound from either reaction is either non-hazardous or less toxic.	N/A	Chemical removal
In-situ chemical oxidation	Soil and groundwater	Organic compounds (heavy metals and radionuclides)	The injection of ozone (O_3), hydrogen peroxide (H_2O_2) or chlorine compounds induces a redox reaction that chemically converts contaminants into less toxic compounds. This may reduce the mobility of contaminants throughout a plume.	Section 4.5.1.15	Containment
Phyto-stabilization	Soil and sediment	As, Cd, Cr, Cu, Hs, Pb and Zn	Process goal: contaminant containment. Plants: Indian mustard, hybrid poplars and grasses. Status: field applications.	Section 4.5.1.17	Phyto-remediation
Slurry phase bioremediation	Soil and sludge	Organic compounds	An engineered process for treating contaminated soils or sludge that relies upon the mobilization of contaminants to the aqueous phase, where they are susceptible to microbial degradation.	Section 4.5.2.12	Biological removal
In-situ solidification	Soil and sludge	Radionuclides and heavy metals	The aim is to lower the mobility of contaminants by injecting binding materials (cement, organic or inorganic polymers) that react with the contaminant, the water and/or the soil to produce a low solubility solid.	Section 4.5.1.10	Containment
Vitrification	Soil and sludge	Radionuclides and heavy metals	The contaminated material is mixed with glass forming constituents and fluxes to produce solid glass blocks or slag-like products.	N/A	Containment
In-situ vitrification (ISV)	Soil and sludge	Radionuclides and heavy metals	Soil is vitrified in situ to immobilize contaminants by applying electrical resistance or inductive melting.	Section 4.5.1.11 to 4.5.1.14	Containment
Excavation	Soil and sludge	All types	Contaminated materials are removed from the site and transferred to a designated disposal site. Conditioning may be required before disposal.	Section 4.3.3.1.2	Physical removal

Technology	Medium	Contaminant	Brief characterization	Detailed description	Type of technique
Thermal desorption (ex-situ)	Soil and sludge	Volatile organic compounds and organic compounds	Excavated soils and sludges are heated to approximately 425°C (high temperature thermal desorption) or to approximately 200°C (low temperature thermal desorption) in an effort to volatilize organic contaminants. An off-gas treatment system is attached to capture and treat vapour phase contaminants.	Section 4.5.2.11	Thermal removal
Incineration	Soil and sludge	Organic compounds	This process involves the combustion of excavated soils and sludges in, for example, rotary kilns or fluidized bed incinerators for the thermal destruction of contaminants. Often conducted off-site, but also on-site in mobile facilities.	Section 4.5.2.11	Thermal removal
Pyrolysis	Soil and sludge	Organic compounds	This process involves anaerobic thermal decomposition of organic contaminants in excavated soil or sludge.	Section 4.5.2.11	Thermal removal
Ex-situ solidification	Soil or sludge	Radionuclides and heavy metals (organic compounds)	A low solubility solid is produced from contaminated soil by mixing it with a reactive binder (cement, gypsum, organic or inorganic polymer). The solid material may be disposed off in situ or at a designated repository.	Section 4.3.3.4	Containment
Phyto-extraction	Soil, sediment and sludge	Metals: Ag, Gd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Zn; Radionuclides: Sr-90, Cs-137, Pu-239, U-238, U-234	Process goal: contaminant extraction and capture. Plants: Indian mustard, pennycress, alyssum, sunflowers and hybrid poplars. Status: laboratory, pilot and field applications.	Section 4.5.2.8	Phyto-remediation
Vegetative cover (evapo-transpiration cover)	Soil, sediment and sludge	Organic and inorganic compounds	Process goal: contaminant containment and erosion control. Plants: poplars and grasses. Status: field applications.	N/A	Phyto-remediation
Rhizo-degradation	Soil, sediment, sludge and groundwater	Organic compound degradation (TPH, PAHsa , pesticides, chlorinated solvents and PCBs)	Process goal: contaminant destruction. Plants: red mulberry, grasses, hybrid poplar, cat's tail and rice. Status: field applications.	N/A	Phyto-remediation
Phyto-degradation	Soil, sediment, sludge, groundwater and surface water	Organic compounds, sludge, chlorinated solvents, groundwater phenols, herbicides and munitions	Process goal: contaminant destruction. Plants: algae, stonewort, hybrid poplars, black willow and bald cypress. Status: field demonstrations.	N/A	Phyto-remediation
Biosorption	Surface water and groundwater	Radionuclides and heavy metals	Certain micro-organisms take up metal ions in their cell walls or on their surface, a process which can be used to concentrate these contaminants. Facilities can be designed as bioreactors or like sewage treatment plants (organic stationary phase).	Section 4.5.2.12	Biological removal
Constructed wetlands	Surface water and groundwater	Radionuclides and heavy metals	Contaminated waters are routed into artificial 'swamps', where the metals are taken up by plant tissue. The plants are harvested and incinerated. The resulting ashes are disposed off.	Section 4.5.1.18	Biological removal

Technology	Medium	Contaminant	Brief characterization	Detailed description	Type of technique
Biological wastewater treatment	Surface water and groundwater	Organic compounds (radionuclides and heavy metals)	Biological sewage treatment plants will also destroy certain organic contaminants. Bacterial populations specialized for certain contaminants may be used. The resulting sludge will also contain the majority of radionuclides and heavy metals and can be collected for further treatment.	N/A	Biological removal
Biosorption	Surface water and groundwater	Radionuclides and heavy metals	Certain microorganisms take up metal ions in their cell walls or on their surface; the processes involved can be used to concentrate these contaminants. Facilities can be designed as bioreactors or like sewage treatment plants (organic stationary phase).	Section 4.5.2.11	Containment
Riparian corridors (non-point source control)	Surface water and groundwater	Water soluble organic and inorganic compounds	Process goal: contaminant destruction. Plants: poplars. Status: field applications.	N/A	Phyto-remediation

Table 4.8 Remediation techniques sorted by radioactive contaminant

Technology	Medium	Contaminant	Brief characterization	Detailed description	Type of technique
Isolation	Soil	All types	Physical barriers, such as slurry walls or sheet piling, are installed to prevent movement of contaminants.	Section 4.5.1.1 to 4.5.1.8	Containment
Excavation	Soil and sludge	All types	Contaminated materials are removed from the site and transferred to a designated disposal site. Conditioning may be required before disposal.	Section 4.3.3.1.2	Physical removal
Ex-situ soil washing	Soil	All types	This ex-situ technique uses pH controlled solutions with the addition of acids or bases, surfactants or chelates to dissolve, desorb and remove contaminants. Organic solvents may be used for organic contaminants. A preceding size fractionation improves efficiency and reduces the volumes of material to be treated.	Section 4.5.2.11	Physical removal
Funnel and gate systems	Groundwater	All types	The pump and treat methods and reactive barriers can be improved by constructing impervious walls, funnelling the water flow towards the well or the reactive barrier.	Section 4.5.1.9	Physical removal
In-situ soil washing	Soil	All types	This technique consists of flushing contaminated material in situ. It entails the injection and extraction of acidic or basic solutions, with added surfactants, chelates, etc., to dissolve, desorb and remove contaminants.	N/A	Physical removal
Pump and treat systems	Groundwater	All types	Groundwater is pumped to the surface and treated by a variety of methods. The efficiency depends on the type of contaminant and the concentration.	Section 4.5.2.1	Physical removal
Phyto-stabilization	Soil and sediment	As, Cd, Cr, Cu, Hs, Pb and Zn	Process goal: contaminant containment. Plants: Indian mustard, hybrid poplars and grasses. Status: field applications.	Section 4.5.1.17	Phyto-remediation
Ex-situ dehalogenation	Soil	Halogenated volatile organic compounds	Contaminants in excavated soils are dehalogenated using one of two processes. Base catalysed dehalogenation involves mixing the soils with sodium hydroxide (NaOH) and a catalyst in a rotary kiln. In glycolate dehalogenation, an alkaline polyethylene glycol (APEG) reagent dehalogenates the volatile organic compounds in a batch reactor. The resulting compound from either reaction is either non-hazardous or less toxic.	N/A	Chemical removal
Phyto-volatilization	Groundwater, soil, sediment and sludge	Chlorinated solvents, phyto-volatilization releases (some inorganic compounds (Se, As and Hg) to air)	Process goal: contaminant extraction from media and release to air. Plants: poplars, alfalfa black locust and Indian mustard. Status: laboratory and field applications.	N/A	Phyto-remediation
Rhizo-filtration	Groundwater and surface water	Metals and radionuclides	Process goal: contaminant extraction and capture. Plants: sunflowers, Indian mustard and water hyacinth. Status: laboratory and pilot scales.	Section 4.5.2.9	Phyto-remediation

Technology	Medium	Contaminant	Brief characterization	Detailed description	Type of technique
Phyto-extraction	Soil, sediment and sludge	Metals: Ag, Gd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Zn; Radionuclides: Sr-90, Cs-137, Pu-239, U-238, U-234	Process goal: contaminant extraction and capture. Plants: Indian mustard, pennycress, alyssum, sunflowers and hybrid poplars. Status: laboratory, pilot and field applications.	Section 4.5.2.8	Phyto-remediation
Vegetative cover (evapo-transpiration cover)	Soil, sediment and sludge	Organic and inorganic compounds	Process goal: contaminant containment and erosion control. Plants: poplars and grasses. Status: field applications.	N/A	Phyto-remediation
Rhizo-degradation	Soil, sediment, sludge and groundwater	Organic compound degradation (TPH, PAHsa , pesticides, chlorinated solvents and PCBs)	Process goal: contaminant destruction. Plants: red mulberry, grasses, hybrid poplar, cat's tail and rice. Status: field applications.	N/A	Phyto-remediation
Biodegradation	Soil	Organic compounds	The generic process utilized in composting, land farming and other bioremediation processes.	Section 4.5.2.11	Biological removal
Bioventing	Soil	Organic compounds	In-situ process of injecting air into contaminated soil at an optimal rate, increasing soil O_2 concentration and thereby stimulating the growth of indigenous aerobic bacteria. Low injection rates keep volatilization to a minimum.	Section 4.5.2.6	Biological removal
Composting	Soil	Organic compounds	Contaminated soil is excavated and placed in specialized facilities. Cellulose, biomass, nutrients and sometimes additional indigenous microbes are added to promote degradation. Specialized bacteria may be added to break down a particular compound.	Section 4.5.2.12	Biological removal
Ex-situ bioremediation	Soil	Organic compounds	The enzyme activity of natural soil microbes to break down contaminants is stimulated in bioreactors, treatment beds and lagoons by the addition of nutrients, oxygen (for aerobic microbes), surfactant, etc. to soils or surface water and groundwater. The process is similar to composting or sewage treatment.	Section 4.5.2.12	Biological removal
In-situ bioremediation	Soil	Organic compounds	Enzyme activity of natural soil microbes to break down contaminants is stimulated by the injection of nutrient, oxygen (for aerobic microbes) or surfactant containing solutions.	Section 4.5.2.6	Biological removal
Land farming	Soil	Organic compounds	Once excavated, contaminated soils are spread over a clean area. The soil is aerated by regular turning or tilling to promote biodegradation.	Section 4.5.2.12	Biological removal
Slurry phase bioremediation	Soil and sludge	Organic compounds	An engineered process for treating contaminated soils or sludge that relies upon the mobilization of contaminants to the aqueous phase, where they are susceptible to microbial degradation.	Section 4.5.2.12	Biological removal
Ex-situ oxidation	Groundwater	Organic compounds	Organic contaminants are oxidatively destroyed in extracted groundwater by UV irradiation, ozone (O_3) sparging and/or hydrogen peroxide (H_2O_2). Off-gases are generally treated by ozonation.	Section 4.5.2.11	Chemical removal

Technology	Medium	Contaminant	Brief characterization	Detailed description	Type of technique
Free product recovery	Groundwater	Organic compounds	A non-miscible, liquid phase organic compound, either lighter or heavier than the groundwater, is removed by pumping from a defined horizon.	N/A	Physical removal
Catalytic oxidation	Soil	Organic compounds	The use of a catalyst helps to lower the reaction temperature, and thus the energy input, for thermal treatment methods.	Section 4.5.2.11	Thermal removal
Incineration	Soil and sludge	Organic compounds	This process involves the combustion of excavated soils and sludges in, for example, rotary kilns or fluidized bed incinerators for the thermal destruction of contaminants. Often conducted off-site, but also on-site in mobile facilities.	Section 4.5.2.11	Thermal removal
Pyrolysis	Soil and sludge	Organic compounds	This process involves anaerobic thermal decomposition of organic contaminants in excavated soil or sludge.	Section 4.5.2.11	Thermal removal
In-situ chemical oxidation	Soil and groundwater	Organic compounds (heavy metals and radionuclides)	The injection of ozone (O_3), hydrogen peroxide (H_2O_2) or chlorine compounds induces a redox reaction that chemically converts contaminants into less toxic compounds. This may reduce the mobility of contaminants throughout a plume.	Section 4.5.1.15	Containment
Biological wastewater treatment	Surface water and groundwater	Organic compounds (radionuclides and heavy metals)	Biological sewage treatment plants will also destroy certain organic contaminants. Bacterial populations specialized for certain contaminants may be used. The resulting sludge will also contain the majority of radionuclides and heavy metals and can be collected for further treatment.	N/A	Biological removal
Reactive barriers	Groundwater	Organic compounds, heavy metals and radionuclides	This is an in situ method of funnelling the natural or enhanced groundwater flow through a physical barrier containing reactive chemicals (oxidation or precipitation), metal catalysts (redox reactions), bacteria (biodegradation) or adsorbents.	Section 4.5.1.9	Containment
Phyto-degradation	Soil, sediment, sludge, groundwater and surface water	Organic compounds, sludge, chlorinated solvents, groundwater phenols, herbicides and munitions	Process goal: contaminant destruction. Plants: algae, stonewort, hybrid poplars, black willow and bald cypress. Status: field demonstrations.	N/A	Phyto-remediation
Biosorption	Surface water and groundwater	Radionuclides and heavy metals	Certain microorganisms take up metal ions in their cell walls or on their surface, a process which can be used to concentrate these contaminants. Facilities can be designed as bioreactors or like sewage treatment plants (organic stationary phase).	Section 4.5.2.12	Biological removal
Constructed wetlands	Surface water and groundwater	Radionuclides and heavy metals	Contaminated waters are routed into artificial ‘swamps’, where the metals are taken up by plant tissue. The plants are harvested and incinerated. The resulting ashes are disposed off.	Section 4.5.1.18	Biological removal
Biosorption	Surface water and groundwater	Radionuclides and heavy metals	Certain micro-organisms take up metal ions in their cell walls or on their surface; the processes involved can be used to concentrate these contaminants. Facilities can be designed as bioreactors or like sewage treatment plants (organic stationary phase).	Section 4.5.2.11	Containment

Technology	Medium	Contaminant	Brief characterization	Detailed description	Type of technique
In-situ solidification	Soil and sludge	Radionuclides and heavy metals	The aim is to lower the mobility of contaminants by injecting binding materials (cement, organic or inorganic polymers) that react with the contaminant, the water and/or the soil to produce a low solubility solid.	Section 4.5.1.10	Containment
In-situ vitrification (ISV)	Soil and sludge	Radionuclides and heavy metals	Soil is vitrified in situ to immobilize contaminants by applying electrical resistance or inductive melting.	Sections 4.5.1.11 to 4.5.1.14	Containment
Vitrification	Soil and sludge	Radionuclides and heavy metals	The contaminated material is mixed with glass forming constituents and fluxes to produce solid glass blocks or slag-like products.	N/A	Containment
Ex-situ filtration	Groundwater	Radionuclides and heavy metals	Contaminated ground or surface water is passed through a filter column to remove contaminated suspended solids. The resulting filter cake requires further treatment and disposal.	N/A	Physical removal
Physical segregation	Soil	Radionuclides and heavy metals	Often contaminants (including radionuclides) adsorb to fine grain size fractions in the soil. Size fractionation by sieving or flotation may thus result in a much smaller volume of contaminated material to be treated.	Section 4.5.2.11	Physical removal
Ex-situ solidification	Soil or sludge	Radionuclides and heavy metals (organic compounds)	A low solubility solid is produced from contaminated soil by mixing it with a reactive binder (cement, gypsum, organic or inorganic polymer). The solid material may be disposed off in situ or at a designated repository.	Section 4.3.3.4	Containment
Ex-situ chemical treatment	Groundwater	Radionuclides and heavy metals (organic compounds)	Ion exchange, precipitation, reverse osmosis, etc. are applied to concentrate contaminants for further conditioning.	Section 4.5.2.11	Chemical removal
Membrane separation	Groundwater	Volatile organic compounds	A vapour-air separation method is used that involves the diffusion of volatile organic compounds through a non-porous gas separation membrane.	Section 4.5.2.11	Physical removal
Soil vapour extraction (SVE)	Soil	Volatile organic compounds	Removes volatile organic compounds from the unsaturated zone by creating a zone of low vapour pressure. Soil vapour extraction is most effective in highly permeable soils.	Section 4.5.2.10	Physical removal
Vacuum extraction	Groundwater	Volatile organic compounds	A vacuum created inside a well forces the groundwater to rise, allowing additional groundwater to flow in. Once in the well, the airflow causes some of the trapped volatile contaminants to vaporize, thus enabling the capture of volatile organic compounds through vapour extraction.	Section 4.5.2.10	Physical removal
Air sparging	Groundwater and soil	Volatile organic compounds and organic compounds	A method is used that promotes volatilization of organic compounds by air injection into the saturated zone; also promotes natural aerobic biodegradation.	Section 4.5.2.4	Physical removal
Ex-situ air stripping	Groundwater	Volatile organic compounds and organic compounds	Removes volatiles in pumped surface or groundwater. Stripping towers (e.g., packed columns) have a concurrent flow of gas and liquid. The waste airstream may undergo further treatment by, for example, activated carbon or incineration.	Section 4.5.2.11	Physical removal
Vapour phase carbon adsorption	Off-gases	Volatile organic compounds and organic compounds	Off-gases collected from ex situ or in situ stripping methods are routed through canisters containing granular activated carbon.	N/A	Physical removal

Technology	Medium	Contaminant	Brief characterization	Detailed description	Type of technique
Thermal desorption (ex-situ)	Soil and sludge	Volatile organic compounds and organic compounds	Excavated soils and sludges are heated to approximately 425°C (high temperature thermal desorption) or to approximately 200°C (low temperature thermal desorption) in an effort to volatilize organic contaminants. An off-gas treatment system is attached to capture and treat vapour phase contaminants.	Section 4.5.2.11	Thermal removal
Thermally enhanced soil vapour extraction	Soil	Volatile organic compounds and organic compounds	Contaminated soil is heated by the injection of hot air or steam, or by electrical resistance or microwave heating, thereby volatilizing contaminants. Off-gases are captured for further treatment.	Section 4.5.2.10	Thermal removal
Riparian corridors (non-point source control)	Surface water and groundwater	Water soluble organic and inorganic compounds	Process goal: contaminant destruction. Plants: poplars. Status: field applications.	N/A	Phyto-remediation
Hydraulic control (plume control)	Groundwater and surface water	Water soluble organic compounds and inorganic compounds	Process goal: contaminant degradation or containment. Plants: hybrid poplars, cottonwood and willow. Status: field demonstrations.	N/A	Phyto-remediation

Table 4.9 Overview of the technologies discussed in this document

Containment technologies

- Subsurface barriers
- Bored piles
- Slurry walls or trenches
- Keyed rammed piles
- Sheet piles
- Injection walls
- Injection curtains
- Ground freezing
- Permeable reactive barriers
- Immobilisation/solidification
    - Chemical immobilization
    - Bio-chemical or biological immobilisation
    - Thermal immobilisation
- In-situ vitrification
- Traditional in-situ vitrification
- Planar in-situ vitrification
- Plasma arc in-situ vitrification
- In-situ chemical oxidation
- Biological barrier walls (bio-walls)
- Phyto-stabilisation
- Constructed wetlands
    - Free water surface systems, or soil substrate systems
    - Subsurface flow systems
    - Aquatic plant systems

Removal of the source term

- Pump and treat for surface water and groundwater
- Enhanced recovery
- Enhanced recovery chemical agent methods
    - Displacement by inert electrolytes
    - Co-solvent solubilization
    - Surfactants and micro-emulsions
        - Micellar solubilization
        - Mobilization
- Enhanced recovery physical methods
    - Hydraulic and pneumatic fracturing
    - Air sparging and venting
    - In-well aeration
- In-situ treatment for contaminant destruction and removal
- In-situ biological remediation
- Phyto-remediation
- Phyto-extraction treatment
    - Overview
    - Uranium removal
    - Strontium removal
    - Caesium removal
    - Phyto-extraction project in Belarus
- Rhizo-filtration treatment
- Non-biological in-situ treatment
    - Dynamic Underground Stripping and Hydrous Pyrolysis Oxidation
    - Soil Vapour Extraction
    - Thermal Methods
        - Electrical resistance heating

- Microwave heating
- Thermal Conductance

- Ex-situ treatment
  - Physical ex-situ techniques
    - * Physical segregation
    - * Segmented Gate Systems
    - * Soil Washing
  - Chemical ex-situ techniques
    - * Chemical/solvent extraction
    - * Heap leaching
    - * Enhanced soil washing
    - * Chemical precipitation
    - * Ion exchange
    - * Adsorption
    - * Aeration
    - * Ozonation and peroxide application
  - Biological ex-situ techniques
    - * Land-farming and bio-piles
    - * Bio-reactors
    - * Bio-leaching
    - * Bio-sorption
  - Thermal ex-situ techniques
    - * Distillation
    - * Incineration
    - * Pyrolysis
    - * Thermal desorption
    - * Fluid bed steam reforming

4.5.1 Containment

4.5.1.1 Subsurface barriers

Underground containment barriers are an important method for limiting or preventing the movement of radiological and non-radiological contaminants into the surrounding geological media and groundwater. In the past, containment has been used primarily at sites where there was no other efficient and cost effective option. However, subsurface barriers can be used in any number of situations where it is necessary to prevent the migration of contamination. Barriers are currently used, for instance as an interim step, while final remediation alternatives are being developed (or considered) in conjunction with other treatment techniques, e.g., reactive barriers. In many instances subsurface barriers are capable of effectively confining the contaminant for extended time periods in a cost effective way.

There are many subsurface barrier technologies commercially available and others are at various stages of development. The purpose and function of the containment system must be determined prior to designing and constructing the barrier. Site characterization is an essential part of choosing an appropriate barrier. Some of the factors that may need to be considered when designing a subsurface barrier are [7]:

- It is important to establish the barrier placement criteria, including location, depth and thickness.
- A stress-deformation analysis needs to be performed on the surrounding area in order to assess the potential impacts of barrier construction.
- A compatibility test needs to be performed to select the most effective barrier materials and, when necessary, appropriate mixture combinations.
- It is necessary to determine the most effective and feasible construction methods.

- Construction quality assurance/quality control is a crucial component of subsurface barrier emplacement.

Different types of subsurface barrier have different construction quality assurance criteria; however, there are two primary concerns. First, the installed barrier must have a hydraulic conductivity equal to or less than that specified in the design. The second concern is barrier continuity, which is difficult to assess; the methods available have had varying degrees of success. There is currently no method of guaranteeing the continuity of a subsurface barrier [7]. Discontinuities may occur during grout application/installation and joint formation. Cracking due to curing, settling or wet/dry cycling may occur over time. Proper emplacement of a subsurface barrier is critical in ensuring the overall effectiveness of the containment system. Once a barrier has been installed, verification and monitoring are crucial. At this time, there is no uniform method for monitoring the emplacement, long term performance or integrity of the barrier.

The construction of subsurface barriers can be grouped into three basic technologies:

(1) Replacement of excavated materials with materials of lower permeability;

(2) Displacement with materials of lower permeability;

(3) Reduction of the permeability of the soil (Figure 4.5).

Impermeable liners made with clays or cement and clay mixtures are widely used in the construction of new landfills. Clay is subject to chemical attack by leachates from the waste material that can degrade the barrier and lead to increased infiltration and contaminant dispersal. Proper moisture content must be maintained to prevent shrinkage cracks in the clay. The development of new barrier concepts, materials and construction techniques is in the process of overcoming these deficiencies, however. The long term stability and effectiveness of new synthetic binders and polymers as sealants is being evaluated. Inorganic grouts are also being studied for use with or without clays.

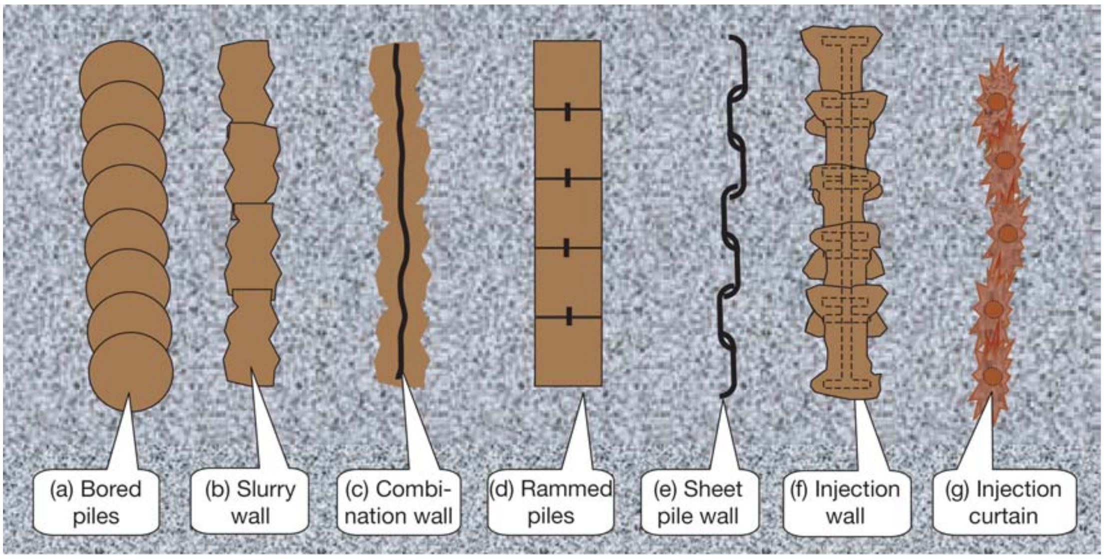


Figure 4.5 Various containment construction techniques

4.5.1.2 Bored piles

Bored piles are a series of overlapping large size boreholes displayed in Figure 4.5 part (a). Rotary drilling equipment, soil mixers or line shaft excavators may be used. The boreholes are backfilled with a cement grout or concrete before the next hole in the row is drilled. Depending on the cement and aggregate used, nearly complete sealing can be achieved. Depths of several tens of metres can be reached. In principle the technique can be applied to many types of soil and rock, but the cost increases with the hardness of the material. Very inhomogeneous soils, containing boulders for instance, may prevent successful application. The technique may be combined with that of slurry walls.

4.5.1.3 Slurry walls or trenches

Slurry walls or trenches as displayed in Figure 4.5 part (b) are constructed by excavating a vertical trench around waste areas to a depth that is at or below the bottom elevations of contaminated soil or waste materials. Trench stability is maintained by placing a liquid slurry of bentonite and water in the trench as excavation progresses. When the trench reaches the proposed maximum depth, the slurry is displaced from the bottom upwards with a dense barrier material consisting of soil bentonite, cement grout, polymers, plastic concrete or other low permeability materials. Using a continuous trenching construction method (see also Figure 4.8), cavities for slurry walls can be continuously excavated with a backhoe or excavator, filled with slurry, and backfilled with low permeability material until the waste disposal areas are completely encircled. Slurry walls can be excavated to depths of more than 30 m and can have permeabilities as low as 10^{-8} to 10^{-9} $m.s^{-1}$.

This technique is easiest to apply in sand and gravel formations and to a certain extent to cohesive materials, such as clays. It is more difficult to implement in hard rocks. Amendments can be added to the injected grouts that will act as additional sorbents for contaminants such as heavy metals and radionuclides. Slurry walls may also be combined with a plastic membrane to form combination walls displayed in Figure 4.5 part (c).

4.5.1.4 Keyed rammed piles

Prefabricated concrete piles may be rammed into the ground using a pile driver. In order to ensure water tightness, they are interlocked with slots and keys, see Figure 4.5 part (d). The applicability of this technique is largely restricted to unconsolidated or weakly consolidated sediments without large boulders.

4.5.1.5 Sheet piles

Sheet piling consists of vertical cut-off walls constructed by driving strips of steel, precast concrete, aluminium or wood into the soil. Sheet metal piling, which are corrugated sheets of iron that are shaped in such a way that they interlock (Figure 4.5 part (e)) with sealable joints, is commonly used. Interlocking sheets are assembled before installation and driven or vibrated into the ground by about a metre at a time until the desired depth is achieved. Sheets are sealed by injecting grout into the joints between the metal sheet piles. Continuous sheet piling walls can potentially be driven to depths of some 90 m in unconsolidated deposits lacking boulders. Bulk hydraulic conductivities of 10^{-8} to 10^{-10} $cm.s^{-1}$ have been achieved in test cells constructed of joint sealed sheet piles.

4.5.1.6 Injection walls

An I-shaped pile is driven into the ground and upon extraction the remaining hollow space is backfilled with a bentonite or cement-bentonite slurry, see Figure 4.5 part (f). Each section overlaps with the preceding one to provide good keying in and water tightness.

4.5.1.7 Injection curtains

Injection curtains are constructed by pushing hollow injection tubes into the ground (unconsolidated materials) or by drilling injection boreholes (rocks), see Figure 4.5 part (g). A variety of inorganic and organic grouts may be injected to fill the pore space of the soils or rocks. Typical inorganic grouts are ordinary Portland cement (OPC), bentonite and water glass. The organic grouts used in civil engineering applications include polymers of methacrylate and epoxy resin. The possible interaction of organic grouts with organic contaminants has to be carefully studied before application, as the contaminants may lead to a dissolution or breakdown of the sealing components, or may prevent polymerization. The technique, in principle, is applicable to all types of soils and rocks. The sealing success depends very much on the homogeneity of the permeability distribution. Preferential pathways may lead to incomplete sealing. Some geological formations may have a too low permeability for injection, but still provide long term migration pathways. In such a case hydro-fracturing allows successful creation of injection curtains. To this end, sand, zirconia or other high strength spherical materials are injected under very high pressure to 'fracture' the rocks. Spherical materials stabilize the open fracture while providing a high permeability infill that allows injection of the actual grout. In addition to providing a hydraulic sealant, injected grouts can also act as sorbents for contaminants. This effect may be less effective for organic contaminants than for metals, including radionuclides.

A variant of injection curtains is the injection of non-miscible fluids with the intention to reduce water permeability. In recent times the effect on water permeability of injecting bio-degradable oils has been explored [7].

4.5.1.8 Ground freezing

Temporary containment can be achieved by a variety of measures, including grouting and ground freezing. Either an impermeable screen around a contamination can be established or the contaminated material itself can be frozen in order to facilitate its handling or excavation. Artificial ground freezing (AGF) has been used for over 100 years to form impermeable barriers and temporary support for excavations, shafts and tunnels [7]. Techniques such as grouting and artificial ground freezing are standard in civil engineering and mining for stabilizing, for instance, highly saturated soils or creating impermeable walls for tunnelling purposes. They are also used when constructing foundations below the groundwater table.

Laboratory studies have shown that frozen soil barriers with very low hydraulic conductivities ($< 4 \times 10^{-12}$ m.s^{-1}) can be formed under saturated soil conditions. The formation of a frozen soil barrier in arid conditions will require a suitable method for homogeneously adding moisture to the soils to achieve saturated conditions. Formation of frozen soil barriers in areas where plumes of low freezing point contaminants (tri-chloro-ethylene, etc.) exist may require low temperature and more expensive cryogenics (e.g., liquid nitrogen and CO_2) [7].

Freezing is effected by a system of pipes that are inserted into or around the contaminated zone (Figure 4.6). A cooling liquid (brine) is circulated (a one phase system) in this pipe system. Another option is an open two phase process whereby liquid nitrogen is pumped into the ground. The N_2 vaporizes and thereby extracts the heat from the soil. Thermosyphons forming a closed two phase system are an alternative. The working fluid is contained in a closed sealed vessel (a thermopile or thermoprobe) that is partially buried. Thermosyphons can function passively in cold climates during the winter months, at which time the above ground portion is subjected to cold ambient air that cools and condenses the working fluid. The condensed fluid gravitates to the below ground portion. Below ground, subjected to warmer temperatures, the working fluid warms, vaporizes and rises upwards to repeat the cycle. A closed two phase system can also be used in an active mode and is applicable when the ambient air temperature is above freezing [7]. Such systems utilize 'hybrid thermosyphons'. A typical system consists of multiple thermoprobes, an active (powered) compressor and condenser, an interconnecting supply and return piping network, and a control system. Thermoprobes consist of an evaporator and a passive condenser section. The hybrid system can function simultaneously in both passive and active modes when the ambient temperatures are sufficiently low, thereby reducing energy costs. Hybrid thermosyphons may operate in northern climates (locations that experience air temperatures below the target soil temperature) without external power. The temperature of the barrier can be adjusted to ensure the necessary liquid-solid phase change even though contaminants may lower the phase change temperature.

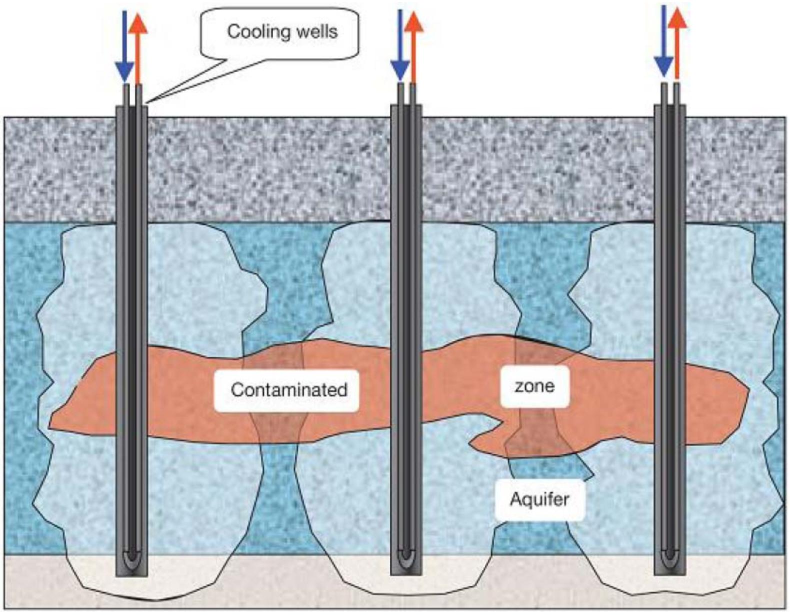


Figure 4.6 The principle of ground freezing as a barrier and to immobilize contaminants

4.5.1.9 Permeable reactive barriers

The use of permeable reactive barriers or walls is distinguished from outright containment by the fact that the contaminant carrier as such (i.e., the groundwater) is not prevented from movement [43]. The objective is rather to remove the contaminants from the mobile phase. Permeable reactive barriers are installed by excavating a portion of the aquifer, disposing of the excavated material and replacing it with a permeable material designed to react with the contaminant and remove it from the flowing water (Figure 4.7). The advantages over pump and treat systems are that no active pumping or process operation and maintenance is required, thus reducing energy and operation and maintenance costs, no treatment sludges are produced, thus reducing waste disposal costs, and no surface facility is required, which allows the land to be returned to productive use. The systems typically rely on the natural gradient of the groundwater table as the driving force. The barrier material must be designed to remain reactive for periods of many years to decades. Furthermore, the barrier permeability must be sustained throughout the duration of the groundwater treatment. The performance of permeable reactive barrier systems must therefore be monitored so that corrective action can be taken when required.

Permeable reactive barriers have been designed and implemented for the treatment of dissolved metals, acid mine drainage, radionuclides and dissolved nutrients. Contaminant removal can be effected in a variety of ways. Treatment processes include adsorption, simple precipitation, adsorptive precipitation, reductive precipitation and biologically mediated transformations [43].

Changing the redox state can be a very effective method of immobilizing certain radionuclides (e.g., uranium and technetium). These radionuclides have two or more oxidation states, and the more reduced oxidation states are less mobile; for example, reduction of the hexavalent uranyl ion UO_2^{2+} to the tetravalent U(IV) state results in the precipitation of sparingly soluble precipitates, including UO_2(s) or mixed U(VI)–U(IV). Zero valent iron is an abundant and inexpensive reducing agent that has been observed to reduce and precipitate uranium and technetium in laboratory studies [43].

The oxidation products generated (e.g., ferric hydroxides) can provide a high capacity sorption substrate also for non-redox sensitive species, but their long term stability in relation to changes in redox conditions has to be carefully evaluated [43].

Permeable reactive barrier systems containing zero valent iron have been installed for the treatment of uranium, technetium and other metals; these barriers demonstrate excellent removal of uranium and technetium. Examination of the reaction products has been conducted at a series of sites of permeable reactive barriers. Although the results of these characterization studies are inconsistent, all the reports indicate that a portion of the uranium entering the barrier system is reduced to U(IV), whereas some portion may remain in the U(VI) oxidation state. Other metals commonly associated with uranium mine waste, including arsenic, molybdenum, selenium, vanadium and zinc, are also removed from the groundwater, possibly as reduced phases (e.g., V_2O_3) or as sulphide minerals (As_2S_3, ZnS) [43].

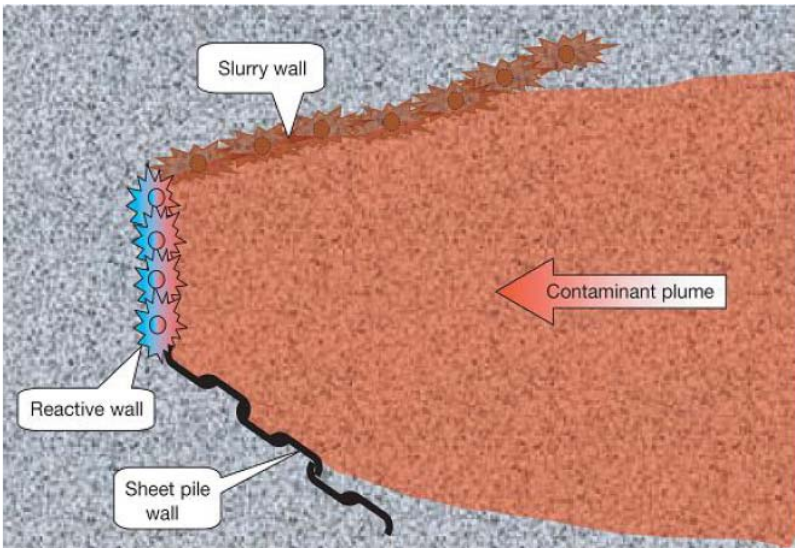


Figure 4.7 Sketch of a permeable reactive wall in combination with a Funnel-and-Gate system

Organic reductants, such as sawdust, have also been used to promote the reduction and precipitation of uranium. Passive treatment systems containing organic carbon have been used to remove both uranium and nitrate from groundwater at sites where these two constituents coexist as a result of releases from nuclear weapon production facilities [43].

Sorption can remove contaminants from groundwater and can maintain low concentrations of radionuclides. Sorptive materials that have been evaluated or deployed in permeable reactive barrier systems for treating radionuclides include zeolites (e.g., clinoptilolite), phosphate based adsorbents (e.g., bone char apatite and Apatite II) and hydrous ferric oxides (e.g., amorphous ferric oxy-hydroxide (AFO)) [43].

The majority of the reactive barriers installed to date have been continuous barriers installed across the entire width of the plume. Contaminant fluxes also can be focused on the reactive barrier by an array of non-reactive barriers, such as slit or slurry walls, to form a Funnel-and-Gate system [43].

Funnel-and-Gate systems reduce the physical length of the treatment portion of the barrier and prevent contaminants from circumflowing the treatment zone. The volume of reactive material required to treat contaminated groundwater is determined by the contaminant concentrations, groundwater geochemistry and flow rate. For many contaminant plumes, the volume of reactive material will be similar, whether a continuous barrier or Funnel-and-Gate configuration is employed. Since the installation of continuous barriers is typically less expensive than that of Funnel-and-Gate systems, this installation technique has been preferred. Furthermore, because Funnel-and-Gate installations focus the flow to across a small cross-sectional area, there is greater potential for clogging by the formation of secondary precipitates.

Depending on the reactive material to be used, deployment techniques may include injection wells (for grouts, gels and soluble reactants) or trenches cut by a suitable excavator (for grouts and particulate material such as granular iron, sawdust, etc.), see Figure 4.8.

Figure 4.8 (a) Continuous trenching machine used to install a 46 m long, 7.3 m deep and 0.6 m wide granular iron permeable reactive barrier [43]

Figure 4.8 (b) Simultaneous excavation and replacement of aquifer material with granular iron as the horizontal trencher advances [43]

Development work on efficient methods to emplace reactive barriers with minimal disturbance, even in awkward places, is ongoing. Adaptation of more novel civil engineering techniques, such as directional or horizontal drilling, the use of guar gum slurries for barrier installation, hydraulic fracturing and jet grouting techniques, can be used for the emplacement of barriers at depths beyond the capabilities of the conventional excavation techniques displayed in Figure 4.9 [43].

Computer simulations conducted using reactive solute transport models can be used to determine design parameters for barrier installation, to predict the potential for barrier clogging and to assess the potential benefits of barrier performance. The performance of a reactive barrier installed at the Elizabeth City US Coast Guard Support Centre was simulated using the reactive solute transport model MIN3P. Comparison of the simulation results with subsequent measurements showed good agreement in Figure 4.10. The performance of the permeable reactive barrier installed at Monticello Canyon, Utah, USA, was simulated using the PHREEQC model [43].

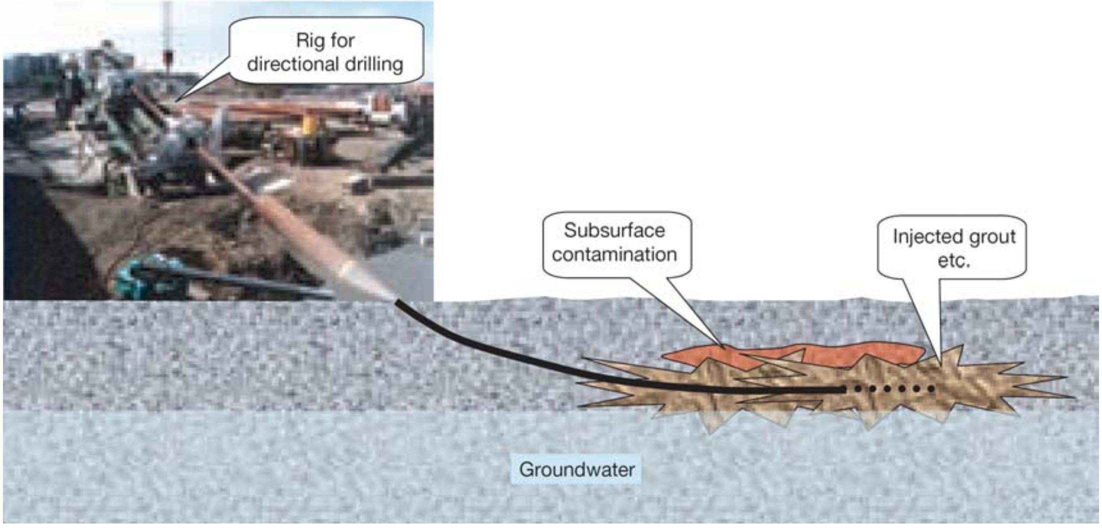


Figure 4.9 The principle of directional drilling and grouting

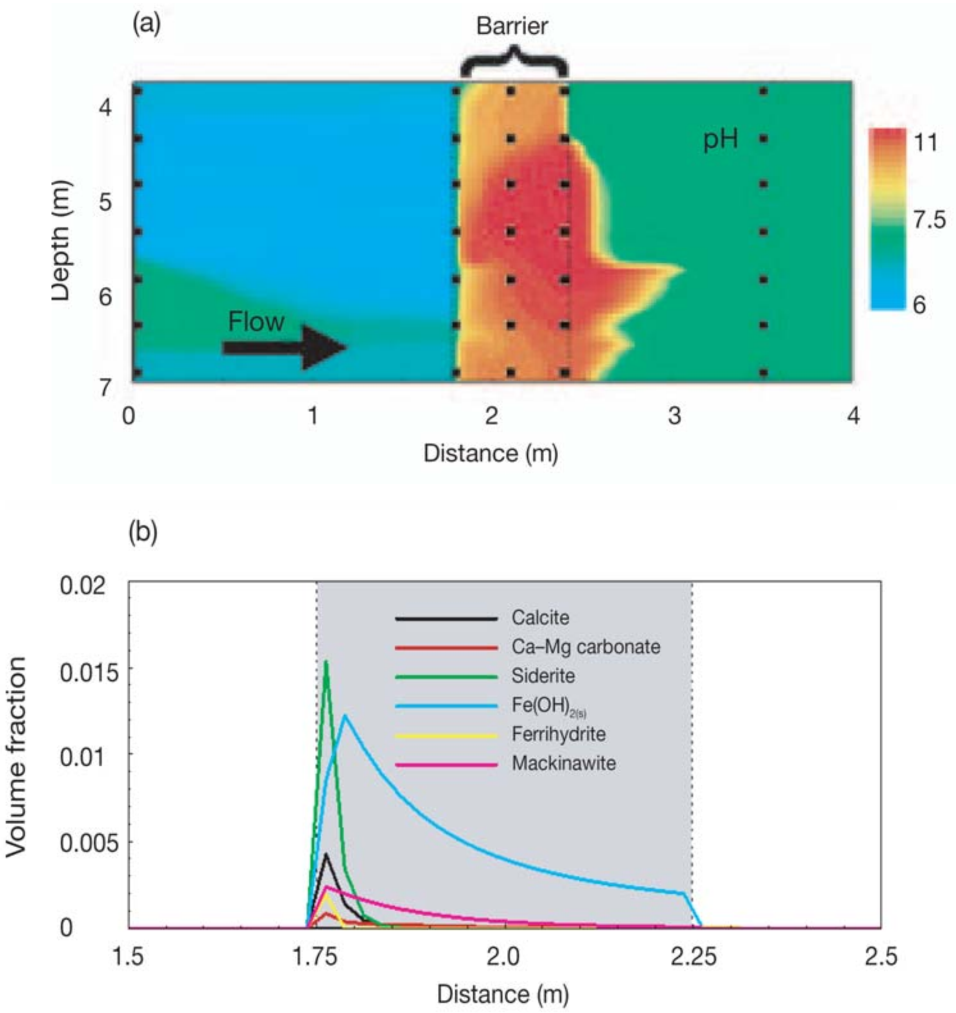


Figure 4.10 Simulated heterogeneous reactions at a permeable reactive barrier at the Elizabeth City US Coast Guard Support Centre [43]

The limitations on permeable reactive barrier performance and lifespan include constraints on the reactive material longevity and the barrier permeability. Of these concerns, the potential for barrier clogging and the permeable reactive barrier evolving into an impermeable reactive barrier is the most significant. Since the total mass of contaminant that accumulates in the barrier is modest, the principal precipitates resulting in clogging are the products of reactions between the barrier material and the major ions present in the water, or between the barrier material and the water itself. The use of zero valent iron (Fe^0), the most commonly used reactive material, results in the reduction of water and an increase in the pH to between pH10 and pH11. This increase in pH favours the precipitation of carbonate minerals, principally calcite ($CaCO_3$) and siderite ($FeCO_3$). Over periods of several years to decades, the accumulation of these precipitates potentially may be sufficient to reduce the pore space of the reactive material and limit barrier permeability. Reactive barrier technology has evolved recently, and the oldest barriers are now approaching ten years of operation. Clogging to a degree that is sufficient to impair barrier performance has yet to be observed, although long term monitoring programmes are required to assess this concern.

The long term fate of the reactive barrier after remediation is complete or after the barrier becomes ineffective depends on the nature of the contaminant and on the characteristics of the barrier. Concerns include the potential for remobilization of contaminants retained in the barrier and the potential for clogging in the barrier to alter natural groundwater flow conditions. In many barrier systems, the contaminant is converted to a form that is stable in the geochemical environment that prevails in the aquifer. Furthermore, because the mass of contaminant is small relative to the mass of the barrier material, the residual barrier material may be classified as non-hazardous. In these systems, it may be acceptable for the barrier to remain in place. In other cases, the mass of contaminant may exceed soil guidelines, the contaminant may have the potential for remobilization or the contaminant may be sufficiently hazardous to warrant excavation of the reactive material and placement in a secure waste disposal facility. In these cases, excavation of the barrier, or a portion of the barrier, may be required.

Although considerable research on the performance of reactive walls is continuing worldwide, some techniques have reached commercial maturity [43].

4.5.1.10 Immobilisation/Solidification

Immobilization, in contrast to physical containment, is intended to treat the contaminated material itself. The objective of immobilization is to change the contaminant form into one that is less susceptible to migration. Two basic options can be distinguished: in-situ and ex-situ treatment [43].

In-situ immobilisation treats contaminants without the contaminated material being removed. Three major methods to effect in-situ immobilization can be distinguished, based on chemical, bio-chemical or thermal treatments:

- *Chemical immobilization* is based on the injection of a variety of grouts or on changing pH and/or redox conditions in the groundwater, for example [43]. These grouts can be based inter alia on ordinary Portland cement (OPC), water glass (sodium silicate), gypsum or organic polymers, for example acrylic or epoxy resins. The suitability of immobilizing agents via injection depends largely on the hydraulic properties of the contaminated material. Ordinary Portland cement and epoxy resins typically have a high viscosity, while water glass and gypsum solutions, or acrylic acid suspensions, can be made up with viscosities equal to that of water. The long term stability of the polymer stabilized material has to be carefully assessed. Breakdown products containing functional groups, such as carboxylic or phenolic groups, may actually act as a vehicle to facilitate transport of radionuclides.

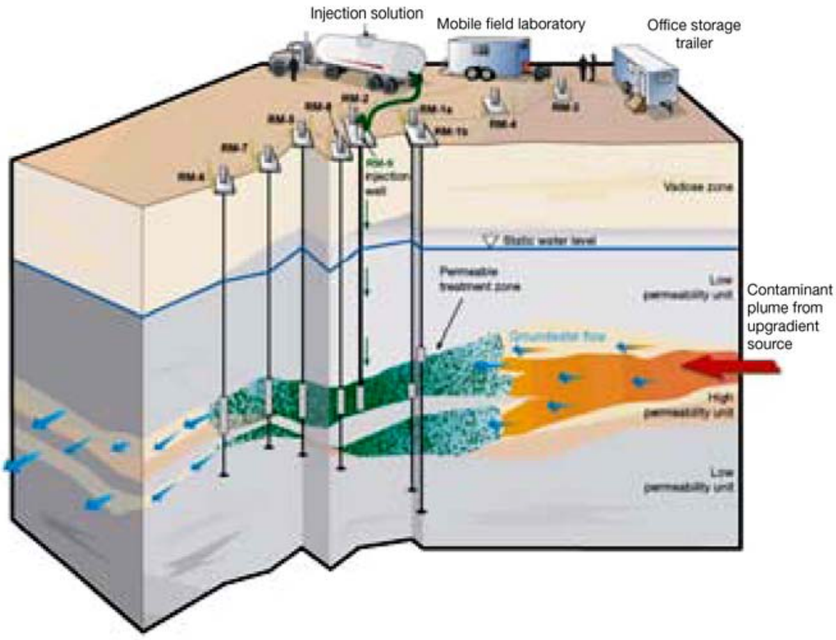


Figure 4.11 In-situ redox manipulation

Injection of chemical reductants, including calcium polysulphide, has been used to promote contaminant reduction and precipitation within aquifers. Contaminants that are well suited to remediation using this approach include metals with a lower solubility under reduced conditions. Injection techniques have been used to treat Cr (VI), through reduction to Cr(III) and precipitation of Cr(III) hydroxides. In-situ redox manipulation (ISRM) [43] is a variation on a chemical injection system, see Figure 4.11. When using in-situ redox manipulation, a strong reductant is pumped into the aquifer, converting oxidized Fe(III) bearing minerals to Fe(II) bearing minerals. These reduced phases remain stationary, and react with oxidized dissolved contaminants that migrate through the treated zone in the aquifer. This approach has been demonstrated on a pilot scale to treat groundwater contaminated by Cr(VI) at the Hanford Site in south-eastern Washington State, USA [43].

- *Bio-chemical or biological immobilisation* methods are based on the introduction or stimulation of micro-organisms that change the chemical environment [43]. Depending on the circumstances and intentions, a (enzymatic) reductive or oxidative precipitation of radionuclides can be effected. The application would be similar to creating a bio-wall, discussed in Section 4.5.1.16.
- *Thermal immobilisation* treatments use heat processes to immobilize the contaminant. Thermal treatment, however, generally is not economically efficient for dispersed radioactive contamination [43].

Ex-situ treatments are carried out in some sort of plant, either on or off the site. After treatment, the material is either returned or disposed of in an engineered repository. A number of treatment techniques can be used for both in-situ and ex-situ treatments, the method of application varying in each case.

Organic polymers and water glass are also used to immobilize surface contamination. The main effect is to enhance the cohesive properties of topsoils, thus preventing wind and water erosion, see Figure 4.12. Depending on the formulation, infiltration of rainwater may also be impeded and thus the downward migration of radionuclides retarded.

Over the years consultants and contractors have developed a wide range of proprietary engineering applications based on the fundamental processes outlined above [43].

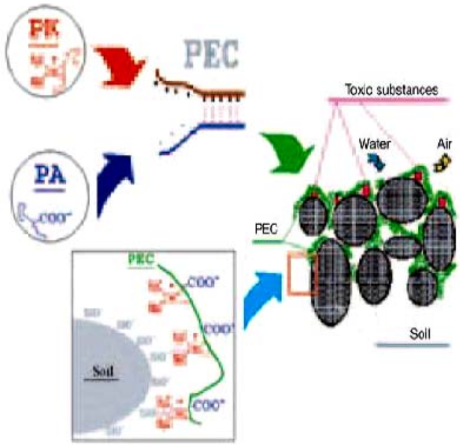


Figure 4.12 Binding of soil particles and entrapment of contaminants using organic polymers

The advantage of immobilisation techniques employing inorganic agents is that these techniques typically need little follow-up and monitoring once their functionality has been verified. In the case of organic solidification agents, the possibility of bio-degradation has to be taken into consideration and some monitoring may be needed.

However, there are some factors that may limit the applicability and effectiveness of in-situ immobilization [7]:

- The depth of contaminants may limit some types of application techniques.
- Certain contaminants are incompatible with solidification agents.
- Reagent delivery and effective mixing are more difficult than for ex-situ applications.
- Future use of the site may be limited after treatment.
- Treatment of contamination below the water table may require prior dewatering.

4.5.1.11 In-situ vitrification

Heat treatment is aimed at in-situ vitrification (ISV) whereby loose sand is fused into a lump containing the contaminants (see Figure 4.13 and Figure 4.14) [7]. Resistance or inductive heating methods are available. They are best suited to areas with contamination in relatively homogeneous media. Mixed contaminated sites that are very heterogeneous, such as buried waste sites, require careful pre-treatment characterization in order to assess the safety of the process implementation and production of a uniformly high quality product. Characterization is needed to identify waste forms, such as intact containers of liquids, pressurized gas cylinders and residues of explosives, which can cause significant pressure excursions during treatment. Characterization is also needed to ensure that the base chemical constituents are suitable and adequate to form an acceptable vitrified product. If not, addition of glass forming constituents, for example sand, may be necessary. Care is also needed if substantial amounts of metal debris are present.

The vitrification process will either destroy organic compounds or volatilize them in its early stages. It has to be considered, however, that an incomplete combustion process may lead to more toxic degradation products, such as dioxins. Another problem with heat treatment may be the volatilization of ^{210}Po, ^{137}Ce, Pb and Hg, where present. This can be overcome, albeit at additional cost, with the installation of abstraction hoods, high efficiency particulate air (HEPA) filtration and exhaust gas scrubbing. Secondary wastes from air emission control may require special treatment and disposal at licensed facilities. The vitrified block may be either left in-situ or removed (Figure 4.15) to an engineered disposal facility.

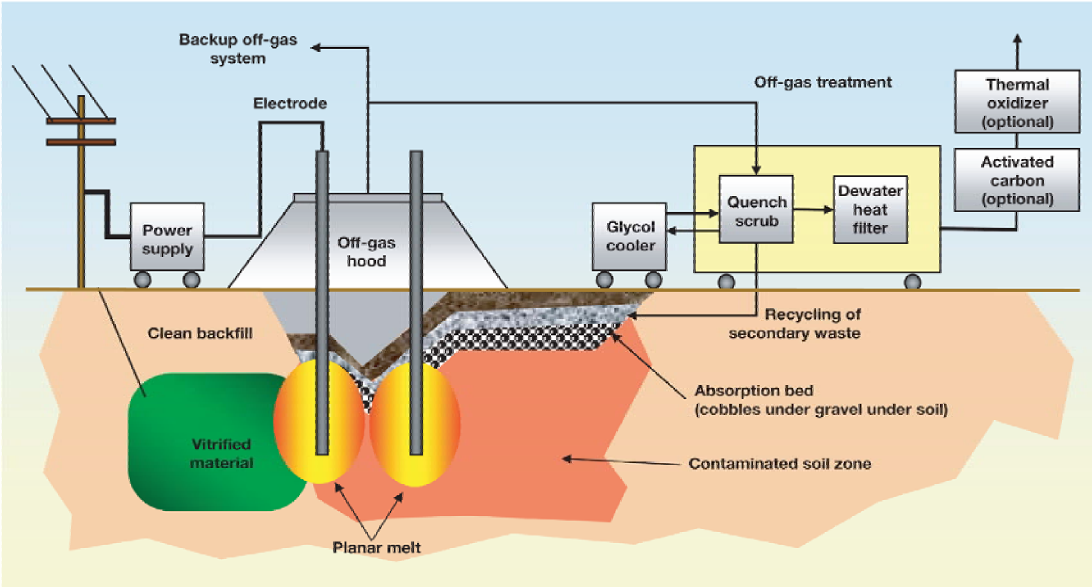


Figure 4.13 In-situ vitrification [7]

Figure 4.14 Examples of in-situ vitrification (after GeoMeltTM)

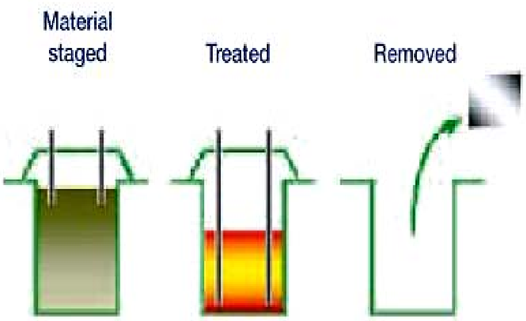


Figure 4.15 In-situ vitrification for removal and disposal (after GeoMeltTM)

The evolution of the in-situ vitrification technology resulted in three different configurations of the process discussed below:

(1) Traditional in-situ vitrification;

(2) Planar in-situ vitrification;

(3) Plasma arc (or bottom-up) in-situ vitrification.

4.5.1.12 Traditional in-situ vitrification

The traditional in-situ vitrification process employs an array of electrodes placed vertically into waste or contaminated soil, and an electric current is passed through the soil between the electrodes. The heat generated from the resistance of the soil to the passage of the current is referred to as Joule heating. As the heated soil melts progressively downwards, the electrodes are allowed to sink through the melted soil, enabling melting depths of 7 m or more.

An off-gas hood covers the entire melt and some distance around the outside edge to control release of gases and airborne particles generated within or near the melt. The off-gases are drawn into the hood by the negative pressure created by a fan, then treated in a process train before being discharged to the atmosphere. When the melting has progressed to the desired depth, the power to the electrodes is shut off and the melt is allowed to cool. The electrodes are left in place in the melt and are sawn off at the ground surface. New electrodes are installed at each new melt location. The final melt is smaller in volume than the original waste and associated soil due to:

- Removal of volatile contaminants;
- Reduced void space;
- Higher density of glass relative to waste materials.

Each melting produces a single block shaped monolith of glass. Most vitrification projects require multiple, overlapping melts to cover the area and the volume of the contaminated site.

4.5.1.13 Planar in-situ vitrification

Like traditional in-situ vitrification, planar in-situ vitrification employs the same Joule heating principle but differs in the application of electric current and in the starter path configuration. In planar in-situ vitrification, the current travels between pairs of electrodes, causing two parallel planar melts to form. As the melts grow downwards and spread laterally, they eventually meet in the centre of the electrode array and fuse together into one melt. The final planar melt has the same size and shape as a traditional in-situ vitrification melt.

4.5.1.14 Plasma arc in-situ vitrification

Plasma arc in-situ vitrification is a newer and much less tested technique based on established plasma arc technology. In this process, electrical energy is applied as direct current between two electrodes within a torch, creating a plasma of highly ionized gases at very high temperatures. The resistance to the flow of current between the two electrodes generates the plasma.

The operation involves lowering the torch into a pre-drilled borehole of any depth and heating the wastes and soil as the torch is gradually raised. The organic fraction of the wastes is pyrolysed and the inorganic fraction is vitrified, thus converting a mass of soil and or waste into a highly stable, leach resistant slag column.

Although this ‘bottom-up’ in-situ vitrification process is experimental, it has advantages over the traditional and planar in-situ vitrification applications. A primary advantage is the ability of gases and vapours to escape the subsurface above the melt zone rather than being trapped beneath it. As a result, the likelihood of melt expulsions is reduced.

The in-situ vitrification process can immobilize extremely hazardous materials and radionuclides that may be difficult to treat.

4.5.1.15 In-situ chemical oxidation

In-situ chemical oxidation is based on the delivery of chemical oxidants into the vadose zone and/or groundwater to oxidize contaminants into carbon dioxide and water. This technique is best applied at highly contaminated sites or directed at source areas to reduce contaminant concentrations. In general this technique is not cost effective for plumes with low contaminant concentrations. The effectiveness of in-situ chemical oxidation is sensitive to variations in the hydraulic conductivity of the soil as well as to the distribution of contaminant mass. Therefore, performance is improved by detailed site characterization.

To date the most common oxidant delivery methods involve injection of oxidants only. Should a significant hydraulic gradient exist, targeted delivery of oxidant to the contaminant zones may require injection and extraction wells. The major benefits of a passive oxidant delivery mode are that treatment of groundwater and disposal of secondary hazardous wastes are avoided.

The common oxidants are hydrogen based Fenton’s reagent and potassium permanganate. In the application of Fenton’s reagent, hydrogen peroxide is applied with an iron catalyst creating a hydroxyl free radical. This hydroxyl free radical oxidizes complex organic compounds. Residual hydrogen peroxide decomposes into water and oxygen in the subsurface and any remaining iron precipitates out. Fenton’s reagent is produced on-site by adding an iron catalyst to a hydrogen peroxide solution. A 50 % solution is common for this application. A pH adjustment may be required as Fenton’s reagent is more effective at acidic pH. The main difference to the oxidation techniques discussed in Section 4.3.2.1 is that here the contaminants are oxidized directly, rather than being broken down in an aerobic microbial process.

The volume and chemical composition of reactants are based on contaminant levels and volume in addition to subsurface characteristics, and may be derived from pre-application testing results. The methods for delivery of the oxidants vary; they can be injected through a well or directly into the subsurface through an injector head; they can be mixed with a catalyst and injected, or combined with groundwater extracted from the site and then re-injected. In the case of hydrogen peroxide, stabilizers are needed because of the inherent instability of this compound.

In-situ oxidation is being used for groundwater, sediment and soil remediation. It can be applied to a variety of soil types (silt and clay). It is used to treat volatile organic chemicals including dichloro-ethene (DCE), trichloro-ethene, trichloro-ethylene (TCE), benzene, toluene, ethylbenzene and xylene, as well as semi-volatile organic chemicals including pesticides, polycyclic aromatic hydrocarbons and **polychlorinated biphenyls (**PCB) [7].

The limitations of the in-situ chemical oxidation technique include [7]:

- Target contaminants may be difficult to oxidize.
- Areal extent of contamination may be too large; in-situ oxidation is best applied to ‘hot spots’ and source zones rather than very large groundwater plumes.
- Geotechnical and hydraulic characteristics of the site may restrict drilling and limit ability to inject oxidant.
- Presence of underground human made structures (i.e., buried pipelines and other utilities) can create short circuits for injected fluids.
- High natural organic content will create a high oxidant demand, thus requiring larger amounts of oxidant that will increase the cost of treatment.

- Inadvertent mobilization of co-contaminant metals, including radionuclides, from increased oxidation states.

4.5.1.16 Biological barrier walls (Bio-walls)

Biological barrier walls, often called "bio-walls" represent an in-situ barrier that relies on biological processes to restrict the migration of radionuclides; the principle is shown in Figure 4.16. The application of the technology is most appropriate to geological formations with significant permeability (e.g., sands, sandstone and permeable limestones) and no preferential flow paths such as open cracks and fissures. A bio-wall can be emplaced downstream from the contaminated site or constructed in-situ via the formation of bio-films and bio-colloids [43]. The development of a bio-wall requires the introduction of suitable micro-organisms and the provision of nutrients and essential elements to further their propagation. Adjustments to the pH or redox potential may also be required to initiate bacterial growth.

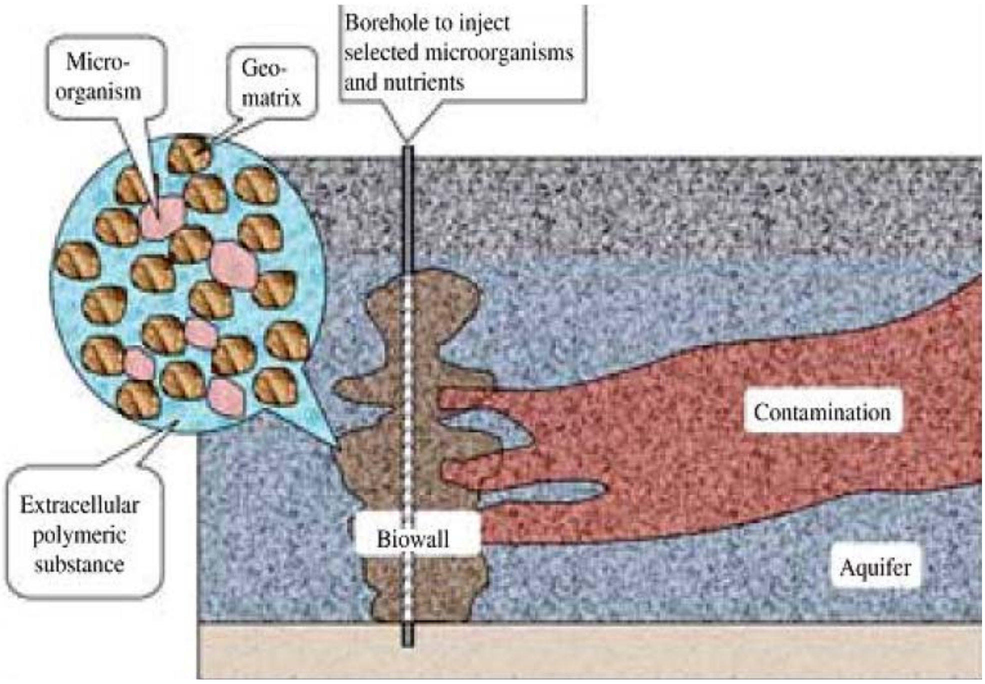


Figure 4.16 The principle of a bio-wall [7]

The effectiveness of bio-walls results from [7]:

- The physical reduction of permeability and hence groundwater flow by the microbial population. This effect can be enhanced by the use of ultra-microcells (less than 100 nm). In the course of growth by metabolism they increase in size and may completely fill the pore space.
- The generation of metabolites capable of restricting the migration of radionuclides through the barrier wall. Such metabolites are mainly extracellular polymeric substances (EPS), commonly termed 'slimes', which the microbial cells use for attaching themselves to the substrate. These extracellular polymeric substances also fill pore spaces and thus reduce permeability.
- The sequestering of radionuclides from groundwaters by complexation, although it should be noted that subsequent mobilization of these colloidal species could constitute an additional transport mechanism. Microbial action can also be utilized to modify groundwater chemistry (e.g., sulphate reducing bacteria) to immobilize redox sensitive species such as uranium or to prevent the formation of acid drainage [43].

The latter two methods would act in a similar way to an inorganic reactive wall. Several microbial strains are commercially available.

The application of bio-walls in fractured rocks might be a problem, partly because their hydraulic behaviour is difficult to predict, and partly because comparatively high flow velocities along the fractures may make attachment of micro-organisms difficult.

4.5.1.17 Phyto-stabilisation

The development of a stable and permanent vegetation cover is called by the term "phyto-stabilization". Such treatment reduces the risk of erosion of contaminated soil from sparsely or non-vegetated land, thus reducing waterborne and dustborne exposure pathways. In addition to preventing erosion, this technique may change the mobility of potentially toxic elements by reducing concentrations in the soil water and on freely exchangeable sites within the soil matrix. Both processes alter the speciation of soil metals, reducing the potential environmental impact. The technologies draw upon fundamental plant and soil chemical processes as well as established agricultural practices. The development of a stable and self-perpetuating ecosystem as a result of this type of treatment may have additional benefits, as in some circumstances plant root activity may also influence metal speciation by changes in redox potential or the secretion of protons and chelating agents. The micro-flora associated with root systems may also be involved in these processes. The rainwater infiltration rate is reduced by plant induced evapo-transpiration, thus reducing the potential for leaching and acid drainage generation. Two applications of phyto-stabilization approaches are presented below: (1) the contaminated area close to the Chernobyl NPP site and (2) the uranium mining dump near Schlema, Germany [43].

Soil stabilization is very important on certain types of arable land to prevent horizontal radionuclide migration due to water and wind erosion. The ^{137}Cs activity in topsoil in valleys may be increased by 30 – 80 % as a result of run-off of fine soil particles, as shown in field experiments in Belarus. Crop rotation with perennial grasses covering up to 50 – 80 % of the cultivated area and avoiding row crops reduces contaminated topsoil loss from 10 - 20 t/ha to 2 - 3 t/ha. On slopes, deep soil tillage without overturning the arable layer is needed. Conventional ploughing with overturning of the arable horizon should only be carried out to destroy and plough in old turf. Good cultivation practices, such as ploughing parallel to the slope, rather than up and down, will also reduce erosion [43].

Wind erosion may occur on sandy soils and on drained peaty soils. It is recommended to eliminate root crops on soils for which soil loss amounts to 8 - 15 t/ha or more. The major area (50 - 80 %) of crop rotation should be under perennial grasses. A smaller area can be allocated to winter and spring cereals and to annual grasses. In any case, soils should be under vegetation cover throughout the year, preferentially under perennial grasses. In such a manner soil loss due to wind erosion can be reduced to 2 t/ha [43].

Practical application of the phyto-stabilisation method close to the Chernobyl NPP site within the Dnieper catchment system is shown in Figure 4.17. This and adjacent drainage basins form a wide area from which contaminated waters flow and sediments are transported downstream through the Pripyat and Dnieper Rivers across Ukraine and to the Black Sea. Phyto-stabilization techniques could in this context also be considered as remedial options. Three phyto-rehabilitation approaches involving willow plantations have been studied [43]:

(1) the effect of willow plantations on vertical migration of radionuclides;

(2) the effect on the stabilization of the Chernobyl cooling pond sediments; and

(3) for lateral erosion control.

The area of interest for studying the vertical migration control by willows was an extremely contaminated zone of 16 km^2 on the left bank of the Pripyat River (between 3.7 and 18.5 TBq/km^2 ^{90}Sr and ^{137}Cs and 0.37 TBq/km^2 Pu), which is partly protected from spring floods by a dam. Through modelling exercises it was shown that, due to their high evapo-transpiration rate, willow short rotation coppice (SRC) stands are expected to lower the groundwater table level by 100 - 200 cm in fertilized stands. Without fertilization, a lowering of the groundwater table level of less than 50 cm was predicted. Since the immobilization potential of ^{137}Cs and ^{90}Sr in the willow wood is limited, the influence of plant uptake on migration remains low.

Following the closure of the Chernobyl nuclear power plant, the water level of the cooling pond (22.5 km^2; depths between 1.5 and 15 m; with about 111 TBq ^{137}Cs and 37 TBq ^{90}Sr) will drop by 4 - 7 m, and 15 km^2 of the sediments will become exposed and may be in need of stabilization. To this end the SALIMAT option was investigated. SALIMATs consist of a roll of willow rods (stems) rolled around central disposable tubes that are unwound by dragging them across the lagoon. Small scale tests have demonstrated that SALIMATs establish well on contaminated pond sediments and produce a full vegetation cover during the second year. The approximated cost of the phyto-stabilization option ranges between € 0.8 million and € 1.9 million for the reclamation of 15 km^2 of sediments, which is low compared with the prospected cost of removal of the sediments ($ 6 million, transport and disposal costs not included) or maintenance of the present water level ($ 200 000 per year) [43].

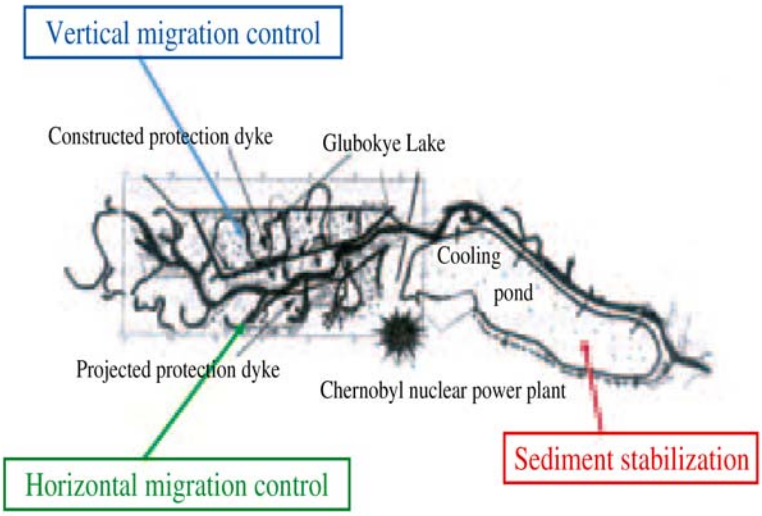


Figure 4.17 Phyto-stabilization approaches at the contaminated area of the Dnieper close to the Chernobyl nuclear power plant

The project area for horizontal erosion control was on the right bank of the Pripyat River, which was significantly less contaminated than the left bank and is not protected by a dam. After inundation, part of the activity is eroded and transported to the Pripyat River with the withdrawing water. It was calculated that even in the event of extremely high flooding, a dense willow plantation will effectively decrease horizontal soil erosion and the concomitant transport of radionuclides into the Dnieper River system.

Vegetation or re-vegetation is a commonly employed measure for the capping of engineered waste disposal facilities and mining residues such as spoil heaps or tailings ponds. The final step in closing out an impoundment for uranium mill tailings is the design and placement of a cover that will give long term stability and control to acceptable levels radon emanation, gamma radiation, erosion of the cover and tailings, and infiltration and precipitation into the tailings and heaps. Surface vegetation can be effective in protecting tailings or a tailings cover from water and wind erosion [43].

Plants chosen within the phyto-stabilisation technique should match the local climatic conditions. From an agro-biological perspective, the nature of the ore and the milling process will largely determine whether uncovered tailings are capable of sustaining growth. Considerable efforts to improve unfavourable properties such as low or high pH values and low plant nutrient content will usually be required before tailings can sustain growth.

Depending on the substrate, re-vegetation requires preparation and amelioration of the topsoil, including removal, for example, of acid generating minerals. Techniques and strategies to overcome such difficulties have been developed, for example hydro-seeding or the use of compost from organic household refuse. The method may be limited to low contaminant concentrations, owing to the (root) toxicity of higher concentrations. An adequate soil cover may need to be established [43].

Another example of the application of the phyto-stabilization remedy technique is at a 35 year old reclaimed site on a *uranium mining dump near Schlema, Germany*. It was concluded that vegetation cover could reduce infiltration by 40 - 60 % due to interception by the canopy (25 - 40 %) and increased transpiration. It was further found that of the 165 000 g/ha of uranium in the soil (30 cm depth), only 4 g/ha was in the above ground plant parts and 510 g/ha in the below ground plant parts. Since most (90 %) of the uranium taken up during the growing season is recycled (returned to the soil) with pine needles, uranium dispersion by uptake through vegetation is minimal. It may be concluded from these preliminary results that forest vegetation may reduce the infiltration rate and will disfavour radionuclide dispersion [43].

The proper design of tailings covers is crucial to ensure their long term stability with respect to plant intrusion. Since plant roots can penetrate compacted sealing layers (trees can have roots reaching down 3 - 4 m) and since trees need to have a certain degree of mechanical support in order to minimize the probability of uprooting, a vegetation substrate depth of at least 1.5 m is required. The vegetation substrate layer must be such that the critical suction is not exceeded at the top of the clay seal. It must be thick enough for plants to find sufficient water and nutrients so as to prevent the generation of a high suction at the seal. Cracks resulting from such suctions become accessible to roots and can be widened as further water is extracted [43].

In addition to the mechanical effects of soil stabilization and water management, re-vegetation has aesthetic benefits and sometimes cultural connotations, in particular on native or aboriginal lands. The choice of vegetation cover may also affect some sort of institutional control; for example, converting contaminated agricultural land into forestry reserves interrupts a potential exposure pathway via the food chain. It has to be ascertained, however, that no other exposure pathway is opened up, for instance via burning contaminated firewood [43].

4.5.1.18 Constructed wetlands

Constructed wetlands are engineered, human-made ecosystems specifically designed to treat wastewater, mine drainage and other waters by optimizing the biological, physical and chemical processes that occur in natural wetland systems. Constructed wetlands can provide an effective, economical and environmentally sound treatment of wastewater, and serve as wildlife habitats. The conceptual design the method, displayed in Figure 4.18, leads to either the (permanent) fixation of the contaminants in-situ or to plant uptake with the view to harvesting shoots later for further treatment and disposal.

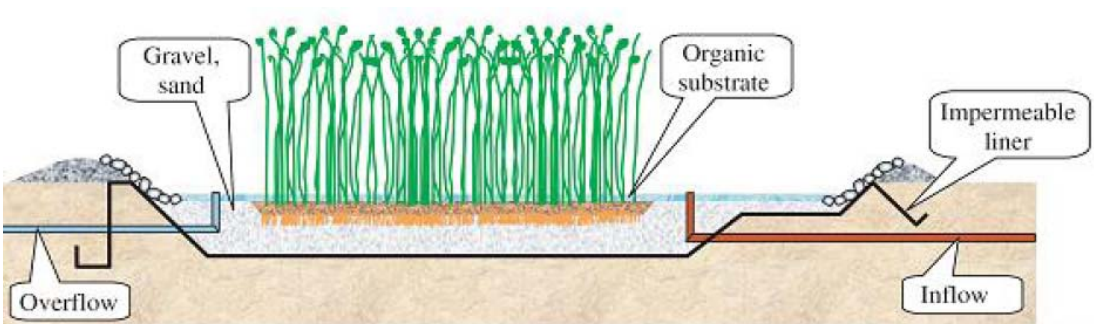


Figure 4.18 Schematic cross-section of a constructed wetland

The concept for such constructed wetlands was originally developed to treat domestic effluents for residual organic material, for example following mechanical and biological (activated sludge) treatment steps, and has found widespread application in particular for the treatment of (acid) mine effluents [43].

Constructed wetland systems are grouped into three main types [43]:

1. *Free water surface systems*, or soil substrate systems, consist of aquatic plants rooted in a soil substrate within a constructed earthen basin that may or may not be lined, depending on the soil permeability and groundwater protection requirements (Figure 4.19). Free water surface systems are designed to accept preliminarily treated, low velocity wastewater, in plug flow, over the top of the soil media or at a depth of between 2 and 45 cm [43].
2. *Subsurface flow systems* are typically gravel substrate systems that are similar to free water surface systems; however, aquatic vegetation is planted in gravel or crushed stone and wastewater flows approximately 15 cm below the surface of the media. The aggregate typically has a depth of between 30 and 60 cm. No visible surface flow is evident in subsurface flow systems [43].
3. *Aquatic plant systems* are also similar to free water surface systems, but the water is located in deeper ponds and floating aquatic plants or submerged plants are used. Where available, natural ponds may be used. Where they exist, natural wetlands and bogs can be used as traps for radionuclides and other metals, although this might be better classed as bio-sorption or natural attenuation, since it is mostly the decaying organic matter that effects retention. Studies on natural analogues for radionuclide migration have demonstrated this mechanism to be effective for thousands of years [43].

Figure 4.19 (a) Image of a constructed wetland [43]

Early research revealed that phyto-extraction via constructed wetlands (used to purify water) was ineffective because it was difficult to remove inorganic elements that precipitated from the water into the sediments. In addition, floating plant systems, with subsequent biomass harvesting, were determined to be inefficient and uneconomic [43].

As an example of application of the technique is a pilot constructed wetland to treat the mine water from the flooded Pöhla Tellerhäuser mine at Wismut, Germany. It was shown that the system removed iron, arsenic, manganese and radium. Removal processes were based on the geochemical characteristics of the contaminants. For manganese and ^{226}Ra, removal was also partially through bio-film formation. Uranium was not removed, given the high pH and the presence of high bicarbonate concentrations. It is hence clear that process effectiveness in constructed wetlands depends on the speciation of the radionuclides concerned and hence on the control of the governing parameters in the surface and pore waters, such as pH, and that waters may need to be subject to enhancement by additives or pre-treatment [43].

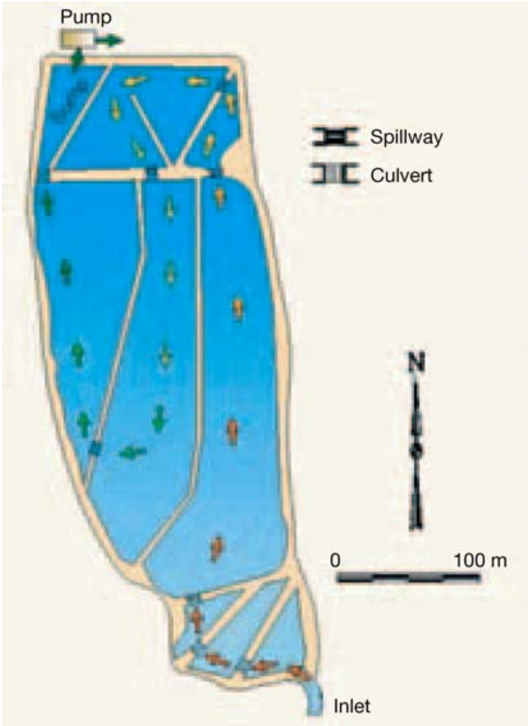


Figure 4.19 (b) Plan view of a constructed wetland [43]

Wetlands may be constructed with the main objective of excluding atmospheric oxygen from material that would generate acid from the oxidation of pyrite and other sulphides [43]. This method, however, is likely to be effective only in regions where precipitation is higher than evapo-transpiration (i.e., in temperate and humid tropical climates). Climatic conditions limit the general applicability of wetlands. Extended periods of deep frost as well as arid conditions are unfavourable. If, however, effluents only arise during frost free periods, it may be possible to operate wetlands in fairly high latitudes or altitudes.

Passive water treatment technologies such as constructed wetlands at abandoned mining sites may be appropriate for small contaminant loads. However, long term stability and resilience with respect to external disturbances and recovery are of major concern for both wetland operators and regulators. Technical guidance for designing and operating constructed wetlands may be limited, owing to a lack of long term operational data. Potential seasonal variability and impact on wildlife may negatively affect system operation and securing permits, respectively. Relatively large parcels of land are required and water consumption is high, owing to large evapo-transpiration rates in some areas [43].

4.5.2 Removal of the source term

4.5.2.1 Pump and treat for surface water and groundwater

The pump and treat technology for groundwater involves drilling wells into contaminated groundwater, pumping it to the surface and treating it to remove the contaminants (Figure 4.20). After removal of contaminants, the treated water is either re-injected into the groundwater via a well in a suitable location or discharged to a surface watercourse or into the sewerage system, depending on availability and permits.

The technology is based on the assumption that contaminant concentrations can be reduced or removed by employing ion exchange or sorption and precipitation processes. Some attempts have been made to use electrolysis or (reverse) osmosis in pump and treat systems. Chemicals have also been added underground in an attempt to enhance recovery rates [43].

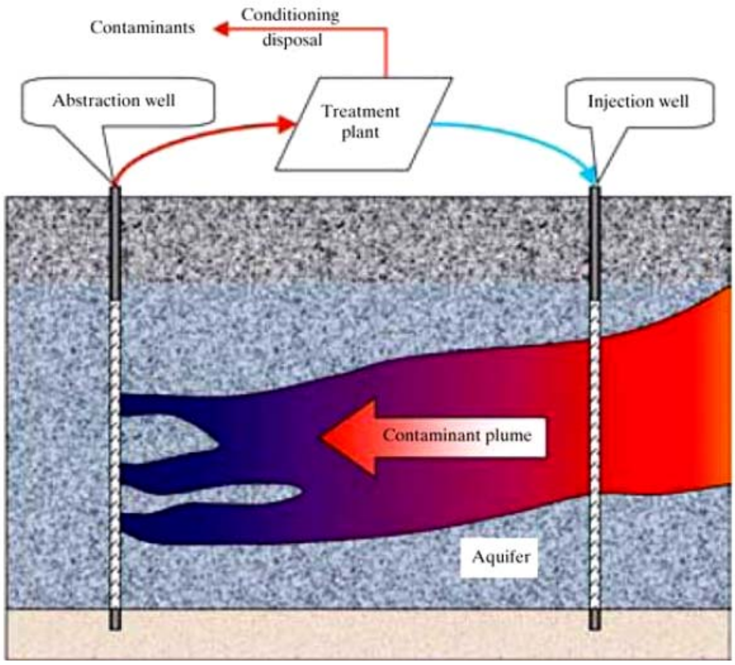


Figure 4.20 Sketch of a pump and treat system

Various techniques are available to treat ex-situ abstracted waters for dissolved contaminants and gases. Section 4.5.2.11 describes ex-situ treatment techniques in more detail whereas many are borrowed from drinking water treatment and other industrial processes.

However, the effectiveness of pump and treat systems can be compromised by a number of factors that are related to the contaminants of interest and the characteristics of the site. As a result, it is usually impossible to reduce dissolved contaminants to below drinking water limits in reasonable time frames, for example less than 10 years at many sites [7].

A report of the National Academy of Sciences of the U.S. provides a comprehensive assessment of the effectiveness of pump and treat systems for the remediation of subsurface contamination [43]. The report found that pump and treat is inefficient as a source removal technology, although it can reduce source term volumes. In line with other methods based on changing the distribution between two different phases of a contaminant, this method becomes increasingly inefficient as the concentration gradient between, for example, species sorbed on the solid matrix and aqueous species diminishes. Large quantities of groundwater may have to be pumped and treated to remove only small amounts of contaminant. Removal in-situ is inefficient, owing to tailing or mass transfer limitations. A further complication arises from the fact that not all pore water is mobile. Contaminants may be trapped in dead end pores and released into the mobile pore water only by diffusive processes, which is one of the mechanisms responsible for the tailing. Although various configurations of abstraction wells, etc., have been investigated with a view to increasing the degree of hydraulic connectedness and hence efficiency, these configurations have been unable to overcome the fundamental constraints on diffusion [43].

Undesirable water properties, for example low pH values, as is often the case with mine effluents or disposal facility leachates, may pose special problems during processing; a neutralization step might be required [43].

For these reasons it is unlikely that simple pump and treat methods will have much scope for application in situations with relatively low levels of contamination.

4.5.2.2 Enhanced recovery

In order to facilitate or accelerate the recovery of radionuclides or to lower residual concentrations in pump and treat scenarios, it may be desirable to chemically treat aquifers.

Such methods are often termed 'soil flushing'. After removal of the contaminant and before being re-injected, the pumped water is dosed with lixiviants, for example acid, surfactants, complexing agents such as ethylenediaminetetraacetic acid (EDTA) and other macro-molecules, or inert electrolytes to replace sorbed radionuclides. However, unwanted side effects, such as dissolution of the rock matrix, may be difficult to predict. Some of the available extraction methods are used in hydrometallurgy to enhance metal value recovery. Figure 4.21 shows the principal layout for the treatment of an aquifer, while Figure 4.22 shows the arrangement for treating the unsaturated zone above an aquifer [43].

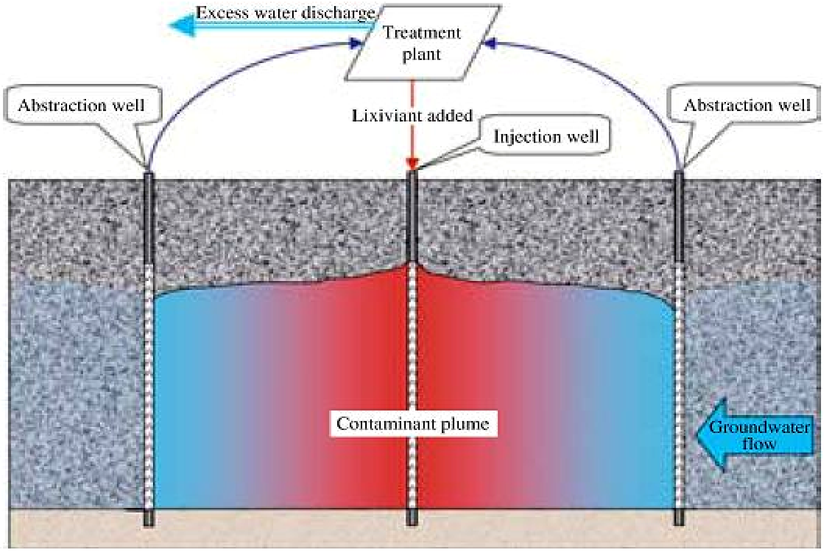


Figure 4.21 Sketch of an in-situ leaching or enhanced recovery arrangement

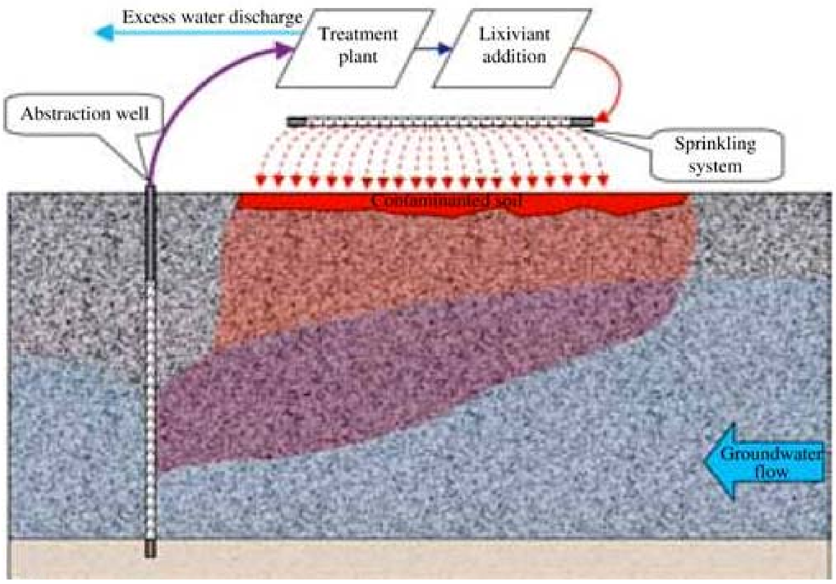


Figure 4.22 Sprinkling of contaminated soil in the vadose zone
to remove contamination

Electrochemical methods for enhancing recovery of radionuclides in aqueous solutions have been proposed [43]. If an electric field is applied to a solution, inorganic and organic ions migrate according to their charges to the respective electrodes (Figure 4.23). Two primary mechanisms transport contaminants through the soil towards one or the other electrode: electro-migration and electro-osmosis. In electro-migration, charged particles are transported through the substrate. Electrolysis arrangements concentrate metal ions on the cathode and can aid the oxidation of organic contaminants. In contrast, electro-osmosis is the movement of liquid containing ions relative to a stationary charged surface. The direction and rate of movement of an ionic species will depend on its charge, both in magnitude and polarity, as well as on the magnitude of the electro-osmosis induced flow velocity. Non-ionic species, both inorganic and organic, will also be transported along with the electro-osmosis induced water flow.

Different types of electrode material have been tested to improve performance, including porous ceramics and the rather novel carbon aerogels that increase the effective surface area. Electro-osmosis may be combined with other techniques to remove contaminants from low permeability geo-matrices such as clays. LASAGNA is a technology demonstration project designed to evaluate a combination of techniques [43].

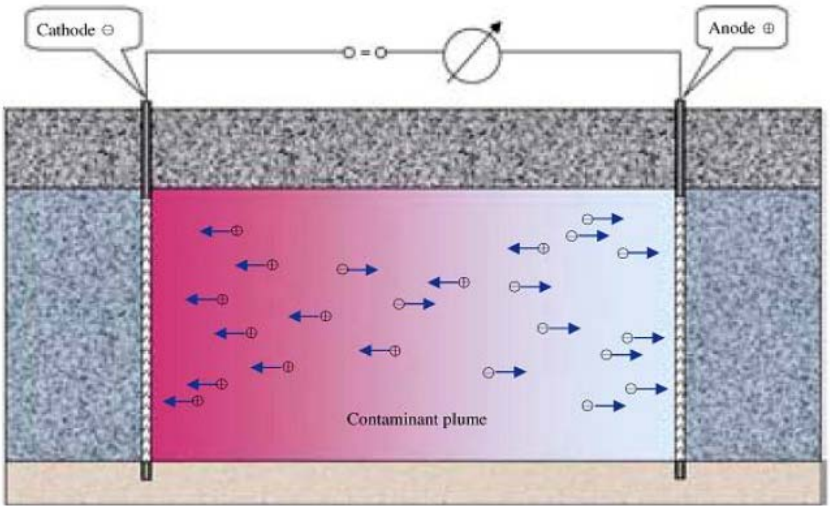


Figure 4.23 Generic layout for remediation by electrolysis and electro-osmosis

Other chemical methods are intended to increase the solubilities of contaminants by changing the redox conditions, by introducing complexing agents, solvents or surfactants. They are described in detail in Section 4.5.2.3.

In addition to the chemical methods, different methods to improve on the recovery rates have been developed:

- Physical methods, e.g., hydraulic and pneumatic fracturing, air sparging and venting and in-well aeration. They are described in detail in Section 4.5.2.4.
- Thermal methods are also applied to enhance the recovery of organic compounds and can be achieved by steam injection heating. They are described in detail in Section 4.5.2.5.
- Biological methods, e.g., biological in-situ leaching appears to be especially suitable for large scale locations, such as former industrial sites. As compared with flushing with inorganic acid (Figure 4.21), biological leaching has the advantage of a higher removal efficiency and/or less damage to the soil matrix. Biological leaching either aims at lowering the pore water pH without adding acid and/or changing the redox conditions due to the biological activity, thus increasing the solubility of inorganic contaminants. A more detailed discussion of biological methods in general is found in Section 4.5.2.6.

4.5.2.3 Enhanced recovery chemical agent methods

Following are some enhanced recovery techniques based on chemical methods:

- *Displacement by inert electrolytes*

  If the retention of the contaminant is primarily controlled by adsorption processes, a reactive agent can be chosen to compete for the adsorption sites. The aquifer may be swamped with an inert electrolyte to replace contaminants from sorption sites on the geomatrix. The effectiveness of these methods depends very much on the nature of the contaminants and the geomatrix. Competition is usually most effective for ionic solutes and least effective in displacing neutral organic molecules partitioned into soil organic matter. In general, competition will be significant only when the adsorption sites are near saturation or when the affinity of the displacing ion for the sorption sites is significantly higher than that of the contaminant. The most effective cation to replace sorbed radionuclides would be protons, as indeed are used in in-situ mining, but these would also affect acid dissolution of some matrix minerals, namely carbonates and oxy-hydroxides. Such dissolution of the matrix may be rather undesirable, because it affects the structural and hydrodynamic properties of the rock and consumes large quantities of acid. An inert, toxicologically acceptable and cheap cation is the sodium ion administered in the form of NaCl (rock salt).

- *Co-solvent solubilization*

  The rate of removal of hydrophobic organic contaminants is often limited by their relatively low solubility in water. However, the solubilities of many of these contaminants are much greater in other solvents. Co-solvents are chemical compounds that are miscible in water and also have a certain affinity for non-aqueous phase liquids (NAPL). These co-solvents promote non-aqueous phase liquid removal through a number of complementary mechanisms, including: reduction of interfacial tension between the aqueous and non-aqueous phase liquid phases; enhanced solubility of the chemical contaminants (non-aqueous phase liquid components) in the aqueous phase; swelling of the non-aqueous phase liquid phase relative to the aqueous phase; and, under certain conditions, complete miscibility of the aqueous and non-aqueous phase liquid phases. The relative importance of these different mechanisms depends on the ternary (water, co-solvent and non-aqueous phase liquid) phase behaviour of the specific system [7]. Co-solvents that preferentially partition into the non-aqueous phase liquid phase are capable of mobilizing the non-aqueous phase liquid as a separate phase due to swelling of the non-aqueous phase liquid and reduction of interfacial tension. In cases where the co-solvent strongly partitions into the non-aqueous phase liquid phase, the non-aqueous phase liquid is effectively removed with about one pore volume of injected fluid. Co-solvents that preferentially stay with the aqueous phase can dramatically increase the solubility of non-aqueous phase liquid in the aqueous phase, and removal occurs by enhanced dissolution rather than in a separate phase.

  Given a sufficiently high initial co-solvent concentration in the aqueous phase (the flooding fluid), large amounts of co-solvent will partition into the non-aqueous phase liquid. As a result of this partitioning, the non-aqueous phase liquid phase expands, and formerly discontinuous non-aqueous phase liquid ganglia can become continuous, and hence mobile. This expanding non-aqueous phase liquid phase behaviour, along with large interfacial tension reductions, allows the non-aqueous phase liquid phase to concentrate at the leading edge of the co-solvent slug, thereby increasing the mobility of the non-aqueous phase liquid. Under certain conditions, a highly efficient piston-like displacement of the non-aqueous phase liquid is possible. Because the co-solvent also has the effect of increasing the non-aqueous phase liquid solubility in the aqueous phase, small fractions of the non-aqueous phase liquid that are not mobilized by the above mechanism will be dissolved by the co-solvent slug.

  Examples of co-solvents that preferentially partition into the non-aqueous phase liquid include higher molecular weight miscible alcohols, such as isopropyl and tertbutyl alcohol. Alcohols with a limited aqueous solubility, such as butanol, pentanol, hexanol and heptanol, can be blended with water miscible alcohols to improve their overall phase behaviour.

In field applications the co-solvent mixture is injected uphill of the contaminated area. The solvent with the dissolved contaminants is extracted downhill of the contaminated area and treated above ground. Physical barriers may be installed to prevent uncontrolled migration of solvent and contaminants.

Co-solvents that are used as substrates by microbes may have the added advantage of promoting co-metabolism of primary contaminants. Small amounts of bio-degradable co-solvent that are difficult to remove from the subsurface will be of less concern because of their eventual transformation. Thus, co-solvents, such as alcohols, are potentially effective reactive agents for chemical enhancement for pump and treat of hydrophobic organic compounds.

Order of magnitude decreases in adsorbed contaminants are generally achieved with co-solvent concentrations greater than 20 %. Fluids containing this amount of co-solvent will have densities and viscosities that differ substantially from the groundwater. Thus, the transport behaviour of these fluids is more complex and more difficult to predict than that for fluids with homogeneous properties.

Co-solvent interaction with clays in the aquifer matrix may either increase or decrease the permeability of the soil. The formation of such high permeability pathways may be particularly troublesome at sites where dense non-aqueous phase liquids (DNAPL) are present. Co-solvents such as methanol can serve as a substrate for subsurface microbes, resulting in bio-fouling of the aquifer. Bio-transformation may substantially alter the geochemistry of the aquifer and promote the reductive dissolution of iron and manganese oxides. These metals can create problems with well clogging and interfere with surface treatment.

- *Surfactants and micro-emulsions*

Surfactants are molecules that have both hydrophilic and lipophilic moieties. The amphophilic nature of surfactant molecules causes them to accumulate at interfaces, such as air-water, oil-water and water-solid, and significantly reduce the interfacial tension [7]. Because of this property, surfactants are useful in enhanced oil recovery and may also be applied to remediation of non-aqueous phase liquid contaminated sites. Surfactants are classified by the nature of their head group. The different types are: cationic, anionic, non-ionic and zwitterionic (both cationic and anionic groups). Different types of surfactant can be more or less effective depending on the particular contaminant involved.

The surfactant must be chosen to be compatible with the solvent under the conditions of use. Inadequate surfactant formulations may result in high viscosity macro-emulsions that are difficult to remove. The surfactant can alter the wetting properties of the soil matrix and cause the non-aqueous phase liquid to become the wetting phase. The non-aqueous phase liquid would then occupy the smaller pores of the soil matrix, thereby exacerbating clean-up efforts.

Introducing alien substances, such as surfactants, into an aquifer is always a concern and may meet with resistance from regulatory authorities. It has to be shown that they are non-toxic and, if possible, bio-degradable; otherwise, the surfactant itself will have to be removed from the treated zone.

There are two main mechanisms by which surfactant can affect recovery of subsurface non-aqueous phase liquids: micellar solubilization and mobilization of the non-aqueous phase liquid due to reduced interfacial tension.

- Micellar solubilization

  A unique characteristic of surfactant molecules is their ability to self-assemble into dynamic aggregates known as micelles [7]. The surfactant concentration at which micelle formation commences is known as the critical micelle concentration (CMC). Micelle formation generally distinguishes surfactants from amphophilic molecules (e.g., alcohols) that exhibit a much lower degree of surface activity and do not form micelles.

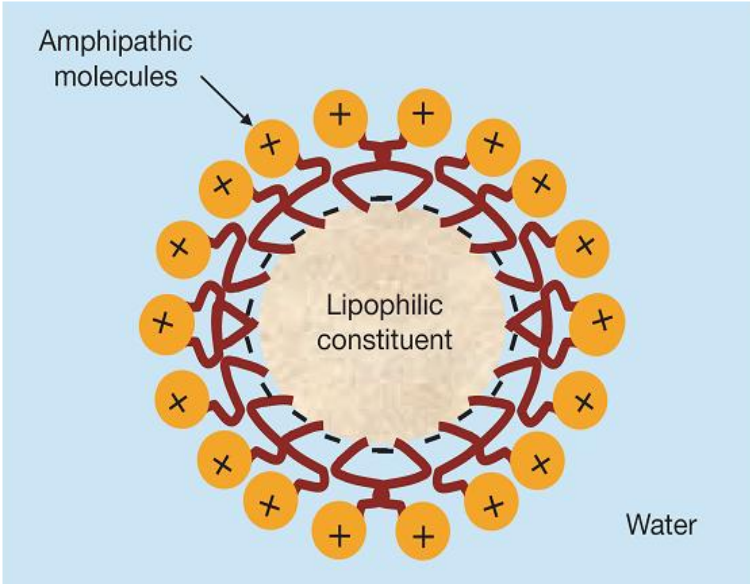


Figure 4.24 The principle of micelle formation

Figure 4.24 shows an example of a micelle. The presence of micelles increases the apparent solubility of the contaminant in water. This in turn improves the mass removal per pore volume. To determine the appropriate amounts of surfactant to add to the systems, batch or column experiments are usually performed. Such experiments have determined that surfactant additions are often rate limited. As the surfactant concentration increases, additional micelles are formed and the contaminant solubility continues to increase [7].

Winsor Type I micelles have a hydrophilic exterior (the hydrophilic heads are oriented towards the exterior of the aggregate) and a hydrophobic interior (the hydrophobic tails are oriented towards the interior of the aggregate). Thus, micelles are analogous to dispersed oil drops; the hydrophobic interior of the micelle acts as an oil sink into which hydrophobic contaminants can partition. Winsor Type II surfactants are soluble in oil, i.e., they have a low hydrophile-lipophile balance, will partition into the oil phase and may form reverse micelles.

Reverse micelles have hydrophilic interiors and lipophilic exteriors; the resulting phenomenon is analogous to dispersed water drops in the oil phase. Surfactant systems intermediate between Winsor Type I micelle systems and Winsor Type II micelle systems can result in a third phase with properties (e.g., density) between oil and water. This third phase is referred to as a middle phase micro-emulsion (Winsor Type III system). The middle phase system is known to coincide with ultralow interfacial tensions; thus, middle phase systems will result in bulk extraction of organic compounds from residual saturation.

Micro-emulsions are a special class of Winsor Type I system in which the droplet diameter of the dispersed phase is very small and uniform. Droplet diameters of oil-in-water micro-emulsions generally range between 0.01 and 0.1 mm. These micro-emulsions are single phase, optically transparent, low viscosity, thermodynamically stable systems that form spontaneously on contact with an oil or non-aqueous phase liquid phase. A properly designed micro-emulsion system can be diluted with water and transported through porous media by miscible displacement. This is in contrast to surfactant based technologies that utilize Winsor Type III middle phase micro-emulsions that depend on an immiscible displacement process to transport the non-aqueous phase liquid phase.

Micro-emulsions are usually stabilized by a surfactant and a co-surfactant. A mixture of water, surfactant and co-surfactant form the micro-emulsion ‘precursor’ and should also be a stable single phase, low viscosity system. Low molecular weight alcohols (propanol, butanol, pentanol, hexanol, etc.), organic acids and amines are all suitable as co-surfactants. There are many surfactants that will form oil-in-water micro-emulsions in the presence of alcohol co-surfactants. Some of these surfactants have been given direct food additive status, for example by the United States Food and Drug Administration, are non-toxic and are readily bio-degradable so that there is little concern over their release into the environment.

However, it is important in applications that surfactant losses due to sorption, precipitation, co-acervate formation or phase changes are minimal, and that environmental acceptance and bio-degradability are assured. Co-solvents can be used to stabilize the system and avoid macro-molecule formation. Recovery and reuse of surfactants will improve the cost effectiveness of a remedial system. Designing a system to recover and reuse the system requires trade-offs based on ease of recovery versus efficiency of the remedial system.

- Mobilization

The second mechanism utilized in surfactant treatment is non-aqueous phase liquid mobilization due to a decrease in interfacial tension. The interfacial tension between the groundwater and the non-aqueous phase liquid produces large capillary forces that retain the non-aqueous phase liquid. This is the reason that conventional pump and treat operations cannot remove the majority of non-aqueous phase liquid at a given site [7]. As the interfacial tension diminishes, the phase becomes virtually miscible. This results in direct mobilization of the non-aqueous phase liquid. Caution must be exercised, however, because the surfactant could cause the contamination to spread too easily and too quickly. This is particularly true with dense non-aqueous phase liquids, which can quickly spread to underlying uncontaminated zones.

In the pump and treat scenario, dilute surfactant solutions are injected into the contaminated aquifer and withdrawn together with the solubilised dense non-aqueous phase liquids. Vertical circulation wells (VCWs) are an alternative application under consideration. The surfactant is injected from one screened section of the well and the contaminant plus the surfactant is extracted from another screened section. The possible advantages of using vertical circulation wells over the multi-well system are:

(1) Reduced cost;

(2) Effective hydraulic control over limited volumes of the formation;

(3) Ability to capture non-aqueous phase liquids that might sink when mobilized;

(4) Application to both light non-aqueous phase liquids and dense non-aqueous phase liquids;

(5) Minimal loss of surfactants;

(6) Reduced volume of fluid requiring treatment;

(7) Induced mounding, which can remediate portions of the contaminated vadose zone around the well.

4.5.2.4 Enhanced recovery physical methods

Following are some enhanced recovery techniques based on physical methods:

- *Hydraulic and pneumatic fracturing*

  These mechanical methods to enhance recovery typically strive to improve the hydrodynamics of the system as a whole or of individual contaminants. Insufficient permeability or hydraulic connectivity can be overcome by hydro-fracturing techniques. These technologies are borrowed from the oil industry, where they were developed in the 1970s for deep wells, and it has recently been shown that the yield of wells for recovering contaminating liquids and vapours from low permeable media at shallow depths can be stimulated [7].

  The fracturing process begins with the injection of water into a sealed borehole until the pressure of water exceeds the natural in-situ pressures present in the soil or rock (e.g., overburden pressure and cohesive stresses) and at flow rates exceeding the natural permeability of the subsurface. A slurry of coarse grained sand and guar gel or similar mixture is then injected. As bedding planes and fractures open up in hard rocks, the sand helps to keep open fractures propagating away from the injection point. Fracture propagation distances of 10 - 20 m are common in hard rock, while unconsolidated materials, such as silts and clays, typically exhibit fracture propagation distances of 5 - 15 m. The oil industry also uses high strength solids, such as zirconia spheres, at greater depths, where higher lithostatic pressures have to be counteracted. The hydro-fracturing increases the effective surface area and the radius of influence of the abstraction wells and promotes a more uniform delivery of treatment fluids and accelerated extraction of mobilized contaminants.

  The increased permeability and hydraulic connectivity may be of benefit not only in pump and treat systems but also for in-situ bio-remediation, oxidation/reduction de-chlorination and soil vapour extraction (SVE) applications. Delivery of liquid substrates and nutrients would be facilitated.

  Alternatively, gases (air) may be used as a fracturing medium. Pneumatic fracturing allows treatment of the vadose zone for enhanced recovery of volatile contaminants. A comparative field demonstration of hydraulic fracturing to enhance mass recovery or emplace reactive barriers was conducted from the autumn of 1996 to the spring of 1998 at the Portsmouth Gaseous Diffusion Plant, Ohio. Hydraulic fracturing demonstrations showed that mass recovery increased from 2.8 to 50 times and radius of influence from 25 to 30 times for pneumatic fracturing at Tinker Air Force Base, Oklahoma. This demonstration treated chlorinated solvents (specifically tri-chloro-ethylene (TCE)) in both the vadose and saturated zones within low permeability silt and clay deposits and was shown to double the hydraulic conductivity and increase the radius of influence by 33 % [7].

  Cohesive or hard low permeability geological media with distinct bedding planes or a pre-existing network of fractures, such as clays, shales or sandstones, are the most appropriate for hydraulic fracturing.

  The baseline against which hydraulic fracturing plus an in-situ remediation technology in low permeability media can be compared is excavation and ex-situ treatment. The advantages of hydraulic fracturing include:

  - Improved accessibility to contaminants and delivery of reagents (steam, oxidant, etc.) due to increasing permeability and hydraulic connectivity (e.g., improved mass transfer rates);
  - Limited site disruption minimizing adverse effects on surface features as fewer wells can be installed.

Hydraulic fracturing is applicable to a wide range of contaminant groups with no particular target group. Factors that may limit the applicability and effectiveness of the process include:

- The technique should not be used in bedrock susceptible to seismic activity.
- Investigation of underground utilities, structures or trapped free-phase contaminant is required.
- A potential to open new pathways exists, leading to the unwanted spread of contaminants.
- Pockets of low permeability may remain after using this technology.
- It is almost impossible to control the final location and size of the fractures created.
- Fractures are anticipated to collapse due to overburden pressure if not reached by the stabilizing media.

- *Air sparging and venting*

In the unsaturated zone, volatile organic compounds (VOC) can exist in gaseous, aqueous, sorbed and liquid-organic phases. A venting system consists basically of wells, or 'extraction' vents, completed above the water table in zones of contamination, very similar to a pump and treat system below the water table. A pump is used to apply a vacuum that induces a subsurface gas flow pattern converging on the extraction vents. Prior to venting operations, the soil gas concentrations are in equilibrium with the existing contamination. The induced gas flow displaces the equilibrated soil gas with fresh air, resulting in mass transfer from the aqueous, sorbed and liquid-organic phases to the sweeping gas phase. Continuous subsurface flushing of fresh air leads towards an almost complete removal of the volatile organic compounds. Fresh air can be either injected through vents or allowed to seep in through the ground surface. The extracted contaminant vapours are collected from the extraction vents and treated as required.

Air sparging systems are designed to inject air below the water table through sparge wells. This process is analogous to above ground air stripping treatment of water. The process is based on increasing the gas exchange surface area and a steep distribution gradient into the clean air bubbles. As the injected gas rises through the saturated zone and contacts contaminated water or liquid-organic phase, volatile organic compounds transfer to the gas phase. The contaminated vapours emerge into the unsaturated zone, where the gas is collected.

While both technologies are limited to removing only volatile contaminants, they provide a means of encouraging biological degradation of organic pollutants by supplying an active source of oxygen to the subsurface. The permeability of the gas bubbles is a limitation. An unwanted side effect could also be the oxidation of iron bearing groundwater, leading to voluminous oxidation products clogging the pore space. However, the iron oxy-hydrates that form may also provide a substrate for sorption and thus increase retention, if such is desired, for radionuclides and heavy metals.

- *In-well aeration*

The in-well aeration technology is also known as a 'vacuum vaporizer well'. This technology was developed in Germany and has been used at several sites [7]. The conceptual basis of this technology is to use air to strip volatile contaminants from water inside a well casing. The essential design of the system involves two screened intervals and a pump to generate vertical recirculation of water within the saturated zone. Depending on type and distribution of contaminants, water flow is either upwards or downwards. Air from the surface is introduced into the well to serve as the stripping agent. A slight vacuum is imposed on the well to collect the contaminated vapour, which can be treated at the surface. The goal is to remove volatile contaminants from the water before they are pumped back into the aquifer. Operation of the system continues until all volatile contaminant mass has been removed from the swept volume of the aquifer (aqueous, sorbed and immiscible liquid phases).

One potential advantage of the in-well sparging system in comparison with 'normal' air sparging involves vapour transport in vertically stratified porous media. In normal air sparging, the contaminant is recovered by use of soil vapour extraction. However, the presence of a water saturated, low permeability stratum between the point of air injection and the vadose zone may impede the vertical movement of the airstream, thereby reducing recovery. This may affect the efficiency and safety of air sparging. The use of in-well aeration eliminates this potential recovery problem. Low permeability strata are advantageous in in-well aeration systems because they increase the swept volume affected by each well.

4.5.2.5 In-situ treatment for contaminant destruction and removal

Treatment technologies are source control technologies that reduce the toxicity and/or volume of the waste by destroying or removing polluting constituents. Treatment technologies are capable of permanently reducing the overall risk posed by wastes.

In-situ treatment technologies allow soil or groundwater to be treated without being excavated and transported, resulting in potentially significant cost savings. However, in-situ treatment generally requires longer time periods than ex-situ treatment, and there is less certainty about uniformity of treatment because of the variability in soil and aquifer characteristics and because the effectiveness of the process is more difficult to verify. The major categories of in-situ treatment processes are biological, physical/chemical, and thermal treatment. In-situ treatment technologies are generally not applicable to bulk waste.

A single technique may not be sufficient for the remediation of a situation with mixed contamination. In the following a range of techniques that specifically address organic contaminants are described that would be complementary to other techniques addressing, for instance, heavy metals and radionuclides:

1. Biological remediation whereas a separate section is addressed to phyto-remediation.
2. Dynamic underground stripping and hydrous pyrolysis oxidation;
3. Soil vapour extraction;
4. Thermal techniques, such as: electrical resistance heating, microwave heating or thermal conductance;

The last 3 groups of non-biological techniques are characterised in detail in Section 4.5.2.10.

4.5.2.6 In-situ biological remediation

In general, bio-remediation technologies employ engineered systems to heighten the effects of naturally occurring degradation mechanisms [7]. Bio-remediation techniques are destruction or transformation techniques directed towards stimulating micro-organisms to grow by using the contaminants as a food and energy source through creating a favourable environment for the micro-organisms. In general, this means providing some combination of oxygen, nutrients and in some cases moisture, and controlling the temperature and pH. Sometimes, micro-organisms adapted for degradation of the specific contaminants are applied to enhance the process. There is a conceptual similarity to techniques used in the context of enhanced natural attenuation, see Section 4.3.2.1.

Bio-degradation methods are likely to gain ground, as disposal related legislation increasingly tends to discourage or prohibit landfilling of bio-degradable materials.

However, the application of bio-remediation techniques, although often cost efficient, may be hampered by licensing procedures [7].

The rate at which micro-organisms degrade contaminants is influenced by the following parameters:

- specific contaminants present;
- oxygen supply: in aerobic conditions mechanical tilling, venting or sparging are used; anaerobic conditions may be used to degrade highly chlorinated contaminants;
- moisture: levels in the range of 20 - 80 % generally allow suitable bio-degradation in soils;
- nutrient supply: if nutrients are not available in sufficient amounts, microbial activity will stop; nitrogen and phosphorus are the nutrients most likely to be deficient in the contaminated environment and are thus usually added to the bio-remediation system in a useable form (e.g., as ammonium for nitrogen and as phosphate for phosphorus);
- pH affects the solubility, and consequently the availability, of many constituents of soil, which can affect the biological activity; many metals that are potentially toxic to micro-organisms are insoluble at elevated pH levels; therefore, elevation of the pH of the treatment system can reduce the risk of poisoning the micro-organisms;
- temperature: the bio-degradation rate will slow down with decreasing temperature;
- availability of the contaminant to the micro-organism (clays can adsorb contaminants, making them unavailable to micro-organisms);
- concentrations of the contaminants (high concentrations may be toxic to micro-organisms);
- presence of substances toxic to micro-organisms, e.g., mercury or inhibitors to the metabolism of the contaminant.

These parameters are discussed briefly in the following and also pertain to ex-situ methods.

A wide variety of process designs and technical layouts have been developed. These may be based on groundwater recirculation (Figure 4.25) or direct injection (Figure 4.26) [7]. The features of the above mentioned techniques are shown in Table 4.6, Table 4.7 and Table 4.8 within Section 4.5.

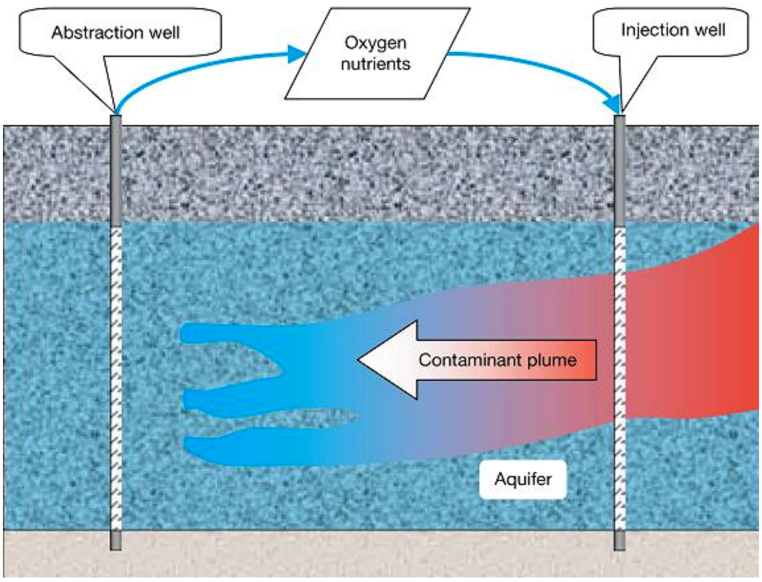


Figure 4.25 Stimulation of in-situ bio-remediation by groundwater recirculation

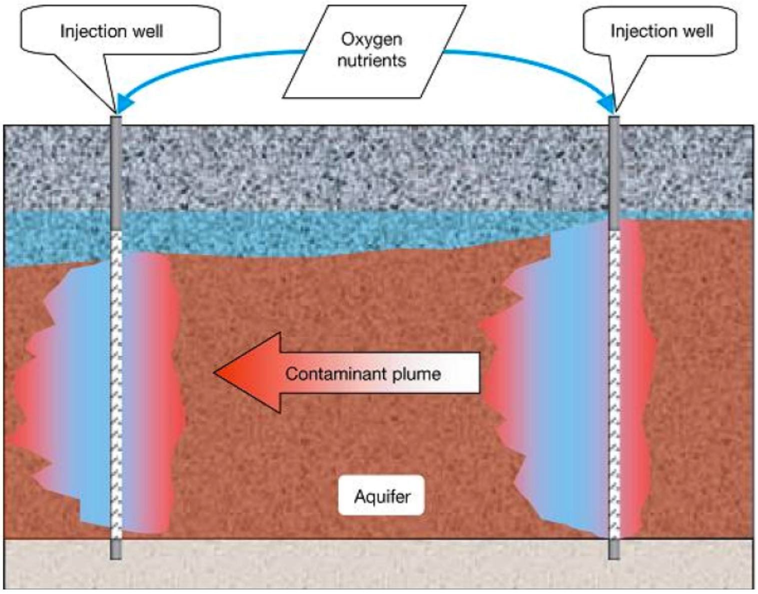


Figure 4.26 Bio-remediation by direct injection of nutrients

Natural micro-biological systems are very complex, difficult to understand in their interactions, and, unlike many engineered systems, difficult to control. In this sense, bio-remediation is not foolproof and it cannot be guaranteed to be successful even in instances where due care was taken in its design and application.

Micro-biologically specific reasons for the poor performance of in-situ bio-remediation systems include [7]:

(a) There is uncertainty with regard to the effect of hydrocarbon availability on the effectiveness of bio-degradation. Can bacteria degrade hydrocarbons adsorbed on surfaces or degrade hydrocarbons with low levels of solubility? Or must the hydrocarbon be solubilized before it can be bio-degraded?

(b) Although petroleum hydrocarbons are amenable to aerobic bio-degradation, for it to occur the indigenous bacteria must have the appropriate genetic information. This genetic information is precise. The presence of a specific hydrocarbon will stimulate the synthesis of an oxy-genase enzyme that is expressly configured to react with that stimulating hydrocarbon. For remediation, the question is whether the indigenous microbes possess the genetic information required for appropriate enzyme production and whether the contaminant stimulates the production of those enzymes.

(c) General microbial stimulation has the potential to produce a large amount of biomass that may not take part in the bio-degradation process and actually be harmful through bio-fouling and plugging of injection wells, galleries or surrounding formations. There is potential to lose critical subsurface mass transport capabilities.

(d) There are practical limits to the degree of clean-up obtainable using bio-remediation. Hydrocarbons at the low ppm level may not be capable of supporting significant levels of microbial activity even under stimulation. Sites with relatively high levels of hydrocarbon impact may actually be better candidates for bio-remediation than those on which the impact is small at levels slightly above regulatory action levels.

It should be noted that many of these factors are better controllable under ex-situ conditions described in Section 4.5.2.11.

4.5.2.7 Phyto-remediation

In-situ bio-remediation may also employ higher plants and is then commonly known under the title phyto-remediation. Here the contaminants are either taken up into the shoots or the roots, or the complex bio-geochemical processes in the root zone either destroy or immobilize the contaminants.

Studies on the efficiency of bio-degradation in the presence of radionuclides and heavy metals are important, since metabolic pathways can be inhibited in their presence. Some fungi have been shown to be tolerant to high metal concentrations. Laboratory research also indicates that fungi that are resistant to metals in symbiotic association with plant roots might positively influence phyto-remediation [7]. An overview of typical phyto-remediation techniques and their applicability to individual type of media and various target contaminants as well as their respective state of development is shown in Table 4.6, Table 4.7 and Table 4.8 within Section 4.5.

Most relevant research has focused on individual contaminants or on certain classes of contaminant and not on mixtures of different types of contaminant.

Details on the phyto-extraction method and its application for uranium, strontium and caesium removal from soil as well as results from a phyto-extraction project in Belarus are given in Section 4.5.2.8.

The Rhizo-filtration method as another example of a phyto-remediation technique suitable for groundwater remediation is described in Section 4.5.2.9.

4.5.2.8 Phyto-extraction treatment

The use of plants to remove contaminants from the environment and concentrate them in above ground plant tissue is known as phyto-extraction. Phyto-extraction requires that the target metal (radionuclide) be available to the plant root, absorbed by the root and trans-located from the root to the shoot; biomass production should be substantial. The metal (radionuclide) is removed from the site by harvesting the biomass, after which it is processed either to recover the metal or further concentrate the metal (by a thermal, microbial or chemical treatment) to facilitate disposal [43].

Research and development efforts have focused on two areas: (1) remediation of contaminants such as lead, arsenic, chromium, mercury and radionuclides; and (2) mining, or recovery, of inorganic compounds, mainly nickel and copper, having intrinsic economic value [43].

Successful implementation of phyto-extraction depends on [43]:

- The bio-availability of the contaminant in the environmental matrix;
- Root uptake;
- Internal translocation of the plant;
- Plant tolerance.

Plant productivity (i.e., the amount of dry matter that is harvestable each season) and the accumulation factor (the ratio of metal in plant tissue to that in the soil) are important design parameters. This is clearly exemplified by the following set of equations and tables. The percentage yearly reduction in soil activity can be calculated as:

$$\text{Annual removal (\%)} = \frac{\text{TF} \times \text{yield}}{W_{\text{soil}}} \times 100 \qquad (1)$$

where TF is the transfer factor or bio-accumulation factor (TF = C_{plant}/C_{soil}, with C_{plant} the concentration of the radio-contaminant in the plant (Bq/g) and C_{soil} the concentration of the contaminant in the soil) and W_{soil} the weight of the contaminated soil layer (kg/ha). As is evident from this equation, the annual removal percentage increases with yield and transfer factor. However, transfer factor and yield values are not independent: a high yield is often associated with lower transfer factors because of growth dilution effects.

Phyto-extraction typically requires several years of operation, and the future trend in radionuclide concentration in the soil can be calculated from:

$$C_{\text{soil},t} = C_{\text{soil},t=0} \exp\left[-\left(\frac{\text{TF} \times \text{yield}}{W_{\text{soil}}} + \frac{0.69}{t_{1/2}}\right) \times t\right] \qquad (2)$$

The second term in the exponent of this equation accounts for radioactive decay ($t_{1/2}$ is the half-life of the radionuclide). For some radionuclides with long half-lives (e.g., $t_{1/2}$ for ^{238}U is 4.5×10^9 a), this component will not affect the phyto-extraction potential. For others, for example ^{137}Cs and ^{90}Sr, with half-lives of 30 years, the phyto-extraction potential will be affected; that is, a yearly loss of 2.33 % in activity occurs merely through radioactive decay. The equation (2) assumes a constant bio-availability of the contaminant (i.e., a constant transfer factor (TF)).

Table 4.10 shows, for a calculated example, the percentage annual removal per hectare for different crop yields and transfer factors, based on a 10 cm deep soil layer that has a mass of 1500 t for a soil density of 1.5 kg/dm^3. It should be borne in mind that if the contamination is spread to a depth of 20 - 50 cm in the soil, annual removal with the biomass is reduced by a factor of 2 to 5, respectively, compared with the figures presented in Table 4.12.

Table 4.10 Percentage yearly reduction of soil contamination due to phyto-extraction and radioactive decay

TF (g/g)	Annual reduction due to phytoextraction (%)					Annual reduction due to phytoextraction and decay (%)				
	Yield (t/ha)					Yield (t/ha)				
	5	10	15	20	30	5	10	15	20	30
0.01	0.003	0.007	0.01	0.013	0.02	2.33	2.34	2.34	2.34	2.35
0.1	0.033	0.067	0.1	0.133	0.2	2.36	2.40	2.43	2.46	2.53
1	0.33	0.67	1.00	1.33	2.00	2.66	3	3.33	3.66	4.33
2	0.67	1.33	2.00	2.67	4.00	3	3.66	4.33	5	6.33
5	1.67	3.33	5.00	6.67	10.00	4	5.66	7.33	9	12.33
10	3.33	6.67	10.00	13.33	20.00	5.66	9	12.33	15.7	22.33

Note: $t_{½}$: 30 a; soil depth: 10 cm; soil density: 1.5 kg/dm^3.

Table 4.11 Ranges for transfer factors (ratio) based on data from references

	Total range (Bq/g plant to Bq/g soil)	Comment on conditions for upper limit
Cs	0.00025–7.5	*Brassica*, organic soil
Sr	0.0051–22	Green vegetables, sandy soil
U	0.000006–21.13	Tubers, sandy soil
Ra	0.00029–0.21	Grass, sandy soil

Yields of more than 20 t/ha and transfer factors higher than 0.1 (Table 4.10) may be regarded as upper limits, except for strontium. This would result in an annual reduction percentage of 0.1 % (decay excluded). When the transfer factor equals 1, the annual reduction is about 1 %. Table 4.11 gives some ranges for transfer factors for the natural radionuclides uranium and radium, predominant contaminants in the natural occurring radioactive materials (NORM) industries, and the long lived fission products ^{137}Cs and ^{90}Sr.

By rearranging equation (2), the number of years needed to attain the required reduction factor as a function of annual removal percentage can be calculated. Table 4.12 presents the number of years required to attain a reduction of the contaminant concentration up to a factor of 100, given an annual extraction percentage or percentage reduction in radionuclide activity varying between 0.1 % and 20 %. With an annual removal of 0.1 % it would take more than 2000 years to decontaminate a soil to 10 % of its initial activity; with an annual removal of 1 %, more than 200 years are required. It is hence clear that measures would need to be taken to increase the annual removal efficiency through crop selection, or to increase the bio-availability by applying soil additives and through technical measures (e.g., decreasing the tilled soil depth).

Table 4.12 Calculated number of years required to decontaminate a soil for a required (desired) reduction factor and a given annual removal percentage

Desired reduction factor	Activity remaining, $C_{soil,t}/C_{soil,t=0}$ (%)	Annual removal (%/a)							
		20	15	10	5	3	2	1	0.1
5	20	7	10	15	31	53	80	160	1650
10	10	10	14	22	45	76	114	229	2301
20	5	13	18	28	58	98	148	298	2994
50	2	18	27	37	76	128	194	389	3910
100	1	21	28	44	90	151	228	458	4603

Note: Soil depth: 10 cm; soil density: 1.5 kg/dm^3.

In most cases one has limited control over the depth of the contamination, although it may be feasible and advantageous to excavate and pile the soil to the desired soil depth for phyto-remediation purposes. One possibility is to excavate the soil and spread it on geo-membranes, which impedes roots from penetrating to deeper layers. These membranes will also limit contaminant dispersal to the underlying clean soil, but a substantial area may be needed for treatment. Decreasing the tilled soil depth increases the removal percentage according to equation (1), and may intensify root-soil contact, and may result in an increased transfer factor.

The other factors influencing radionuclide bio-availability, such as crop selection and measures to increase the bio-availability of the radionuclide of concern, are generally radionuclide specific. To maximize the metal content in the biomass, it is necessary to use a combination of improved soil management measures, for example optimizing the soil pH and mineral nutrient contents, or the addition of agents that increase the availability of metals.

Apart from the application of soil additives to increase export with the plant biomass, plant selection may also be important for improving the phyto-extraction potential. As already mentioned, there is a significant interspecies variability in transfer factors (Table 4.15). Since the values are seldom obtained for similar soil and growth conditions, the effect of plant species on the transfer factors cannot be unambiguously derived. Observed differences between plant varieties or cultivars have been up to a factor of 2 [43].

Improved genotypes with optimized metal uptake, translocation and tolerance, and improved biomass yield, may also be an approach to improved phyto-extraction. Plant breeding and genetic engineering may open further alleys to develop hyper-accumulating plants, but actual research and technology development is mostly limited to heavy metals [43].

Although positive effects have been obtained following applications of soil amendments that increase element bio-availability, the effect of continuous treatment on soil quality, plant growth and bio-accumulation is not clear. There also remains the question of long term effectiveness: will transfer factors remain constant or will they decrease as radionuclide concentrations decrease.

Effective extraction of radionuclides and heavy metals by hyper-accumulators is limited to shallow soil depths of up to 30 cm. If a contamination is found at substantially greater depths (e.g., 2 - 3 m), deep rooting perennial crops could in principle be employed, but the fraction

.of their roots exploring the contaminated zone would be small and hence also the phyto-extraction potential.

There are concerns that contaminated leaf litter and associated toxic residues may result in uncontrolled dispersion of the contaminants. Finding a safe use or disposal route for contaminated biomass will be a major element in developing a phyto-extraction scheme [43].

Little is known about the economics of phyto-extraction, which not only depends on the extraction efficiency but also on the costs associated with crop management (i.e., soil management, sowing or planting (yearly returns for annual crops), harvesting, post-harvest biomass transport, biomass treatment, potential disposal costs and site monitoring). The treatment of 1 m^3 of contaminated soil (10 m^2 for a 1 dm soil layer) will result in about 10 to 20 kg of biomass (~ 2 - 4 kg of ash) annually.

- *Uranium removal*

  Free UO_2^{2+} is the uranium species most readily taken up and translocated by plants. Since this uranium species is only present at a pH of pH5.5 or less, acidification of uranium contaminated soils may be necessary for phyto-extraction. The uranyl cation also binds to the soil solids and organic matter, reducing the extent of plant uptake. Therefore, in addition to acidification, soil amendments that increase the availability of uranium by complexation may also be required. In testing the role of acidification and chelating agents on the solubilization of uranium it was found that, of the organic acids and chelating agents tested, citric acid was the most effective for increasing uranium in the soil solution. Following citric acid treatment (20 mmol/kg) the uranium accumulation in Indian mustard (Brassica juncea) was increased 1000-fold and in beet (Beta vulgaris) tenfold [43].

  Similar results were obtained when testing the potential for phyto-extraction of uranium from a low level contaminated sandy soil using rye grass (Lolium perenne cv. Melvina), Indian mustard (Brassica juncea cv. Vitasso) and redroot pigweed (Amarathus retroflexus) [43]. The annual removal of the soil activity with the biomass was less than 0.1 %. Addition of citric acid increased uranium uptake up to 500-fold, and extraction percentages of 2 – 5 % appear achievable. Citric acid addition, however, resulted in a decreased dry weight production (all plants tested) and even plant death and crop re-growth (in the case of rye grass). Depending on the desired contamination reduction factor (e.g., 5 - 50), it would still take between 30 and 200 years for the target to be met (Table 4.12).

- *Strontium removal*

  Table 4.13 shows the annual crop removal of ^{137}Cs and ^{90}Sr. It is clear from this table that in normal agricultural systems the annual caesium flux is small compared with the reservoir present in the soil. The ^{137}Cs removal rates are all less than 1 %, and the highest removal is found for grassland. The high sorption of ^{137}Cs in soil and the typical potassium levels in soil required for optimal plant growth all limit removal rates.

  The removal of ^{90}Sr with biomass is higher than that of ^{137}Cs because the availability of ^{90}Sr is typically tenfold above that of caesium. The transfer factors of ^{90}Sr in green vegetables and Brassica plants are typically around unity and the upper levels are around 10. Phyto-extraction of ^{90}Sr has not yet been investigated at the field scale. The high removal rates in agricultural crops (Table 4.13) suggest that phyto-extraction may be worth while to explore [43].

  The highest transfers of ^{90}Sr are typical for leguminous perennial grasses (Trifolium family) and Brassica plants. Field experiments in Belarus were carried out at the Belarussian Research Institute for Soil Science and Agrochemistry (BRISSA) on light-textured soil contaminated with ^{90}Sr (Table 4.14). It was found that cow clover (Trifolium pratense) has annual green mass yields of up to 65 - 75 t/ha (6 - 7 t/ha dry mass). The ^{90}Sr removal values were in the range 2.5 - 3.6 % of the total radionuclide reservoir in the soil. A change of soil pH from neutral (pH6.8) to moderately acid (pH4.9) enhanced the ^{90}Sr transfer by a factor of almost 2, but the yield of clover was reduced, so the total accumulation of radionuclide per unit area was increased only by a factor of 1.5. It should be noted that when the clover is used as animal fodder, the greater part of ^{90}Sr activity will end up in dung and in normal agricultural practice would be returned back to the fields. An alternative, non-dispersive use of the biomass has not yet been developed for this example in Belarus [43].

Table 4.13 Annual removal by crop biomass of ^{137}Cs and ^{90}Sr for some agricultural crops, expressed as a fraction of total content in the tilled layer (arable crops) or in the 0 - 12.5 cm layer (grassland)

	Yield (dry matter) (t/ha)	Caesium TF (g/g)	Caesium crop removal (% of total in soil)	Strontium TF (g/g)	Strontium crop removal (% of total in soil)
Cereals (grain)	5–7	0.0004–0.25	0.0005–0.06	0.02–0.94	0.0037–0.22
Potato tuber	6–10	0.003–0.89	0.0006–0.3	0.03–1.4	0.006–0.5
Leafy vegetables	5–10	0.008–1.7	0.001–0.6	0.45–9.1	0.07–3.0
Grassland	10–15	0.01–1.0	0.007–1.0	—	—

Note: The TF ranges were derived from Ref. [409].

Table 4.14 ^{90}Sr accumulation by clover on podzoluvisol loamy sand soil in Belarus (deposition: 37 kBq/m^2) [43]

Fertilizer treatment	Crop yield (green mass) (t/ha)	^{90}Sr activity (Bq/kg)	^{90}Sr accumulation in yield (kBq/ha)	^{90}Sr accumulatior (% of total soil concentration)
For soil pH (KCl) = 4.9				
P_{60}	36	243	8 809	2.4
$P_{60}K_{60}$	46	238	10 948	3.0
$P_{60}K_{120}$	54	223	12 098	3.3
$P_{60}K_{180}$	65	207	13 455	3.6
For soil pH (KCl) = 5.9				
P_{60}	40	198	7 871	2.1
$P_{60}K_{60}$	49	188	9 165	2.5
$P_{60}K_{120}$	57	178	10 191	2.8
$P_{60}K_{180}$	72	160	11 440	3.1
For soil pH (KCl) = 6.8				
P_{60}	46	169	7 732	2.1
$P_{60}K_{60}$	55	153	8 339	2.3
$P_{60}K_{120}$	64	151	9 589	2.6
$P_{60}K_{180}$	75	123	9 194	2.5

It may hence be concluded that, except for ^{90}Sr, annual removal of contaminants with plant biomass is generally too low to allow phyto-extraction to be efficient without soil additives that increase bio-availability. The high removal rates in agricultural crops for strontium suggest that phyto-extraction could be explored with benefit for this element.

- *Caesium removal*

Given its similarity to potassium, the soil potassium status will affect ^{137}Cs availability. Generally, the higher the soil potassium, the lower the transfer factor. Extremely low soil fertility with regard to potassium may increase ^{137}Cs transfer factors tenfold to 100-fold, but will also decrease plant growth. A decrease in pH and decreased ammonium levels generally increase caesium soil to plant transfer, but the effects are generally limited (a factor of 2) [43].

The effect of ammonium addition on the phyto-extraction potential of ryegrass and Brassica grown on caesium contaminated soil has been tested. Ammonium addition increased the dry weight yield by 20 % and the transfer factor by 80 %, resulting in a transfer factor of 0.8 g/g. With a realistic yield of 20 t/ha under field conditions, this would result in an annual reduction of 3.3 % (decay included). This would imply in turn that 50 years of continued phyto-extraction would be needed to reach a reduction of the soil contamination level by a factor of 5 (Table 4.12) [43].

Amarantus species have transfer factors as high as 3.2 g/g. With a yield potential estimated at around 30 t/ha/a (based on two harvests per year) and a target fourfold reduction in soil activity, the phyto-extraction process would require 16 years to complete [43].

In a normal agricultural land use system the annual ^{137}Cs removal with plant yield is rather small compared with the total amount of contamination derived ^{137}Cs present in the soil. It is known that the highest caesium uptake typically occurs in perennial grasses. As found recently in several field experiments in Belarus, ^{137}Cs removal rates for perennial grasses with an annual dry matter yield of 2 - 5 t/ha are less than 0.1 %. Phyto-extraction of caesium in normal agricultural practice therefore appears not to be a very efficient process [43].

- *Phyto-extraction project in Belarus*

The phyto-extraction effect of rape (Brassica sp.) is significant. Rape has a high ability to accumulate ^{90}Sr [43]. In the BRISSA field experiments the annual accumulation of ^{90}Sr in pods and straw reached approximately 3 % of the ^{90}Sr content in the soil (Table 4.15). Radionuclides incorporated in straw ploughed in just after harvesting will be unavailable for one to two subsequent growing seasons, until the final mineralization of the straw. The degree of ^{90}Sr immobilization by straw is comparable in size to the reduction of soil contamination due to radioactive decay.

Table 4.15 ^{90}Sr accumulation by varieties of spring rape related to podzoluvisol loamy sand soil with a deposition of 37 kBq/m^2 (1997–1998) [43]

Variety	Seed yield (t/ha)	^{90}Sr activity (Bq/kg)		^{90}Sr uptake (kBq/ha)		^{90}Sr uptake (% of total soil content)		
		Seeds	Straw	Seeds	Straw	Seeds	Straw	Total
Hanna (standard)	1.9	265	663	514	5 141	0.14	1.39	1.53
Yavor	1.9	240	648	451	4 873	0.12	1.32	1.44
Likosmos	2.0	264	686	541	5 628	0.15	1.52	1.67
Lirovel	1.8	275	688	501	5 005	0.14	1.35	1.49
Licoll	2.2	310	868	682	7 638	0.18	2.06	2.25
PF 7118/93	2.2	314	879	675	7 561	0.18	2.04	2.23
PF 7045/91	2.1	319	479	670	4 019	0.18	1.09	1.27
PF 7056/92	1.9	322	902	570	6 383	0.15	1.73	1.88
Iris	1.9	338	744	629	5 532	0.17	1.50	1.67
Orakel	2.1	344	826	726	6 968	0.20	1.88	2.08
PF 5045/88	2.2	345	759	742	6 527	0.20	1.76	1.96
PF 7369/94	2.3	358	967	816	8 815	0.22	2.38	2.60
Lizonne	1.7	395	1 027	675	7 025	0.18	1.90	2.08
PF 7410/94	1.9	407	1 140	765	8 570	0.21	2.32	2.52
Liazon	2.0	436	1 221	855	9 571	0.23	2.59	2.82
PF 7041/91	1.8	477	1 336	844	9 456	0.23	2.56	2.78
PF 7008/91	2.4	478	1 338	1 166	13 063	0.32	3.53	3.85

The phyto-remediation effect of growing rape may be increased by removing straw from the field and disposing of it safely. However, the disposal option is likely to be rather expensive and will deprive the soil of the necessary raw material for humus formation. Thus while phyto-remediation with rape appears feasible in principle, it might be more sustainable to operate the scheme as a means for enhanced attenuation.

Available data indicate a significant interspecies variability in the transfer of radionuclides from soil to plants. However, hard experimental data for the evaluation of phyto-extraction potential and for the development of an appropriate crop rotation scheme are rather scarce. Experimental data from Belarus show differences in the accumulation of ^{137}Cs for 32 varieties of spring rape between years of up to 1.8 - 2.7 times, and for ^{90}Sr of up to 1.8 - 4.0 times. It should be noted that these differences are radionuclide specific, meaning that one variety that accumulates less ^{137}Cs does not necessarily accumulate less ^{90}Sr. The experimental results from Belarus allow the identification of varieties that have the desired uptake properties: more uptake for phyto-extraction purposes or less uptake for minimizing the radionuclide content in the food pathway [43].

4.5.2.9 Rhizo-filtration treatment

Rhizo-filtration is the use of plants to sequester compounds from aqueous solutions through adsorption on the roots or assimilation through the roots and eventual translocation to the aerial biomass (phyto-extraction). Rhizo-filtration is being investigated for the removal of radionuclides from aqueous waste streams, including groundwater and wastewater [43].

Rhizo-filtration is particularly effective in applications with low concentrations and large volumes of water. Plants that are efficient at trans-locating metals to the shoots should not be used for rhizo-filtration, since additional contaminated plant residue is produced [43].

The removal of a radionuclide from an aqueous waste stream is governed by the plant dry weight production and the concentration factor (CF) (ratio of Bq/g plant to Bq/ml water or soil solution). Since adsorption in (waste)water per volume is lower than in soil, the concentration factor is higher than the transfer factor. This becomes clear when considering the relationship between the transfer factor and the concentration factor, which is:

$$TF = CF/K_D$$

in which K_D is the solid-liquid distribution coefficient of a radionuclide (e.g., dm^3/kg) (i.e., the ratio of radionuclide activity concentration in the solid phase to that in the soil solution). Since the value of K_D for most radionuclides is generally substantially higher than 1, it is clear that the concentration factor exceeds the transfer factor by the same factor and that rhizo-filtration is generally more effective than soil phyto-extraction [43].

A plant suitable for rhizo-filtration applications can remove toxic metals from solution over an extended period of time with its rapid growth root system. Various plant species have been found to effectively remove toxic elements such as arsenic, copper, cadmium, chromium, nickel, lead and zinc from aqueous solutions [43].

Pilot scale research on rhizo-filtration has found that the roots of sunflowers (Helianthus annuus L.) reduced levels of lead, copper, zinc, nickel, strontium, cadmium, U(VI), manganese and Cr(VI) to concentrations near to or below regulated discharge limits within 24 h. Beans and mustard were less effective than sunflowers in uranium removal. Virtually all uranium was concentrated in the roots, and almost none in the shoots. Removal was higher (by a factor of 2) at pH5 than at pH7 [43].

Uranium is clearly removed much faster from contaminated pond water than caesium and strontium (Figure 4.27). Sunflowers showed higher caesium and strontium removal rates than timothy, meadow foxtail, Indian mustard and peas [43].

However, rhizo-filtration has its limits. In an experiment with rather highly contaminated wastewater (1 mg/l U) and high flow rates (1.05 l/min), 95 % of the uranium was removed by 6 week old sunflowers grown for 2 weeks in the wastewater, resulting in effluent concentrations of 40 - 70 µg/l, which are above the 20 µg/l drinking water limit [43].

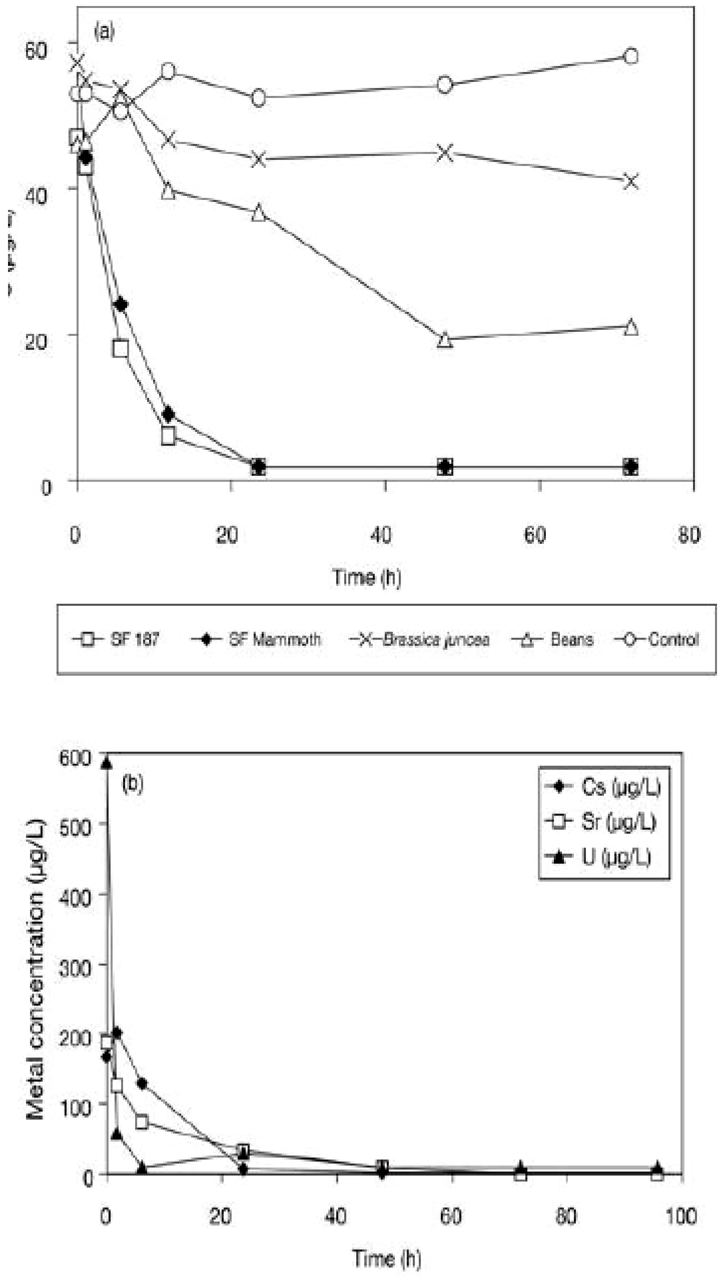


Figure 4.27 Removal of uranium by different sunflower cultivars (a) and removal of caesium, strontium and uranium by sunflowers (b) [43]

4.5.2.10 Non-biological in-situ treatment

Non-biological in-situ treatment comprises the following technologies:

- *Dynamic underground stripping and hydrous pyrolysis oxidation*

  Dynamic underground stripping and hydrous pyrolysis oxidation (DUS/HPO) is a combination of technologies that can rapidly remove organic contaminants from the subsurface where other technologies may take decades or more to achieve the desired clean-up criteria. For instance, in two field-scale applications, dynamic underground stripping and hydrous pyrolysis oxidation has achieved remediation performance in less than one tenth the time of conventional pump and treat methods, both above and below the water table, and at less overall cost [7]. Major elements of the technique include steam injection, air injection, vacuum extraction, electrical resistivity heating, groundwater extraction, surface treatment of vapour and groundwater, and underground imaging and monitoring.

Dynamic underground stripping is an innovative thermal remediation technology that accelerates removal of organic compounds, both dissolved phase liquids and dense non-aqueous phase liquids (DNAPL), from soil and groundwater. In dynamic underground stripping, steam is injected at the periphery of the contaminated area to volatilize and solubilize compounds bound to the soil. Centrally located vacuum extraction wells then remove this volatilized material from the subsurface. A steam front develops in the subsurface as permeable soils are heated to the boiling point of water, and volatile organic compounds are vaporized from the hot soil. The steam sweeps the permeable zones between the injection and extraction wells. Steam injection then ceases, while the vacuum extraction continues once the front reaches the extraction wells. The vapour and any groundwater pulled through the extraction wells are treated above ground. When the steam zone collapses, groundwater re-enters the treatment zone and the steam-vacuum extraction cycle is repeated.

For application in dense clays, electrical resistive heating can also be used to enhance contaminant removal. Water and contaminants in the conductive zone are vaporized and forced into the permeable zone, being swept by the steam and then subjected to vacuum extraction.

In hydrous pyrolysis oxidation, steam and air are injected into paired wells, creating a heated oxygenated zone in the subsurface. When injection is halted, the steam condenses and contaminated groundwater returns to the heated zone where it mixes with oxygen-rich condensed steam, which destroys dissolved contaminants in-situ.

An integral component of dynamic underground stripping and hydrous pyrolysis oxidation is a sophisticated imaging system known as electrical resistance tomography (ERT), which allows real time three dimensional monitoring of the subsurface. Electrical resistance tomography is based on a cross-hole tomography system that maps changes in resistivity over time. Changes in resistivity both laterally and vertically can be related to the migration of steam through various zones between the injection and extraction wells. Electrical resistance tomography is utilized to make process adjustments to optimize the performance of dynamic underground stripping and hydrous pyrolysis oxidation.

Limitations include:

- The process requires a large amount of energy.
- Above ground treatment systems must be sized to handle peak extraction rates and the distribution of volatile organic compounds (VOC) in the extracted vapour and liquid streams.
- Steam adds significant amounts of water to the subsurface, and precautions must be taken to prevent mobilization of contaminants beyond the capture zone.
- It is not applicable at depths of less than 1.5 m; to date it has been used at depths of up to 40 m.
- Micro-organisms destroyed by steam can foul the system, and small particles pumped to the surface can clog the system.
- Treated soils and groundwater can remain at elevated temperatures for years after clean-up, which could affect site reuse plans.

\- *Soil vapour extraction*

It may be necessary to capture and remove toxic or explosive gases before or while addressing other contaminants bound to the soil or in the groundwater. Soil vapour extraction uses a vacuum to remove volatile and some semi-volatile contaminants from the soil. The vapour-soil gas mixtures will be treated and discharged according to the applicable air discharge regulations. Extraction wells are typically used at depths of 1.5 m or greater, and have been successfully applied as deep as 90 m. Groundwater pumps may be used in conjunction with soil vapour extraction to keep groundwater from rising into the vadose zone as a result of the vacuum, or to increase the depth of the unsaturated zone. This area, termed the capillary fringe is sometimes highly contaminated, as it holds non-aqueous phase liquids lighter than water and vapours that have escaped from dissolved organic compounds in the groundwater below or from dense non-aqueous phase liquids. In soils where the contamination is deep or when there is low permeability, injecting air into the soil assists in extraction. During full-scale operation, soil vapour extraction can be run intermittently (pulsed operation) once the extracted mass removal rate has reached a steady state level. Because the process involves the continuous flow of air through the soil, it often promotes bio-degradation of low volatility organic compounds that may be present.

Soil vapour extraction can also be used ex-situ on piles of excavated soil. A vacuum is applied to a network of piping in the pile to encourage volatilization of organic compounds from the excavated media. A system for handling and treating off-gases is required.

A field pilot study is necessary to establish the feasibility of the method as well as to obtain information necessary to design and configure the system.

The soil vapour extraction technique is typically applicable to volatile organic compound and/or fuel contamination. It works only on compounds that readily vaporize (i.e., that have a high Henry's law constant). Some limitations of the soil vapour extraction technique include:

- A high soil moisture content requires higher vacua.
- Soils with high organic content or soils that are extremely dry have a high affinity and retention capacity for volatile organic compounds. These conditions limit its effectiveness.
- Soils with low permeability also limit its effectiveness.
- Applying a vacuum to the subsurface soils can raise groundwater levels. As the soils become saturated, some contaminants may dissolve into the groundwater. As a result, groundwater can show increased contamination levels, especially at the start of this process.
- It will not remove heavy oils, metals, **polychlorinated biphenyls (PCB)** or dioxins.
- Exhaust air from in-situ soil vapour extraction systems may require treatment. Off-gas treatment is usually carried out by adsorption onto granular activated carbon.
- It is not applicable to the saturated zone (except in the form of air sparging in wells).

- *Thermal methods*
    - *Electrical resistance heating* uses an electric current to heat less permeable soils such as clays and fine grained sediments so that water and contaminants trapped in these low conductivity materials are vaporized and ready for vacuum extraction. An array of electrodes is placed directly into the soil matrix and an (alternating) electric current passed through the soil, the resistance loss of which then heats the soil and the contaminants, increasing the vapour pressure of the latter. The heat also dries out the soil causing it to fracture. These fractures make the soil more permeable, increasing the removal rate of contaminants by soil vapour extraction. In addition, the heating creates an in-situ source of steam

to strip contaminants from the soil, inter alia reducing the viscosity of trapped liquids and eventually allowing them to be removed by soil vapour extraction. Six phase soil heating is a typical layout that uses a low frequency electric current delivered to six electrodes in a circular array to heat soils.

The following factors may limit the applicability and effectiveness of the process:

* It may be self-limiting, since as the clays heat up, they dry out and the current will stop flowing [7].
* Debris or other large objects buried in the media can cause focusing of the electrical field or short-circuiting.
* The performance is very much dependent on the type of organic substance involved and its vapour pressure, as well as the temperature and heat flows that can be achieved in the process selected.
* There is an optimum soil moisture content as the resistance increases with decreasing moisture content and the permeability in turn decreases with increasing moisture content.
* A low permeability will hinder the flow of steam and organic vapours towards the soil vapour extraction, thus leading to a low efficiency of the process due to the high energy input to increase vacuum and temperature.
* Soil with a highly variable permeability may result in accessibility to the contaminated regions being uneven.
* High soil organic matter content may reduce the efficiency of the technique due to the high affinity of organic contaminants for these constituents.
* Air emissions will need to be controlled to be below the limits of regulatory concern or permissions may need to be sought. Off-gas treatment and permits will increase project costs.
* Residual liquids and spent activated carbon may require further treatment or disposal.

- *Microwave heating* is based on the phenomenon that dipole molecules, such as those of water, can be stimulated in their vibrational movements by high frequency electromagnetic radiation. This vibrational energy is then dissipated in the form of heat. While many organic molecules are flexible enough to adjust themselves to the electromagnetic field, they still absorb photons, which may lead to the breaking of weak bonds. Such bonds can be either within the molecule or between the molecules and a surface. Thus, microwave applications will enhance recovery of organic contaminants by either volatilizing them, by reducing the viscosity due to increased ambient temperature or by detaching them from the geomatrix [7]. The microwave oven principle can be applied to soils in-situ, albeit on a grander scale.
- *Thermal conductance*: In-situ thermal treatment to enhance contaminant removal can also be accomplished by a technique where heat and vacuum are applied simultaneously to soil, sediments or buried wastes. Heat flows into the soil by conduction from heaters operated at approximately 800 - 1000 ºC. Vertical thermal wells are used for deep contamination and horizontal thermal wells are used for shallow contamination. Multiple wells are installed to span the areas requiring treatment. Electric heaters are installed in the wells and wired together with power tapped from utility poles or other power sources. Vapours are extracted from some of the wells to ensure the boundaries of the heated zone are under vacuum.

Most of the contaminant destruction occurs underground near the heat source. As soil is heated, contaminants in the subsurface are volatilized or destroyed by several mechanisms, including:

* Evaporation;
* Boiling;
* Oxidation;
* Pyrolysis;
* Steam distillation.

Volatilized contaminants not destroyed in the subsurface are recovered and treated above ground. A wide range of soil types can be treated by this process. The high temperatures applied over a period of days result in an extremely high destruction and removal efficiency even of contaminants with high boiling points such as **polychlorinated biphenyls**, pesticides and other heavy hydrocarbons.

Special consideration is needed when applying this process to sites with radionuclides and or toxic metals, such as mercury, as the heating process may change the oxidation state of these contaminants, which can make them more or less mobile in the environment.

4.5.2.11 Ex-situ treatment

Ex-situ treatment is the maximum intervention option. These technologies rely on bringing the waste or radioactively contaminated material to the remediation technology, rather than the other way around. The aims of ex-situ processing are to ensure a more consistent standard of clean-up, and avoid the difficulties inherent with in-situ techniques. Such techniques may not be suitable for the very low concentrations of activity likely for widespread contamination problems, due to small concentration gradients [3].

Ex-situ treatments of materials radioactively contaminated by non-radioactive substances such as oil, solvents, heavy metals and other chemicals have been applied on an industrial scale. The technologies adopted include soil washing, solidification, biological treatment and incineration.

Technologies to clean-up ground and surface waters contaminated with hazardous waste usually rely on pumping followed by ex-situ above ground treatment. The technologies applied closely resemble traditional water treatment technologies used to treat industrial and municipal wastewater.

If the waste is not diluted in the water, these ex-situ technologies are based on the effectiveness of the pumping system in capturing the wastes and bringing them to the surface with the groundwater for treatment. If pumping cannot remove the particles with the adsorbed contaminants from the aquifer, the ex-situ treatment technologies do not have an opportunity to treat them.

Enhancements to traditional pump and treat technologies include pulsed pumping, reinjection, and chemical extraction. These enhancements promote more efficient removal/treatment of less mobile contaminants in less homogeneous, less permeable aquifers.

Extraction of radioactively contaminated groundwater for treatment can be achieved by extraction wells or trenches. The regulatory authorities normally set criteria that must be met before the treated groundwater can be released or re-injected into the environment. The residual wastes from a groundwater treatment system may be radioactive enough to require disposal. If natural flushing is the appropriate procedure for aquifer restoration, the groundwater clean-up period may be shortened using gradient manipulation to direct the flow, injection wells to increase the flow rate, and limited extraction, treatment and re-infection.

Overall, ex-situ techniques are just a potential component in an overall waste/remediation strategy. Even if they are not applied directly to the waste, as in the groundwater examples above, they are of benefit for the treatment of secondary wastes generated by other treatment techniques. (An example is the use of solidification for conditioning of ion exchange resins used in the treatment of groundwater.)

The main ex-situ treatment technologies for all wastes fall into three categories: physical, chemical and biological. A separate section is also addressed to thermal treatment methods which were difficult to place into the mentioned categories.

4.5.2.12 Physical ex-situ techniques

These technologies rely on the physical properties of the materials to achieve separation or to fix the contamination to prevent the spread of activity. However, since physical separation of radionuclides is almost always associated with the removal of the clay fraction of the soil matrix, the process will result in a decrease in soil fertility. If the land is to be used for crop production, addition of soil conditioners such as fertilizers will be necessary to restore land fertility after the remedial activity.

Physical separation may be used with chemical extraction to produce fractions with higher concentration of contaminants in smaller volumes. The physical separation technologies may also be suitable for removing radionuclides which have been deposited as solid particulate in the soil.

- *Physical segregation*

  Contamination is often associated with particular size fractions or mineral phases of a soil. Separation and segregation of the contaminated fraction will greatly reduce the amount of material requiring further treatment and disposal, while freeing the reminder for reuse.

  A variety of separation techniques have been borrowed from mineral processing, including mechanical sieving and screening, hydraulic size fractionation in, for example, settling tanks or hydro-cyclones, specific gravity separators such as shaking tables or sluices, surface chemistry related processes such as froth floatation, and processes based on the different magnetic susceptibilities of different minerals. A combination of these techniques may be required to isolate the relevant fractions. Segregation is often the first step before one of the above chemical extraction methods is applied. The latter are also referred to as soil washing, if they form part of an extraction procedure.

  Liquid-particle separation involves removal and collection of dispersed or colloidal solid particles in a fluid suspension. Liquid-particle separation categories include: screening, membrane filtration, cycloning, flotation, thickening/sedimentation, filtration and centrifugation.

  Among these, filtration is the most widely used liquid-particle separation process applied to groundwater treatment from radionuclides and heavy metal contaminants.

- *Segmented gate systems*

  The segmented gate system (SGS) is a characterization and sorting technology that measures the radioactivity of soil, sand, dry sludge or any material that can be transported by conveyor belts, and mechanically separates radioactive contaminated material into clean and contaminated waste streams. This is accomplished by passing the material on a conveyor belt under an array of sensitive, rapidly reacting, radiation detectors that measure radionuclide concentrations. Material above the desired clean-up limits is automatically diverted into a separate waste stream. In this system, contaminants are isolated and removed by locating small particles of dispersed radioactive material, thus significantly reducing the overall amount of material requiring disposition as radioactive waste.

A variety of sensors can be utilized for detection of specific contaminants (i.e., sodium iodide, calcium fluoride or high purity germanium). Typical radionuclides that can be measured by segmented gate systems include ^{137}Cs, ^{60}Co, ^{226}Ra, ^{232}Th, ^{238}U and ^{241}Am. While the detection level for the system depends on the ambient radiation background, conveyor belt speed, thickness of the material layer on the conveyor, and contaminant gray energy and abundance, lower limits of detection, 0.074 Bq/g for ^{241}Am and 0.185 Bq/g for ^{226}Ra, have been successfully demonstrated.

- *Soil washing*

This ex-situ technique uses pH controlled solutions with the addition of acids or bases, surfactants to dissolve, desorb and remove contaminants. Organic solvents may be used for organic contaminants. A preceding size fractionation improves efficiency and reduces the volumes of material to be treated.

Soil washing techniques are promising for an application to soils contaminated with a wide variety of heavy metal, radionuclide and organic contaminants. Complex mixtures of contaminants in the soil, such as a mixture of metals, non-volatile organic compounds and semi-volatile organic compounds, and heterogeneous contaminant compositions throughout the soil make it, however, difficult to formulate a single suitable washing solution that will consistently and reliably remove all of the different types of contaminant. For such cases, sequential washing, using different washing formulations and/or different soil to washing fluid ratios, may be required. Soil washing is a media transfer technology, i.e., the resulting contaminated water or other solvents need to be treated with a suitable technique and disposed of. The technique offers the ability for recovery of metals and can clean coarse grained soils from a wide range of organic and inorganic contaminants:

- Aliphatic hydrocarbons, i.e., mineral oils;
- Polycyclic aromatic hydrocarbons (PAHs);
- Heavy metals such as Cu, Zn, Pb, Cd, Cr, Hg, Co, Ni and Sn;
- Pesticides such as insecticides, herbicides and fungicides;
- Other organic halogenated compounds (e.g., **polychlorinated biphenyls**) or phenolic compounds;
- Inorganic contaminants, such as arsenic or cyanide compounds (free or complexed).

A major disadvantage of soil washing is that in many cases it will destroy the (biological) functionality of the soil, in particular when applied to topsoil. The functionality of topsoils depends on the mixture between different grain sizes, the clay and humus contents, and the indigenous microbial flora and fauna. Often a sterile product results, as the latter two constituents are removed or destroyed. Experiments are under way in various countries to reconstitute functionality by adding compost to the soil before returning it to nature.

4.5.2.13 Chemical ex-situ techniques

Ex-situ chemical methods are based on chemical or physico-chemical extraction of soils treated with inorganic and organic solvents to dissolve and selectively remove metals, including radionuclides or to enhance physical separation. For liquids, the aim is to reduce the volume of material to be handled by selective removal of contaminants.

- *Chemical/Solvent extraction*

The effectiveness and efficiency of a given solvent will depend on the type of binding between the radionuclide and the soil substrate and on the chemical species of the radionuclide. The choice of chemicals that can be applied is much more varied than for in-situ treatment, given the better control of the processes and the fact that the operation can be carried out in closed reaction vessels. Considerations of environmental impact from the remediation operation, for example unwanted effects on the groundwater and aquifers, are restricted to considerations that apply to similar industrial operations.

This method uses a chemical extractant to remove the contamination from the waste, with the aim of concentrating the activity into a separate liquid stream, which can then be treated/disposed separately. The conditions for chemical extraction (temperature, contact time, etc.) will have a significant affect on the efficiency of extraction. The various applicable chemical extraction techniques for solids include extraction with:

- Water;
- Inorganic salts;
- Mineral acids, and
- Complexing agents.

For liquids, solvent extraction is more usual, where a solvent is used to selectively remove the contaminant from the wastewater stream. Solvent extraction is viable when there is a high concentration of contaminant to be removed.

However, care must be taken in the selection of the solvent; firstly so that regeneration of the solvent is possible by stripping out the contaminant (to avoid creation of an additional waste), and secondly that the residual solvent in the cleaned wastewater will not result in adverse effects (e.g., non-radioactive pollution of the aquifer or enhanced mobilization of residual activity) [3].

- *Heap leaching*

The contaminated material (generally soil) is excavated and placed (heaped) on an impermeable pad on the surface of the ground. The pad is sloped towards a sump at the bottom edge of the heap. The selected leaching reagent(s) are pumped to the top of the heap and distributed with a drip irrigation system or aerial sprayers. The reagent travels down through the soil, solubilizing and mobilizing the contaminants. The leachate is collected from the sump and pumped to a leachate treatment and regeneration system. The principle of the method is displayed in Figure 4.28.

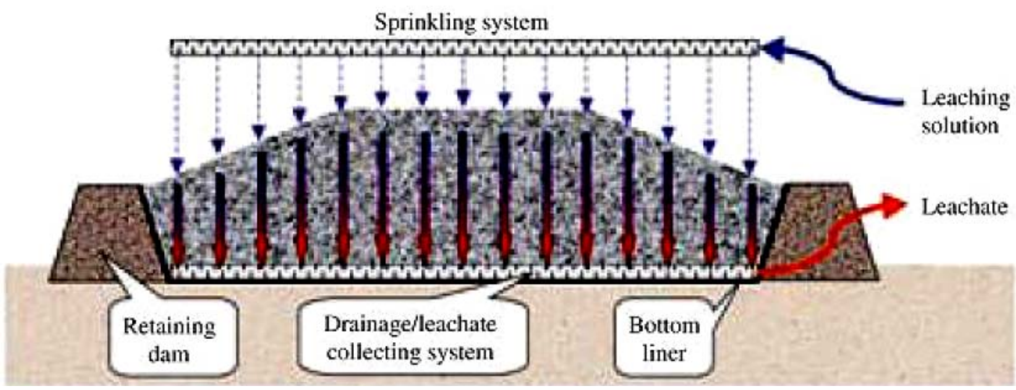


Figure 4.28 A heap leaching system

- *Enhanced soil washing*

  This method combines the physical separation of soil washing with chemical extraction. The net result is a concentration of the waste material into the fines fraction, and reduced loadings of contaminants in the coarse fractions. The enhancement of standard soil washing improves the decontamination of the cleaned material for return to site.

  Additional processes may be added to the basic soil washing process (e.g., crushing, froth flotation, activated carbon addition) and the wash medium may operate with chemical additives to enhance performance, e.g., pH adjusters, detergent addition, coagulants/flocculants, etc.

- *Chemical precipitation*

  Chemical precipitation is used to remove soluble activity from liquids, both as a volume reduction method and to permit it to be disposed of separately. This also includes related techniques such as coagulation and floe precipitation. Because of concentration effects and solubility limits, these techniques are more effective for high concentrations of contaminants.

  The precipitation has long been a primary method of treating metal laden industrial waste and drinking waters. Because of the success of this process in these applications, the technique is often considered and selected for use in groundwater remediation containing heavy metals, including their radioactive isotopes. In groundwater treatment, the metal precipitation process may be used as a pre-treatment for other treatment techniques (such as chemical oxidation or air stripping) where the presence of metals would otherwise interfere with the other treatment processes.

  In the specific case of radium contamination, barytes ($BaSO_4$) can be used to co-precipitate radium from the water, as radium can substitute for barium in the mineral structure. Attempts have been made to clean radium contamination from mining waters. In addition, barytes is a desired admixture in any radioactively contaminated materials due to its effective attenuation of gamma radiation [3].

- *Ion exchange*

  Ion exchange is the complement to chemical removal. This removes soluble activity from liquid wastes and concentrates it onto a solid ion exchange material. The ion exchange materials function at lower concentrations of activity than chemical removal. Selection of the correct ion exchange material is important. Certain materials are used to hold the activity for disposal, others can be regenerated using an eluting agent (normally a mineral acid or similar). In the latter case, the concentrated eluant may then be treated by chemical methods.

  Ion exchange can remove dissolved metals and radionuclides from aqueous solutions. Other compounds that have been treated include nitrate, ammonia and silicate. There are a number of factors that affect the applicability and effectiveness of the process:

  - Oil and grease in water may clog the ion exchange media.
  - A suspended solid content higher than 10 ppm may cause resin binding.
  - Low pH values of the influent may lead to effective competition of the protons with the contaminant ions for binding sites and, hence, a reduction in the efficiency of the process.
  - Strong oxidants in the water may damage the ion exchange resin.

- *Adsorption*

  This method uses adsorption of the contaminant by various media, such as granular activated carbon, which is a common medium for drinking water treatment; activated alumina, which can be used for the treatment of some radioactive compounds; and selective complexes, which essentially complex the contaminant and are not regenerable. It is therefore similar to the use of ion exchange.

The physico-chemical process of adsorption can be used to remove contaminants from liquids, slurries or gases. The process is based on the affinity of some constituents for certain types of surface. An adsorbent, for example certain types of clay, zeolites and granulated activated carbon, is brought into contact with a contaminated medium. After saturation has been reached, the adsorbent with the contaminant attached is removed for further processing. The contaminant is either desorbed, i.e., the adsorbent is 'regenerated', or the adsorbent is conditioned and treated, for example cemented into drums, for storage and disposal.

The most common adsorbent is granular activated carbon. Other natural and synthetic adsorbents include: activated alumina, forage sponge, lignin, sorptive clays and synthetic resins [7].

Adsorption can also be used for radon if decontamination of slowly released gas is required. Polyethylene coated activated carbon is used to adsorb the radon gas, as the polyethylene coating is permeable for radon diffusion but can stop any other gas or vapours which can reduce the adsorption quality of carbon.

The target contaminants for adsorption processes are most organic contaminants and selected inorganic contaminants from liquid and vapour streams. Factors that may limit the applicability and effectiveness of these processes include:

- Poor sorption of water soluble organic compounds and monovalent ions;
- High costs if used as the primary treatment on waste streams with high contaminant concentrations;
- Typically not applicable to sites with high levels of oily substances;
- Not practical where the concentrations of contaminants are so high that sorption capacities are quickly reached and frequent replacement of the adsorption unit is necessary.

- *Aeration*

Aeration is used to remove volatile compounds from wastewater. Generally, this is to remove organic compounds with the potential to complex radionuclides. In the context of radioactively contaminated wastewaters, aeration can be used to sparge out radon, which can then be treated. In addition, aeration can be used to alter the redox potential of the wastewater prior to subsequent chemical treatment, to facilitate removal of certain radionuclides (e.g., uranium).

- *Ozonation and peroxide application*

Oxidation processes including ultra-violet radiation, ozone and/or hydrogen peroxide are used to destroy organic contaminants as water flows into a treatment tank. If ozone is used as the oxidizer, an ozone destruction unit is used to treat collected off-gases from the treatment tank and downstream units where ozone gas may collect, or escape.

Ultraviolet oxidation is a destruction process that oxidizes organic and explosive constituents in water by the addition of strong oxidizers and irradiation with ultra-violet light. Oxidation of target contaminants is caused by direct reaction with the oxidizers, ultra-violet photolysis and the synergistic action of ultra-violet light, in combination with ozone (O_3) and/or hydrogen peroxide (H_2O_2). If complete mineralization is achieved, the final products of oxidation are carbon dioxide, water and salts.

The main advantage of ultra-violet oxidation is that it is a destruction process, as opposed to air stripping or carbon adsorption, for which contaminants are extracted and concentrated in a separate phase. Ozonation is routinely applied in waterworks to disinfect raw water during the production of drinking water.

Similarly, hydrogen peroxide is a strong oxidant that has been used to disinfect water and to oxidize organic contaminants. Peroxide can also be applied to slurries or soils made into slurries. The disadvantages are relatively high costs and the fact that a considerable portion of the peroxide is consumed by the soil organic matter. An unwanted side effect is that a largely sterile soil will result due the latter effect.

Practically any organic contaminant that is reactive with the hydroxyl radical can potentially be treated by oxidation and ultra-violet oxidation. A wide variety of organic and explosive contaminants are susceptible to destruction, including petroleum hydrocarbons; chlorinated hydrocarbons used as industrial solvents and cleaners, and explosive compounds such as tri-nitro-toluene (TNT), cyclo-trimethylene-trinitramine (RDX) and high melting point explosive, cyclo-tetramethylene-tetranitramine (HMX). In many cases, chlorinated hydrocarbons that are resistant to bio-degradation may be effectively treated by ultra-violet oxidation. Typically, easily oxidized organic compounds, such as those with double bonds (e.g., tri-chloro-ethylene (TCE), per-chloro-ethylene (PCE) and vinyl chloride), as well as simple aromatic compounds (e.g., toluene, benzene, xylene and phenol), are rapidly destroyed in ultra-violet oxidation processes.

4.5.2.14 Biological ex-situ techniques

These methods use the same generic treatment processes as for in-situ remediation (see Section 4.5.2.6). Unlike the in-situ processes, however, for ex-situ treatment the contaminated material, micro-organisms and nutrients are added to a suitable mixing vessel. Conditions are then optimized to degrade the contaminants. Most biological treatment is aimed at degradation of organic materials, and so will have value with mixed (hazardous/radioactive) contamination.

The use of mobilizing micro-organisms (siderophores, bio-mimetic analogues, etc.) is also feasible. These use bio-chemistry to convert the radionuclides to a soluble form. The process results in a leach solution that is treated to remove and concentrate the contaminants. The treated leach solution is then recycled to minimize costs and secondary wastes.

The main advantage of ex-situ soil treatment is that it generally requires shorter time periods than in-situ treatment, and there is more certainty about the uniformity of treatment because of the ability to homogenize, screen and continuously mix soils. An advantage over thermal treatment is that no volatile radionuclides need to be contained. However, ex-situ treatment requires excavation of soils, leading to increased costs, equipment engineering requirements, possible permission needs, and material handling and worker exposure considerations.

A difficulty with the use of biological methods is their viability, both in terms of maintaining a viable bio-culture (nutrient supply, temperature variations, absence of biocides in the material to be treated), and with the low tolerance of certain micro-organisms to high radiation fields.

This group of techniques usually involves spreading excavated contaminated soils in a thin layer on the ground surface and stimulating aerobic microbial activity within the soils through aeration and/or the addition of minerals, nutrients and moisture [7].

Examples of biological ex-situ treatment methods are:

- *Land farming and bio-piles*

  Land farming (Figure 4.29) has been proven effective in reducing concentrations of nearly all the constituents of petroleum products. Petroleum products generally contain constituents that possess a wide range of volatility. In general, gasoline, kerosene and diesel fuels contain constituents with sufficient volatility to evaporate from a land farm. Lighter (more volatile) petroleum products (e.g., gasoline) tend to be removed by evaporation during land farm aeration processes (i.e., tilling or plowing) and, to a lesser extent, to be degraded by microbial respiration. Depending upon the regulations for air emissions of volatile organic compounds, these emissions may need to be controlled, for example by putting the land farm under a tent. The midrange hydrocarbon products (e.g., diesel fuel and kerosene) contain lower percentages of lighter (more volatile) constituents than gasoline. Bio-degradation of these petroleum products is more significant than evaporation. Heavier (non-volatile) petroleum products (e.g., heating oil and lubricating oils) do not evaporate during land farm aeration; the dominant mechanism that breaks down these petroleum products is bio-degradation. However, higher molecular weight petroleum constituents, such as those found in heating and lubricating oils, and, to a lesser extent, in diesel fuel and kerosene, require a longer period of time to degrade than do the constituents in gasoline.

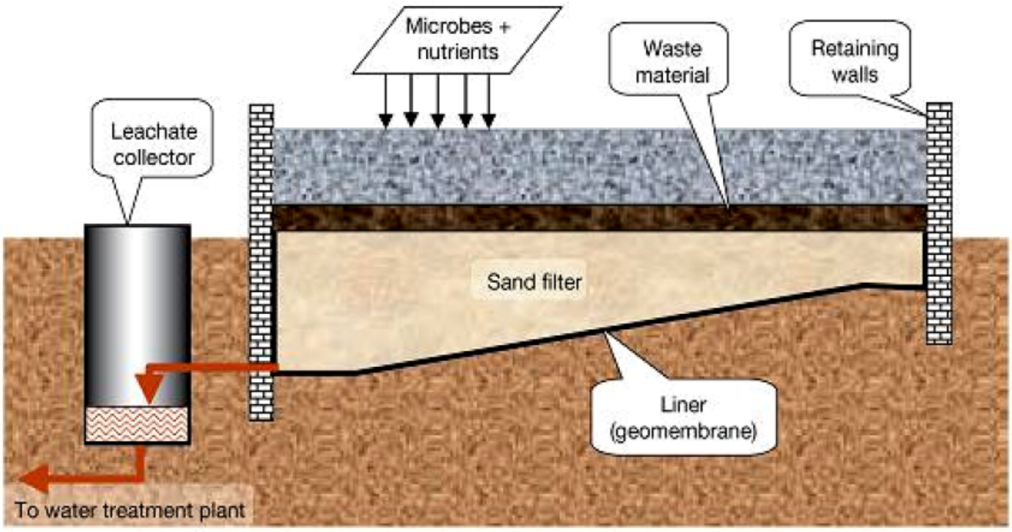


Figure 4.29 Land farming to treat organic wastes

While the technological and process control requirements are not very sophisticated, a large land area may be required for larger quantities of contaminated soil. Typical land farms are uncovered and, therefore, exposed to climatic factors including rainfall, snow and wind, as well as ambient temperatures. Rainwater that falls directly onto, or runs onto, the land farm area will increase the moisture content of the soil and may cause erosion. During and following a significant precipitation event, the moisture content of the soils may be temporarily in excess of that required for effective bacterial activity. On the other hand, during periods of drought, the moisture content may be below the effective range and additional moisture may need to be added. Erosion of land farm soils can occur during windy periods and particularly during tilling or plowing operations. Wind erosion can be limited by plowing soils into windrows and applying moisture periodically. In colder regions the length of the land farming season typically ranges from 7 to 9 months. In very cold climates, special precautions can be taken, including enclosing the land farm within a greenhouse type structure or introducing special bacteria (psychrophiles) that are capable of activity at lower temperatures. In warm regions, the land farming season can last all year.

The technical arrangements for land farming or bio-piles may include the construction of leachate capture and treatment systems as well as vapour and odour control (Figure 4.29 and Figure 4.30). Control of soil moisture, for example by drainage, may also be required to provide optimum growth conditions. Soils may need to be pre-treated to adjust pH to the optimum, circum-neutral range for most organisms. Growth can be stimulated by addition of nutrients, for example nitrogen and phosphorus, or essential elements, if respective deficiencies exist in the soils to be treated. Cattle or chicken manure is a typical additive, which also introduces additional micro-organisms. Microbial strains specialized to particular contaminants may be obtained as inoculants from commercial suppliers.

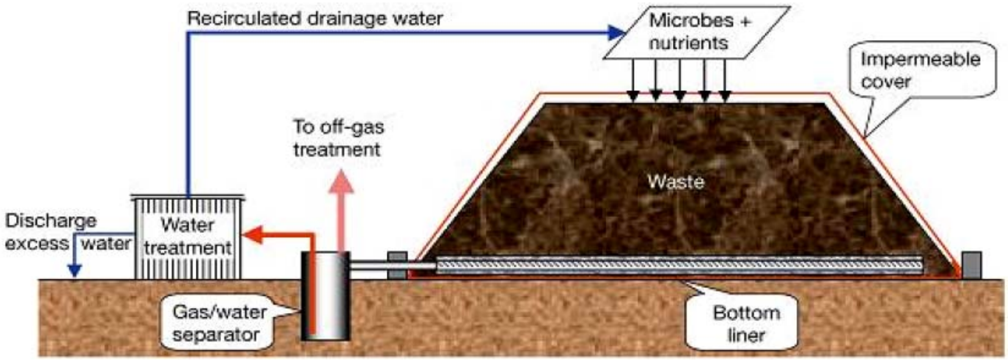


Figure 4.30 The principle of bio-pile arrangements

- *Bio-reactors*

The principles of the treatment process in bio-reactors are rather similar to those of land farming except that the process takes place in a closed vessel and is, therefore, amenable to tighter process control.

Slurry phase biological treatment involves the controlled treatment of excavated soil in a bio-reactor (Figure 4.31). The excavated soil is first processed to physically separate stones and rubble. The soil is then mixed with water to a predetermined concentration dependent upon the concentration of the contaminants, the rate of bio-degradation and the physical nature of the soils. Some processes prewash the soil to concentrate the contaminants. Clean sand may then be discharged, leaving only contaminated fines and wash water to bio-treat. Typically, a slurry contains from 10 to 30 % solids by weight [7].

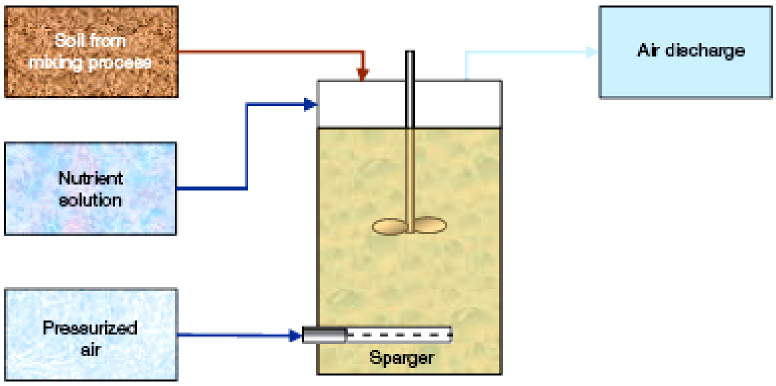


Figure 4.31 A typical bio-reactor arrangement

The solids in a reactor vessel are maintained in suspension and mixed with nutrients and oxygen. If necessary, an acid or alkali may be added to control pH. Micro-organisms also may be added if a suitable population is not present. When bio-degradation is complete, the soil slurry is dewatered. Dewatering devices that may be used include clarifiers, pressure filters, vacuum filters, sand drying beds and centrifuges. Slurry phase bio-reactors may be classified as short to medium term technologies.

A variety of bio-remediation methods have been developed for ex-situ metal recovery. These methods may range from complex, process controlled sets of bio-reactors to relatively simple heap leaching arrangements (see below). Such methods can have the added value of recovering metals in relatively high purity making them a marketable commodity that would help to pay for the treatment [7].

Factors that may limit the applicability and effectiveness of the slurry phase bio-treatment process include [7]:

- Excavation of contaminated media is required, except for lagoon implementation.
- Sizing of materials prior to putting them into the reactor can be difficult and expensive. Non-homogeneous soils and clayey soils can create serious material handling problems.
- Dewatering soil fines after treatment can be expensive.
- An acceptable method for treating and disposing of non-recycled wastewater is required.

\- *Bio-leaching*

Bio-leaching occurs naturally when micro-organisms assist in the slow weathering of out-cropping sulphide ore bodies. Bio-leaching is an established bio-technological process for the dissolution and hence mobilization of valuable metals from ores by micro-organisms. Metals for which this technique is mainly employed are copper, cobalt, nickel, zinc, gold, silver and uranium. It is estimated that about 20 - 30 % of the world's copper production originates from bio-leaching; in the case of uranium it is judged to be about 5 - 10 %. Bio-leaching has also been promoted as a cost efficient method for metal value recovery in developing countries, and its applicability in this context has recently been reviewed [43].

Bio-leaching also has scope for application in reworking waste material from mining for enhanced recovery of metals, including radionuclides, which has the potential to reduce the environmental burden. The method has been explicitly applied to the remediation of uranium and other mining legacies. The pathways of the resulting contaminated waters have to be carefully controlled, for example by arrangements similar to those for heap leaching (see Section 4.5.2.11). Microbially mediated leaching processes frequently have the unwanted side effect of acid mine drainage (AMD) generation, for example by pyrite oxidation [43].

The types of ore that are amenable to bio-leaching comprise sulphides, carbonates and oxides. The groups of micro-organisms involved are mainly bacteria and fungi. In some cases algae and lichens may also play a role. Various mechanisms are involved, depending on the type of ore in question.

In the case of sulphidic minerals the predominant dissolution causing micro-organisms are acidophilic (meaning organisms living between pH0 and pH5) bacteria of the sulphur and iron cycles, namely *Acidithiobacillus* (abbreviation A., former name Thiobacillus) *ferro-oxidans*, *A. thio-oxidans*, *Leptospirillum* (abbreviation *L.*) *ferro-oxidans*, *A. caldus*, *Metallogenium* sp., *Sulfobacillus thermosulfido-oxidans*, *Sulfolobus* sp., *Acidianus brierleyi* and several others. The species of *Acidithiobacillus* live in the moderate temperature range (0 - 45 ºC), *Metallogenium* and *Sulfobacillus* thrive at elevated temperatures (40 - 65 ºC) and *Sulfolobus* and *Acidianus* are thermophiles growing from 65 to 90 ºC.

The dissolution is generally effected by two mechanisms, depending on the type of mineral to be dissolved:

- Pyrite and molybdenite and a few other minerals of the same structure can only be dissolved by an oxidizing attack on their crystal lattice, owing to their electronic configuration (non-bonding outer orbitals) [43]. The bacteria able to do this are the Fe(II) oxidizing *A. ferro-oxidans*, *L. ferro-oxidans* and *Acidianus* sp. This mechanism is known as the thio-sulphate mechanism.

- All other sulphidic minerals possess bonding outer orbitals and thus are more or less dissolvable by a hydrolytic attack involving protons. In addition, Fe(III) ions further the dissolution by an oxidizing attack. These minerals may consequently be dissolved by all the above mentioned bacteria of the sulphur and iron cycles. This dissolution process is known as the polysulphide mechanism.

In both cases, the dissolution of the mineral is mainly effected by bacteria attached to the surface of the respective mineral. The compounds mediating such attachment are exopolysaccharides (EPS) (‘slimes’). The exopolysaccharides consist, from a chemical point of view, mainly of lipids, carbohydrates, sugar acids (uronic acids) and complexed, inorganic ions such as Fe(III) ions. The distance between the bacterial cell and the mineral substrate surface is of the order of 20 to 50 nm. This space is filled with the exopolysaccharide, creating a reaction space with unknown conditions of pH, redox and ion concentrations; the reaction space is an extension of the radius of action of the cell, thus allowing it to augment its food supply. As a consequence, biological leaching becomes considerably accelerated (sometimes more than 100-fold) compared with the purely chemical process utilizing Fe(III) ions and/or protons only. In the latter process the freely suspended planktonic cells also have to be considered, since their effect is mainly the re-oxidation of the iron ions in solution. Bio-leaching is thus an interface process and belongs to the area of nano-bio-technology.

Final products of dissolution are metal cations, Fe(III) ions, sulphate and/ or sulphuric acid. The energy of the oxidation is partially conserved by the bacteria for metabolic purposes and growth. The bacteria possess specialized cell components allowing them to conserve some of the energy in a utilizable form (adenosine tri-phosphate (ATP), nicotinamide adenine dinucleotide (NADH)). Furthermore, they need only carbon dioxide from the air to build up their cell mass and inorganic trace elements. These are therefore very specialized organisms; this type of metabolism is called litho-autotrophy.

The above mentioned bacteria are generally not important for carbonate and/or oxide ores. Bacteria and fungi are used for dissolving such minerals, which, due to an unbalanced metabolism, excrete organic acids. This requires an ample supply of exogenous carbon sources, which they metabolize, and as a consequence of either too much substrate, or a lack of essential nutrients or trace elements such as nitrogenous compounds or minerals, excrete partly in an intermediate oxidation state. Excreted acids are, for example, citric, oxalic, succinic, malic, acetic and/or formic acid, and sugar (uronic acids) or amino acids. These acids dissolve and/or complex metal cations and thus solubilize them.

The bio-leaching technique is employed in several forms:

(a) In the case of low grade ores that for economic reasons cannot be processed by conventional roasting or other similar processes, a heap leaching process is applied (see Section 4.5.2.11). In the majority of cases in which this technique has been applied to date, the ore contained copper, zinc and trace elements. A limited number of experiments of this type have been performed for extracting uranium from low grade ores. One experiment was carried out near Ronneburg, Germany, by Wismut in the 1980s, another one at Elliott Lake in Canada. For this purpose large amounts of low grade ores are placed on leach pads (plastic liners) or dumped in valleys with a known and impermeable geological strata and sprinkled regularly with acidified bacteria-containing solution (which originates from similar operations or from acid mine waters). The dissolved metals and sulphate plus sulphuric acid are left to accumulate to a concentration at which extraction processes such as solvent extraction, ion exchange and/or electro-winning become viable. Residence times for such operations range from several months to a few years. If these heaps are constructed without consideration of the underlying geology and/or abandoned without care, acid mine-rock drainage (ARD) or acid mine drainage (AMD) may result. Abandoned mines, mine shafts, open pits, etc., might also produce and release acid mine-rock drainage (ARD). Owing to the acidity combined with dissolved heavy metals, this might result in serious environmental damage and/or even create new ecosystems (as in Rio Tinto, Spain).

(b) Bio-leaching has been employed experimentally at the field scale in Germany to treat heavy metal contaminated sediments [43]. The generic scheme from the raw sediment to a viable soil substrate is illustrated in Figure 4.32.

(c) In the case of sulphidic concentrates, bio-leaching is increasingly used for extracting precious metals. In recent years several plants have gone into operation that use acidophilic leaching bacteria for extracting gold, nickel and cobalt. The operation usually consists of stirred tanks (bio-reactors) with volumes of up to 1000 m^3 in continuous operation. Residence times are in the range of 3 to 7 days.

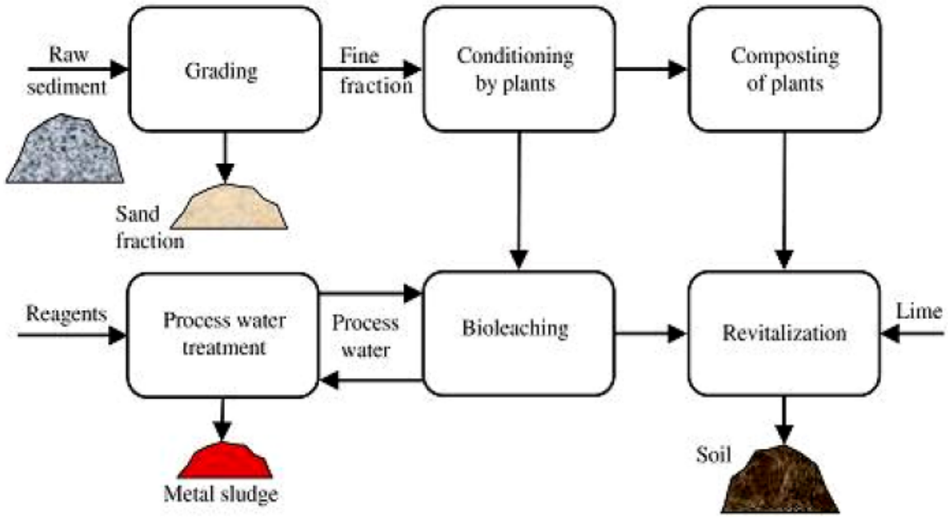


Figure 4.32 The experimental process from raw contaminated sediment to reconditioned soil [43]

In the case of radioactive minerals, there may also be another, unwanted effect: an enhanced emission of radon. Comparison of the radon emission rates and bio-leaching activity at the above mentioned leaching waste heaps near Ronneburg, Germany, has shown that high cell numbers of leaching bacteria were found at sites with high radon emissions, whereas at sites with low emissions only low cell numbers occurred. An explanation for this effect comes from the mineralogy of the ore. At Ronneburg the uranium is embedded in pyrite. Once this pyrite has been attacked by bio-leaching, radon is liberated and may escape into the atmosphere. This causes an additional exposure for the local population and requires measures to reduce or even inhibit the biological process.

- *Bio-sorption*

Micro-organisms, such as bacteria or fungi, have been used as minute biological reactors that can efficiently and economically carry out specialized operations. Microbial biomass, whether living or not, has been shown to selectively sequester and retain elements from dilute aqueous solutions via a process named bio-sorption.

Through the process of bio-sorption the bio-sorbed species are selectively removed from the solution and are retained inside the microbial cells (biomass) in concentrations that are several orders of magnitude higher than those in the original solution. Heavy metals and radionuclides are taken up into cellular components such as the cell walls of certain micro-organisms, which then can be harvested, carrying along the sequestered radionuclides. Bio-sorption is being explored in hydrometallurgy to concentrate metal bearing solutions, for example from heap leaching, and in the treatment of contaminated mining effluents [43].

Engineering developments in the area of bio-sorption have led to the design of engineered bio-sorbents, microbial biomass cells or cellular components immobilized on or within various matrices, thus acquiring the form of small particles such as those of conventional adsorbents (e.g., activated carbon) or ion exchange resins. Organic cellular material derived from higher plants or algae have also been proposed as the basic material for manufacturing bio-sorbents that can be used for the extraction of metals, including radionuclides [43].

Bio-sorption methods are largely ex-situ methods applicable for diluting contaminated solutions such as groundwaters or seepage. The contaminated solution is pumped into engineered reactors, in which it contacts the immobilized microbial biomass under optimized conditions (solution pH, flow rate, etc.). The contaminants are retained in an insoluble form by the biomass and the treated solution is let out of the reactor. The process of bio-sorption is reversible under certain conditions, which means that after the bio-sorbent is exhausted it could potentially be used for regeneration, releasing the previously held radionuclides in a small volume of the regenerating solution. Alternatively the bio-sorbent could be used once through and then disposed of appropriately.

Bio-sorption is an equilibrium process, with solution pH playing the role of the master variable, since it defines the speciation of the elements in the solution. This also means that the key driving force that dictates the bio-sorptive uptake capacity of the biomass in terms of mass of bio-sorbed species per unit mass of bio-sorbent (also referred to as the loading capacity) is the residual concentration of the contaminants after treatment and not the initial contaminant concentration [43].

The optimal bio-sorption pH depends on the biomass used and on the elements being removed; for example, the bio-sorption of uranium by the fungus Rhizopus arrhizus appears to be optimal at pH4, with significant reduction of the metal uptake capacity as the pH drops to pH2. The increased concentration of hydrogen ions at the acidic pH along with the chemical effects on the cell walls of the micro-organisms is responsible for this reduction in capacity. However, increasing the pH towards neutral values may again create operational problems, depending on the composition of the contact solution. The hydrolysis and subsequent precipitation of ferric ions which adsorb on to (coat) the bio-sorbent adversely affect the bio-sorption process [43].

The bio-sorption of metals by algal biomass is another example in which the sequestering of metals such as lead, zinc or copper by micro-organisms such as Chlorella vulgaris, Chlorella regularis or Chlamydomonas sp. is optimal in the range of pH6 to pH8. The bio-sorption of oxy-anions such as chromates or selenates by the same type of algae has an optimal bio-sorption pH in the acidic range of pH2 to pH3 [43].

Bio-sorption of ^{226}Ra by several types of micro-organisms, such as Rhizopus arrhizus, Aspergillus niger and Streptomyces niveus, exhibited an optimal contact pH in the neutral to alkaline range, with corresponding radium equilibrium uptake capacities in the range of tens of MBq/g. It is therefore obvious that optimization of bio-sorption processes should be made on a case-by-case basis and requires increased care so that the process will perform satisfactorily.

Considerable efforts have been made to understand the underlying mechanisms of bio-sorption and to improve the process efficiency. The available information has shown that cell walls are the major bio-sorption functional sites for heavy metals, uranium and thorium. It has also been shown that extracellular polymeric substances (EPS) play a significant role in bio-sorption [43]. The molecular level understanding of the bio-sorptive processes is still limited to selected pairs of metals and micro-organisms. The microbial biomass provides ligand groups on to which the metal species bind. In addition, sorptive and hydrolysis processes play a role. Three major classes of microbial bio-polymers (proteins, nucleic acids and polysaccharides) provide bio-sorption sites. Different ionic species of a given element might exhibit preference for a different binding site. Should the preference of one metal ion for a ligand be similar to that of another ion, a bio-sorption competition effect might be observed if both elements are simultaneously present in the contact solution.

A model of bi-sorption competition effects that is based on Pearson's classification of metals has been reported as a basic tool for understanding such effects. On the basis of this model, significant ionic competition effects can be observed for metals belonging to the same Pearson classification class. Elements belonging to different classes demonstrate limited competition, while elements belonging to the Pearson's classification borderline class are affected by the presence of competing co-ions. Additional systematic work for the mechanistic understanding of bio-sorptive processes and the associated ionic competition effects is required [43].

Numerical simulation techniques play an important role in designing and assessing remediation processes, including those using bio-technological methods [43]. Although bio-sorption using inactive microbial biomass has been demonstrated to be effective in substantially removing (and in some cases recovering) targeted radionuclides such as uranium, radium and thorium from contaminated solutions, a full scale commercial application is not yet available. The use of living micro-organisms in innovative reactor configurations has recently been under investigation for the same purposes as conventional bio-sorption. This approach to the biological sequestering of metals has substantially different requirements and operating conditions than conventional inactive biomass bio-sorption. This alternative bio-technological approach is often referred to as bio-accumulation or bio-precipitation and is showing excellent potential.

4.5.2.15 Thermal ex-situ techniques

Excavated contaminated soils or sludges are also the subject of heat treatment ex-situ when other methods are not applicable. Described methods below include:

- distillation as a heat chemical separation technique;
- incineration as a destruction method to transfer contaminants from soil and sludge to a safer state;
- pyrolysis used for decomposing organic contaminants in excavated soil or sludge by heat in anaerobic conditions;
- thermal desorption of soil and waste to temperatures in which organic contaminants become volatile and desorb;
- vitrification for destroying or removing organic compounds and immobilizing most inorganic compounds in contaminated soil or sludge (method described in Section 4.5.1.11);
- fluid bed steam reforming to destroy organic contaminants by high temperature steam.

Features of the above mentioned techniques are:

- *Distillation*

  Basically, distillation is a chemical separation process involving vaporization and condensation that is used to separate components of varying vapour pressures (volatilities) in a liquid or gas waste stream. Simple distillation involves a single stage operation in which heat is applied to a liquid mixture in a still, causing a portion of the liquid to vaporize. These vapours are subsequently cooled and condensed to a liquid product termed the distillate or overhead product. The distillate is enriched with the higher volatility components. Conversely, the mixture remaining in the still is enriched with the less volatile components. This mixture is termed the bottoms product. Multiple staging is utilized in most commercial distillation operations to obtain better separation of organic components than is possible in a single evaporation and condensation stage.

Most organic contaminants and certain radionuclides (^{210}Pb and ^{210}Po), heavy metals (Hg) and cyanide are volatile. The volatility increases with temperature so that such contaminants can be driven off by heating the soils concerned and recovering the gaseous contaminants. Distillation is also a side effect of the various in-situ thermal treatment methods discussed in Section 4.5.2.5. Ex-situ, the process can be made more efficient, if carried out in a vacuum. The variation in boiling points between various hydrocarbons and other volatile contaminants can be used to drive off and recover selectively the various compounds (fractionation distillation).

- *Incineration*

During incineration, high temperatures, 870 - 1200 °C, are used to volatilize and combust (in the presence of oxygen) halogenated and other refractory organic compounds from contaminated soils or wastes. Auxiliary fuels are often employed to initiate and sustain combustion. The destruction and removal efficiency for properly operated incinerators exceeds 99.99 % for hazardous and toxic organic compounds. Incinerator off-gases require treatment by an air pollution control system to remove particulates and neutralize and remove acid gases (HCl, NO_x and SO_x). Baghouses, venturi scrubbers and wet electrostatic precipitators remove particulates; packed bed scrubbers and spray driers remove acid gases. The end products are CO_2, water and ash.

Typical incinerator designs include circulating bed combustors, fluidized bed combustors, infrared combustion combustors and rotary kilns:

(1) Circulating bed combustors (CBCs) use high velocity air to entrain solids and create a highly turbulent combustion zone that destroys toxic hydrocarbons. These combustors operate at lower temperatures than conventional incinerators (790 - 880 °C). Effective mixing and the low combustion temperature of circulating bed combustors reduce operating costs and potential emissions of such gases as nitrogen oxide and carbon monoxide.

(2) Circulating fluidized beds use high velocity air to circulate and suspend the waste particles in a combustion loop, and operate at temperatures up to 880 °C.

(3) The infrared combustion technology is a thermal processing system that uses electrically powered silicon carbide rods to heat organic materials and wastes to combustion temperatures. Wastes are fed into a primary chamber and exposed to infrared radiant heat (up to 1010 °C) provided by silicon carbide rods above the conveyor belt. A blower delivers air to selected locations along the belt to control the oxidation rate of the waste feed. Any remaining combustible substances are incinerated in an afterburner.

(4) Commercial incinerator designs are rotary kilns, equipped with an afterburner, a quench, and an air pollution control system. The rotary kiln is a refractory lined, slightly inclined, rotating cylinder that serves as a combustion chamber and operates at temperatures up to 980 °C.

Incineration is used to remediate soils contaminated with explosives and hazardous wastes, particularly chlorinated hydrocarbons, **polychlorinated biphenyls (**PCBs) and dioxins. Factors that may limit the applicability and effectiveness of the process include:

- There are specific feed size and materials handling requirements that can have an impact on the applicability or cost at specific sites.
- Heavy metals can produce a bottom ash that requires stabilization.
- Volatile heavy metals and radionuclides, such as lead, cadmium, mercury and arsenic, as well as ^{210}Po and ^{137}Cs, will collect in the off-gas scrubbers and will require treatment and disposal.
- Metals can react with other elements in the feed stream, such as chlorine or sulphur, forming more volatile and toxic compounds than the original species. Such compounds are likely to be short lived reaction intermediates that can be destroyed in a caustic quench.
- Sodium and potassium form low melting point ashes that can attack the brick lining and form a sticky particulate that fouls gas ducts.
- Some organic compounds require rather high temperatures to be broken down completely along with careful process control in the cooling phase.
- The formation of dioxins and furans is a well known problem resulting from poor process control and too low temperatures during combustion.

Flameless combustion in electrical furnaces with better temperature gradient control may overcome this problem [7]. These problems, together with the high energy demands and the resulting sterile material when applied to soils, have generally resulted in incineration finding disfavour in many countries.

In addition to conventional flame or flameless incineration, interest in microwave methods for (radioactive) waste treatment is increasing, (see Section 4.5.2.10). With organic materials a volume reduction of 90 % can be achieved, the residuals being glass-like slags or molten metals. Again, off-gas treatment for volatile constituents is needed. Owing to the absence of a hot combustion gas stream, however, the volumes to be treated are lower.

- *Pyrolysis*

Pyrolysis is a form of incineration that chemically decomposes organic materials by heat in the absence of oxygen. Pyrolysis occurs under pressure and at operating temperatures above 430 ºC. In practice, it is not possible to achieve a completely oxygen-free atmosphere. Because some oxygen is present in any pyrolysis system, a small amount of oxidation occurs.

In pyrolysis systems, organic materials are transformed into gases, small quantities of liquid, and a solid residue containing carbon and ash. The off-gases are typically treated in a secondary thermal oxidation unit. Particulate removal equipment is also required, which can include scrubbers and high efficiency particulate air (HEPA) filtration.

Several types of pyrolysis units are available, including rotary kilns, rotary hearth furnaces and fluidized bed furnaces. These units are similar to incinerators except that they operate at lower temperatures and with less air supply.

Pyrolysis is not effective in destroying or physically separating inorganic compounds, including radionuclides, from the contaminated medium. Volatile metals in the off-gas stream must be captured in a scrubbing unit. Residuals containing heavy metals may require chemical stabilization before final disposal. When the off-gases are cooled, liquids will condense producing an oil/tar-like residue and contaminated water. These oils and tars may be hazardous and require further treatment prior to disposal.

The target contaminant groups for pyrolysis are semi-volatile organic compounds (SVOC) and pesticides. Pyrolysis is applicable to the separation of organic compounds from refinery wastes, coal tar wastes, wood treatment wastes, soil contaminated with creosote and hydrocarbons, mixed (radioactive and hazardous) wastes, synthetic rubber processing wastes and paint wastes. Factors that may limit the applicability and effectiveness of the process include:

- There are specific feed size and materials handling requirements that affect applicability or cost at specific sites.
- Soil requires drying to achieve a low moisture content (< 1 %).
- Highly abrasive feed can potentially damage the processor unit.
- High moisture content increases treatment costs.
- Treated media containing heavy metals may require stabilization.

- *Thermal desorption*

Thermal desorption physically removes volatile hazardous and toxic organic compounds and volatile heavy metals (cadmium, lead and mercury) and radionuclides (^{210}Pb, ^{210}Po and ^{137}Cs) from contaminated soil and wastes by application of heat. The target contaminant groups are non-halogenated volatile organic compounds (VOC), semi-volatile organic compounds (SVOC), polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), pesticides and fuels. Thermal desorbers are designed to heat soil and wastes to temperatures sufficient to cause contaminants to volatilize and desorb. Although they are not designed to decompose/destroy organic constituents, thermal desorbers can, depending upon the specific organic compounds present and the operating temperature, cause some of the constituents to completely or partially decompose. The vaporized organic compounds are generally treated in a secondary treatment unit (e.g., an afterburner, catalytic oxidation chamber, condenser or carbon adsorption unit) prior to discharge to the atmosphere. Afterburners and oxidizers destroy organic constituents. Condensers and carbon adsorption units trap organic compounds for subsequent treatment or disposal.

Some pre- and post-processing of soil and wastes is necessary when using thermal desorption. Soil must be screened to remove large (greater than 5 cm diameter) objects, which may be sized (e.g., crushed or shredded) and then re-introduced back into the feed material. Waste streams may also be ground in a homogenizer mill to a size less than 5 mm before treatment. After leaving the desorber the soil is cooled, remoistened to control dust, and stabilized (if necessary) prior to disposal or reuse.

Thermal desorption is applicable to constituents that are volatile at temperatures as high as 650 ºC. Most desorbers operate at temperatures of 150 - 540 ºC. They are constructed of special alloys that can operate at temperatures up to 650 ºC. More volatile constituents (e.g., gasoline) can be desorbed in the lower operating temperature range, while semi-volatile contaminants (e.g., diesel fuel) generally require temperatures in excess of 370 ºC, and relatively non-volatile contaminants (e.g., lubricating oils) require even higher temperatures.

Thermal desorption systems fall into two general classes: stationary facilities and mobile units. Contaminated soil is excavated and transported to stationary facilities; mobile units are operated directly on-site. Desorption units are available in a variety of process configurations including rotary desorbers, thermal screws and conveyor furnaces.

The presence of moisture in the soil and wastes to be treated will determine the residence time required and the heating requirements for effective removal of contaminants. In order for desorption of organic constituents to occur, most of the moisture must be evaporated in the desorber. This can require significant thermal input to the desorber and excessive residence time. Soil and wastes with excessive moisture contents (> 20 %) must be dewatered prior to treatment. Typical dewatering methods include air drying, mixing with drier soil and mechanical dewatering.

The presence of metals can have two implications:

(1) Limitations on disposal of residual solid wastes;

(2) Limitations on metal concentrations due to air emission requirements.

However, at normal operating temperatures, heavy metals and most radionuclides are not likely to be significantly separated from soils.

Factors that may limit the applicability and effectiveness of the process include:

- There are specific particle size and material handling requirements that can have an impact on applicability or cost at specific sites.
- Dewatering may be necessary to achieve acceptable soil moisture content levels.
- Highly abrasive feed can potentially damage the processor unit.
- The presence of chlorine can affect the volatilization of some metals, such as lead.
- Heavy metals in the feed may produce a treated solid residue that requires stabilization.
- Clay, silty soils and high humid content soils increase reaction time as a result of binding of contaminants.

\- *Fluid bed steam reforming*

Steam reforming destroys the hazardous organic portion of mixed wastes by exposing it to high temperature steam [7]. The process occurs in two phases. In the first phase, waste streams are exposed to steam at moderate temperatures. This volatilizes the organic components and separates them from the inorganic components of the waste stream (similar to thermal desorption). The volatilized organic compounds are transported to another reaction chamber for the second phase treatment, where the gaseous organic compounds are exposed to very high temperature steam, which destroys the organic compounds (Figure 4.33). The radionuclides and non-volatile heavy metals remain in the primary reaction chamber in their solid form. Fluid bed steam reforming uses superheated steam and co-reactants in a fluidized bed to evaporate liquids, destroy organic compounds, convert nitrates, nitrites and nitric acid into nitrogen gas and immobilize heavy metals, including radionuclides. To provide high nitrate and mineral conversion rates, steam reformers are operated in a strongly reducing environment. Carbon and iron based additives (reductants) are used to convert nitric acid, nitrates and nitrites directly to nitrogen gas in the reformer. Clay or other inorganic co-reactants are added to the waste feed, or bed, to convert the radionuclides, alkali metals, sulphate, chloride, fluorine, phosphate and non-volatile heavy metals into an immobilized mineral product. The final waste form is highly stable and leach resistant [7].

Gases and fine particulate matter entrained in the gases from the reformer are treated in a secondary unit that can also absorb metal fumes from any volatile metals in the waste stream. When treating waste containing any radioactivity, high efficiency particulate air (HEPA) filtration is provided. The only significant gaseous releases are carbon dioxide and water vapour emissions.

Fluid bed steam reformers are operated at 600 - 800 ºC under a small vacuum. The fluidized bed material is generally a granular product solid that accumulates in the bed during processing. Small units can be heated electrically. For production scale units, the energy is supplied by the incoming superheated steam and the introduction of oxygen with the steam to provide oxidation of the organic compounds and carbon from the wastes.

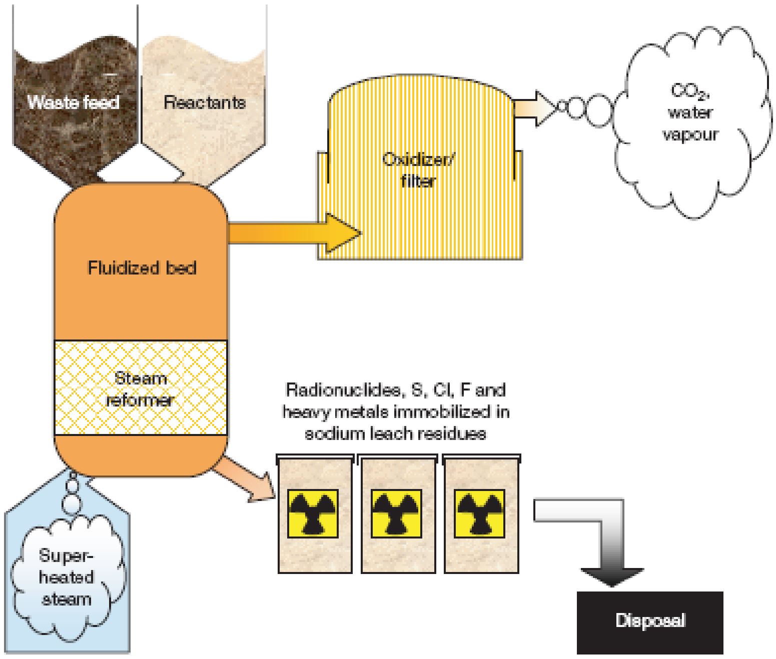


Figure 4.33 Simplified flow diagram of fluidized bed steam reforming process [7]

Wastes and contaminated materials that can be effectively treated by steam reforming include: radioactive waste with/without hazardous constituents, organic solvents, spent activated carbon, sludges, off-gas scrubber recycle streams, decontamination solutions, oils, polychlorinated biphenyls (PCB), ion exchange media and resins, plastics, sodium hydroxide solutions and wastes with high concentrations of Cl, F, S, P and heavy metals, where the final waste must be stabilized to meet heavy metal and radionuclide leach resistance and disposal site performance criteria.

During operation, the contaminated material is introduced into the system at the bottom of the fluid bed. Water in the wastes is evaporated and superheated to the bed temperature by the large mass of hot fluidized product solids. As the water in the waste feed evaporates, the temperature of dried waste solids rises to reaction temperatures. Organic compounds in the wastes are volatilized and pyrolysed upon contact with the hot bed solids. The volatile organic compounds are subjected to steam reformation in the bed. The nitric acid, nitrates and nitrites are converted to nitrogen gas when they come into contact with the reducing agents in the bed.

Alkali metals, non-volatile heavy metals, radionuclides, S, Cl, F, P and other inorganic constituents combine with co-reactants such as clay to form stable, high melting point, crystalline minerals that become the final solid product. The superheated steam, residual acid gases and fine particulates are carried into secondary units for further treatment. The accumulated product solids are semi-continuously removed from the bottom of the reformer as a fully immobilized, water insoluble, product.

The main energy requirements include: evaporation and superheating any incoming water in the waste feed, heating the organic and inorganic constituents, and supplying the heat of reaction for endothermic reformation reactions of steam with carbon and organic compounds. The main sources of energy for the reformer are the superheat of the incoming steam fluidizing gas, the reaction of nitrates with reductants to form nitrogen gas and the oxidation of organic compounds and carbon reductants in the bed.

4.6 Remediation implementation activities

4.6.1 Development and implementation of a remediation plan

Remediation of a contaminated area comprises the preparation and approval of a remediation plan; remediation operations; and the management of waste resulting from the remediation activities.

Before planning and implementing a specific remediation programme, the nature of the problem and the associated concerns should be appropriately characterized. All relevant information concerning the past and present management of the situation and any emergency response actions taken should be compiled so as to be available for consideration in the development of the remediation strategy.

An appropriate assessment of both the radiological and non-radiological impacts of the situation and the benefits and detriments associated with possible remedial measures, including the associated restrictions and institutional arrangements following remediation, should be performed and an optimum strategy should be established.

In each specific situation, remedial measures should be based on reference levels established as part of the decision making process.

When the organization (or organizations) responsible for implementing the remedial measures is (are) specified, it (they) should prepare a remediation plan. A remediation plan showing that remediation can be accomplished safely should be prepared for each contaminated area, unless otherwise required by the regulatory body. The remediation plan should be subject to the approval of the regulatory body prior to its implementation. The approved plan should state, as a minimum: the goal for the remediation; reference levels for remediation; the nature, scale and duration of the remedial measures to be implemented; the waste disposal or storage site, as appropriate; any post-remediation restrictions; and the monitoring and surveillance programmes and arrangements for institutional control for the remediation area.

Before the formal termination of the remediation programme and the release from further responsibilities of the organization responsible for implementing the remedial measures, compliance with criteria should be verified and the termination should be subject to the approval of the regulatory body.

In the event that the approved goals have not been met, further assessment should be performed and decisions should be taken on whether further remedial measures or additional restrictions are required. If either the remediation fails to meet the termination criteria, or the extent or complexity of the contamination is greater than was originally determined, the implementing organization should assess the new situation. An optimization should be performed by the responsible organization to determine a new course of action, which may include placing reliance upon restricting access to the affected area. Any such modification to the remedial measures should be subject to the approval of the regulatory body [14].

4.6.2 Operational aspects of remediation

4.6.2.1 General

Once the preferred option has been selected and the planning for remediation has been completed and approved, implementation of the remediation should begin within an appropriate time frame, normally within one to two years.

During the implementation of remedial measures, consideration should be given to radiation safety, transport safety and waste safety, so as to minimize hazardous impacts, and to the potential for prolonged exposure after termination of remediation operations. Consideration should also be given to general health and safety issues and environmental issues.

Activities for predisposal waste management should be undertaken, where appropriate, to treat and condition the contaminated material arising from remediation operations, including secondary waste generated by the remediation activities. The associated safety programme should include considerations of occupational protection and safety, such as training, the use of protective clothing and respiratory equipment, and cleaning facilities.

For the management of radioactive waste arising from the implementation of remedial measures, the objective of the protection of human health and the environment now and in the future without imposing undue burdens on future generations, as set out in the IAEA Principles of Radioactive Waste Management [47], should all apply, with due consideration of the amounts, characteristics, properties and types of radioactive waste [14].

The following sections identify issues that should be addressed during the implementation phase.

4.6.2.2 Radiation protection during remediation

Remediation workers will receive doses only if remedial measures are introduced. In the implementation of remedial measures, the exposure of workers should be controlled under the system of radiation protection for practices. The actual radiological conditions and the effectiveness of specific protective actions taken during the remediation should be compared with initial estimates of exposures and releases and the goals established for their control.

If the remediation operations would give rise to exposure of the general public living in or near the contaminated areas, the resulting doses should be controlled under the system of radiation protection of the public that is applied for practices. Normally, these doses would be justified in the light of future doses that would be averted by the remediation. If the doses would be significant, evacuation or relocation of the public should be considered based on the intervention levels for these measures and the system of protection for interventions should be applied. Unacceptable effects on the environment should also be avoided during the remediation, and environmental protection programmes should be considered, to minimize any harmful consequences that might result in the near term or that might occur in the future [12].

4.6.2.3 On-site and off-site monitoring during remediation

The area should be monitored and surveyed regularly during remediation so as to verify the levels of contamination and to ensure compliance with the requirements for waste management. Regular surveillance should also enable the organization responsible for the remediation to detect any unexpected levels of radiation and to modify the remediation plan accordingly. Revisions to the remediation plan should be subject to the approval of the regulatory body. There may need to be several iterations of review and revision of the remediation plan [14].

The extent of on-site and off-site monitoring programmes should be determined on the basis of the activities that will be performed during the remediation and the degree of uncertainty concerning the performance of these activities, and should be consistent with longer term monitoring programmes set up to verify the long term stability of exposure conditions (e.g., by monitoring the covering of mining residues, protection against the infiltration of water and protection against erosion or atmospheric dispersion).

Monitoring should be performed to evaluate the expected and actual level of safety of workers and the public and protection of the environment during the remediation. On-site monitoring should be conducted to provide information for use in identifying and mitigating hazards. It should be ensured that all potential exposure pathways are monitored. Off-site monitoring should be designed to monitor whether and to what extent discharges to the environment occur and to verify that regulatory requirements for the protection of the public and the environment are being met [12].

4.6.2.4 Waste management

The waste arising from remediation operations should be accommodated within an existing waste management system established for practices, particularly if the amounts of wastes expected are small. Waste may include: solid waste, such as vegetation or metallic waste from initial activities for site preparation; soil and rock; material from buildings or other structures; used personal protective equipment; disposable items used during the collection, preparation or packaging of samples; liquid and solid residues from samples sent for analysis; liquid and solid waste from hygiene and changing facilities; and water used for cleaning and decontamination or water abstracted from groundwater on the site. If the existing waste management system is not capable of dealing with the types and quantities of waste that will be generated during the remediation activities, the system should be adapted or supplemented accordingly. During the planning activities, the inventory of contaminated areas should include an evaluation of the amounts and characteristics of the waste that could be generated by the remediation operations. The management of radioactive waste arising from the implementation of remedial measures should be considered one component of the entire decision making process. The costs of transport and disposal of the waste, the radiation exposure of and other risks to the workers handling it, and, subsequently, the exposure of the public associated with its disposal should all be taken into account in the process of determining the optimum option for remediation.

The management of radioactive waste should include predisposal management, transport and disposal. The management of radioactive waste should comply with the international and national requirements for waste management facilities. An additional dose criterion of the order of 10 μSv/a should be used for the clearance of material from a site that contains radionuclides of artificial origin. For material that is contaminated with radionuclides of natural origin (except for ^{40}K), a clearance criterion of an activity concentration of 1 Bq/g could be used.

The following factors should be considered for the operations relating to the management of the waste arising during the implementation of the remediation programme:

- The types of waste may be very different, ranging from spent fuel and fission products following a nuclear accident, to naturally occurring radionuclides resulting from past industrial processes such as fertilizer production and the mining and processing of uranium and thorium ores;
- The amount of waste arising from the remediation operations may be very high (e.g., in the event of the removal of contaminated soil);
- Transport options to disposal sites may be limited;
- There may be no appropriate waste management facilities available for dealing with waste of these types, or such facilities may be limited in capacity.

The above factors should already have been dealt with in the optimization process when the remediation option was selected; however, during remediation activities, situations may arise that necessitate modification of the remediation programme in response to changing conditions. The regulatory body and the organization responsible for the remediation should then evaluate whether there is a need to return to the justification and optimization process that is required for interventions [12].

4.6.2.5 Emergency planning

A programme for emergency planning that is applicable for remediation activities should be established and described in the remediation plan. Operating organizations should ensure that procedures for dealing with unforeseen events that may occur during remediation are prepared and put into place. Personnel should be trained in emergency procedures. Provision should be made for the periodic testing and updating of these procedures by conducting periodic exercises. In the event of an unforeseen incident happening during remediation, the responsible parties should without delay notify the regulatory body [12].

4.6.2.6 Site security

Appropriate means, commensurate with the associated hazards, for restricting access to the area should be maintained throughout the remediation activities. These measures should be described in the remediation plan.

4.6.2.7 Quality assurance

The organization conducting remediation activities should implement an appropriate quality assurance programme under its management system. Activities for remediation and waste management should be performed by properly trained individuals in accordance with approved work procedures. Work procedures should be prepared for each activity. In the development of the quality assurance programme, the need for the acquisition and retention of records and information relevant to the area being remediated should be emphasized.

A record should be maintained of each task carried out in the remediation operations. Accurate and complete information concerning the locations, configurations, types and amounts of radionuclides remaining in the area after remediation is essential and should be acquired and maintained. For the unrestricted release of the area, these records should be used to demonstrate that all the radioactive material that was present at the beginning of the activities has been properly accounted for and that its ultimate destinations and uses have been specified and confirmed [12].

4.6.2.8 Ensuring compliance with requirements

The regulatory body should confirm that the remediation criteria were correctly chosen and applied by the responsible party. The regulatory body is required to ensure compliance with the legal and regulatory requirements, and should verify that the remediation end criteria have been met.

The responsible party should be required to submit to the regulatory body a final remediation report, including any necessary final confirmation survey that shows that the remediation criteria have been met. The regulatory body should use the information in the remediation report to develop a confirmation plan and should implement this plan as an independent confirmation of the responsible party’s survey data.

The regulatory body should compare the data presented in the results of the final confirmation survey with the information presented in the responsible party’s final survey report, and should verify compliance with the requirements. If there is an assurance that the remediation end criteria have been met, the regulatory body should agree that remediation has been concluded. If it is determined that compliance with the requirements has not been achieved, the responsible party should evaluate how to proceed. The options to be considered should include further remedial work or the imposition of institutional controls. Again, preference should be given to meeting the original objectives. If revision of the remediation plan is envisaged, the process for a new consideration of possible options as discussed in Section 2.3.2 and illustrated in Figure 2.4 should be followed.

Any quantitative recommendations will be difficult to implement unless there are agreed approaches to the estimation of exposures for the purpose of demonstrating compliance with the recommendations. Long term scenarios should be specified to characterize the individuals potentially exposed and the ways in which they may be exposed.

The quantification of uncertainties should be an integral part of the estimation of annual radiation doses. Methods for estimating uncertainties may vary significantly, ranging from qualitative judgements about variability to more rigorous approaches that include a statistical analysis of distributions for a range of input values that have a bearing on the dose estimate.

Uncertainty analysis is evolving rapidly, and techniques for estimating dosimetric uncertainties are still being developed. Whenever possible and appropriate, annual doses should be assessed as a distribution of possible values rather than as single point values.

Radioactive residues are usually unevenly distributed in space, creating heterogeneous situations of prolonged exposure. These should be addressed on a case-by-case basis by making realistic assumptions about the patterns of individual exposures. The selection of methods for evaluating heterogeneous exposure will depend on the situation and on the objectives of the evaluation.

Annual doses in exposure situations involving long lived radionuclides should be estimated on the basis of the assumption of unrestricted use of the site under remediation. This assumption implies that all exposure pathways that could realistically apply at any time in the future should be taken into account. However, the outcome of the optimization process may be restrictions on area use. Restrictions on use may preclude certain pathways and thus may reduce exposures, thereby achieving some advantages while introducing the disadvantage of having the restriction imposed. Scenarios describing restricted use following remediation of a site will be case specific. Furthermore, decisions about possible restricted uses may vary significantly within and between different countries. Restricted use will usually involve some form of ongoing institutional control such as by means of a land use registry. The possibility of the failure of this institutional control should be taken into account in the estimation of exposures. For areas that are contaminated with long lived radionuclides, consideration should be given to the fact that most restrictions and institutional controls have a limited time period of implementation, and sometimes this period is not commensurate with the half-life of the radionuclide.

For areas where there is more than one site giving exposure at high levels, the necessary degree of remediation should be determined by taking account of the annual doses arising from all the high exposure sites as well as those arising from the area as a whole. When there are sites giving high exposure levels within a larger area where exposure has been prolonged, remediation of these sites giving high exposure levels may be governed by local regulations for decontamination [12].

4.6.3 Implementing remediation actions

The implementation of remediation actions should include: procurement of the selected technology; preparation of the site; development of a health and safety plan; development of operations procedures; staff selection and training; completion of site clean-up; verification; waste disposal; and release of the site for any future use.

At the completion of remediation activities, the site should meet the remediation objectives set at the outset as demonstrated in final verification activities. Long term monitoring may be necessary. Quality assurance protocols should have been applied to all programme activities [3].

4.6.3.1 Special considerations

The general approach to remediation of radioactively contaminated sites may require special adaptation to address sites covering very large surface areas, or those which are deep and difficult to access. Small localized sites may benefit from removal or isolation approaches which are not feasible for very large sites. In addition, rigorous quality assurance techniques may be very important to demonstrating success of these projects as remediation criteria approach environmental background values. Each of these special considerations is addressed in the sections below [3].

4.6.3.2 Remediation of areas of extensive surface contamination

Radioactive contamination of the environment, such as caused by nuclear explosives testing, or nuclear accidents resulting in environmental dispersion, can cover surface areas of hundreds of square kilometres. These areas may include urban areas (roofs, walls, streets, yards), agricultural and open areas (crop lands, grasslands, parks) and forested regions (undeveloped, forest product areas).

Although contamination for such events is largely spread over a large area, the radionuclides can be redistributed both laterally and vertically with time. For example, rainfall may assist in moving the contaminants into deeper sections of the soil and potentially into the groundwater. Runoff or flooding can also redistribute the contaminants thus contaminating river flood plains, or causing accumulation of radionuclides behind engineered structures such as dams. Wind may also spread contamination.

The clean-up associated with this type of contamination can itself result in secondary radioactive waste streams which may be difficult or impractical to recover and process further. For example, the following waste types requiring further management and disposal may be generated during remediation or by other activities occurring in the contaminated zone: radioactively contaminated municipal sanitary wastes; sludge arising from waste water treatment; radioactively contaminated ash from domestic heating facilities that use radioactively contaminated firewood and peat; and radioactively contaminated dredged soils.

The selection of the methods to be used to clean-up an area should consider site specific factors such as the type of contamination, how it was deposited, soil types, value of the land, alternative land use, population distribution, size of the affected area, and the equipment available. Many techniques and types of equipment may be required. The methods selected should prevent contaminants from entering the food chain and should have minimal ecological impact. In addition, the methods should be safe, practical and cost effective because of the logistic problems and huge costs associated with the clean-up of large areas and the subsequent need to dispose of the wastes [3].

- Agricultural and forested zones
  For radioactively contaminated agricultural areas, selected technology should provide in-situ, effective and economical remediation, as well as ecological safety and respect of the environment. In some cases, they should allow the utilization of the remediated areas for agricultural production. Some technologies such as in-situ bio-remediation and land farming have already been demonstrated but need further development and improvements for optimal application. Past experience in remediation of forests includes the decontamination of wood cuttings, as well as measures to preserve the forest while radionuclide decay occurs (e.g., protecting the forests from pests and diseases; improving fire-protection capabilities; and so on).

  The clean-up of land can be carried out by selectively separating the radionuclides from the soil matrix, by deep ploughing to remove the contamination from the surface and the root zone or by removing the vegetation and/or top layer of soil containing the contaminants. The volume of wastes arising from the clean-up would be smallest for deep ploughing and largest for layer removal. The volume of wastes from the separation technique would depend on how well the separation could be done. The cost of storing, transporting, additional treatment and/or disposal of radioactively contaminated soils and vegetation is an important factor in selecting the proper method [3].

- Urban zones
  In urban zones, consideration should be given to people occupying the areas as well as to their personal health and safety. The nature of land uses, structures and utility systems present should also be considerations.

  A large variety of decontamination techniques and chemical mixtures have been developed over the years to assist in removing contamination from various surfaces.

These were developed in association with nuclear facility decommissioning or for facilities used in support of environmental remediation. A decontamination process must be selected on the basis of site specific considerations taking into account a wide variety of parameters such as the following [3]:

- type of material: metal, asphalt, concrete, soil, wood, etc.;
- type of surface: rough, porous, coated (paint, plastic, etc.);
- the method of deposition: the distribution of the contaminant and its adherence to the surface; can depend on whether the deposition was wet or dry;
- nature of the contaminant: activation or fission products, actinides, etc.;
- chemical and physical form of the contaminant: solubility, aerosol, flocculent particles, complex compound with other materials, etc.; for many decontamination processes, the smaller the particle, the more difficult is to remove it from a surface;
- specification of clean-up standards;
- potential future re-use for decontaminated materials, and
- the proven efficiency of the process.

Other factors which are important in selecting the method and equipment include the following [3]:

- availability, cost and complexity of the decontamination equipment;
- the need to condition the secondary waste generated;
- occupational and public doses resulting from decontamination;
- other safety, environmental and social issues;
- availability of trained staff; and
- the amount of work involved and the difficulty in decontaminating the equipment used for the clean-up if it is to be reused.

4.6.3.3 Remediation of areas of localised contamination

Localized accidental spills and intentional dumping have resulted in contamination in soils to extensive depths, in groundwater, and within surface waters. Waste forms can be in both liquid (surface and groundwater) and solid (solid wastes and radioactively contaminated soils) form. For example, in the past, liquid radioactive effluent has been directly disposed to the soil, injected directly into the groundwater, or disposed to natural surface drainage. Some holding tanks for high-level radioactive wastes have leaked into the soil. Solid wastes from nuclear weapons processing or medical applications were commonly buried directly into soil trenches, without sufficient packaging. Moving plumes of contamination underground, which may be many metres below the surface, are difficult to detect, monitor and access, in order to conduct remedial operations.

Although the remediation of these sites is probably more complicated and more expensive on a per unit volume basis than for the sites considered previously in this section, the approach and the process leading to a decision are not fundamentally different. Nevertheless, one must consider the importance of the cost factor during the evaluation of the necessity for remediation [3].

4.6.3.4 Remediation of radioactively contaminated sites from extraction and processing of ores

Another potentially significant area of radioactive remediation activities is found in the mining field. Natural radionuclides may be contained in non-radioactive ores and, depending on the chemical and physical properties of the elements in the ore, may be enriched during the smelting process and later found in products or in residues (slag and other). In these residues, the radionuclides of the decay chain are frequently not in radioactive equilibrium, because the daughter products have shorter half-lives relative to the parent products. Also, flue dust and other air-borne smelting residues found in exhaust air can contain decay products like ^{210}Po and ^{210}Pb.

Site remediation at mining and associated nuclear materials sites include the mines themselves, on-site plants and structures, tailings impoundments, and facilities where mine products are processed, stored or used. The scale of such remedial projects can be large [3]. The methods and technologies used in the remediation and decommissioning of uranium mining and related facilities are dealt with in detail in the relevant IAEA reports.

4.7 Conducting post-remediation activities

Once remediation activities have been completed and verified, the remediated site can be released for restricted or unrestricted use. However, in most cases it is necessary to impose certain post-remediation activities on the area of concern. These activities may vary in comprehensiveness and duration according to the degree of remediation that has been achieved.

If institutional control has been seen as necessary, then post remedial activities should occur in a controlled context and, normally, should include the following [3]:

- monitoring the long term stability and performance of barriers which isolate or contain residual radioactively contaminated materials;
- monitoring environmental indicators within and down gradient of the remediated site;
- maintenance of barriers and other protection systems;
- prevention of intrusion;
- adherence to licensing conditions that may have been imposed;
- regulation and administration of administrative controls, and
- assembly, distribution, and safekeeping of all project and post-remediation period data, analyses, and records.

4.7.1 Post-remediation activities

After the remediation has been completed, the degree, the extent and the duration of control, if any, ranging from monitoring and surveillance to restriction of access, should be reviewed and formalized with due consideration of the residual risk. The organization responsible for the surveillance and verification of activities should be clearly identified.

If necessary, specific restrictions should be established for the following purposes [14]:

- To control the removal of radioactive material from contaminated areas or the use of such material, including its use in commodities;
- To control access to contaminated areas;
- To control the future uses of contaminated areas, including use for the production of foodstuffs and water use, and to control the consumption of foodstuffs from contaminated areas.

4.7.1.1 Release of areas

There are several possible end points for the remediation process [12]:

- Use of the area may be unrestricted;

- Use of the area may need to be restricted in some or all parts and control may need to be exercised, for example, through a system of planning consents;
- Access to the area may need to be restricted and measures may need to be put into place to enforce this.

In each case, further surveillance and monitoring may be required to confirm the long term effectiveness of the programme of remediation, and additional controls may need to be imposed on the basis of the monitoring results.

The degree, the extent and the duration of control, if any, ranging from monitoring and surveillance to restriction of access, should be reviewed and formalized with due consideration of the residual risk.

4.7.1.2 Unrestricted use

If the chosen remediation process involved the removal of contamination itself, and if the area meets the required remediation end criteria, the area may be released without restrictions. In this situation, the prevailing conditions are considered to be the residual background conditions for a new practice or for use of the land for habitation [12].

The remediation of the site for any new practice should be conducted on the basis of the guidance presented in [6].

4.7.1.3 <u>Restricted use</u>

The term 'restricted use' means that some types of use are allowed while others are not; for example, in certain cases the use of an area for forestry may be possible but its use for agriculture may be prohibited. Where a significant part of the exposure due to residual contamination arises from the food chain, the use of agricultural countermeasures should be considered. Similarly, the use of an area for recreational, industrial or certain agricultural purposes may be appropriate, but its residential use may not be. Impacts of the residual contamination on aquifers should also be considered in this evaluation.

In cases where all reasonable remediation options are insufficiently protective or in cases where the optimized remediation options do not include removal of the contamination itself, specific restrictions on the future uses of the contaminated areas may be required to be imposed. Specific restrictions may also be required to be established for controlling the removal of material from such areas or the use of such material [12].

4.7.1.4 Restricted access

Restriction of access to contaminated areas will be required to be maintained in cases of serious residual contamination. The degree of any such restrictions should be determined by the regulatory body. Depending on the type and levels of residual contamination, access control measures may vary from the placing of warning signs to fencing of various types and guarded control stations. Area control personnel should have the legal authority to deny access to the area, if required [12].

4.7.1.5 Removal of restrictions

If the monitoring and surveillance programme has verified the long term effectiveness of the remedial measures in eliminating unacceptable risks to human health and the environment, consideration should be given to removing any restrictions applied to the area and ending or reducing the extent of the monitoring and surveillance. If the option of ending or reducing these services is considered, the value of the monitoring and surveillance in promoting and maintaining public confidence should be taken into account. In considering the long term effectiveness of remedial measures, the environmental influence of physical, chemical, geological and other factors should be evaluated. In particular, contamination of groundwater may not become apparent for some time and may do so at some distance from the source of the contamination. Such considerations should be documented in the remediation plan [12].

4.7.1.6 Monitoring and surveillance plan

A monitoring and surveillance plan should be required to be prepared for any remediated areas where restrictions are maintained after remediation has been completed. The plan should be subject to periodical review and to approval by the regulatory body.

The extent of such monitoring and surveillance plans should be based on the residual risks and their degrees of uncertainty and on the need to verify the long term stability of the radiological conditions. Monitoring and surveillance programmes should include, as necessary, environmental monitoring (of dose rates, activity concentrations in soil, water and air, biological indicator species and foodstuffs), whole body monitoring (if applicable) and dose assessment.

Decisions regarding the routine maintenance of such monitoring and surveillance programmes should be documented in the remediation plan. The results of the monitoring and surveillance programmes should be required to be documented and made readily available to interested parties to assist in maintaining public confidence. An invitation to interested parties to participate in the decision making should be required also in the post-remediation phase [12].

4.7.1.7 Record keeping

Records are required to be kept to document the remediation programme and any lessons learned and changes made during its implementation. Such records should include: descriptions of activities performed; data from the monitoring and surveillance programmes; occupational health and safety records for the remediation workers; records of the types and quantities of waste produced and of their management and disposition; data from environmental monitoring; records of financial expenditures; records of the involvement of interested parties; records of any continuing responsibilities for the site; identification of locations that were remediated and those with residual levels of contamination remaining; specifications of any areas that remain restricted and the restrictions that apply; statements of any zoning and covenant restrictions or conditions; and statements of lessons learned.

Failures in the implementation of remedial measures may arise from a lack of consensus among interested parties, often in the negotiations during the decision making process regarding the implementation of the remediation plan. While some conflicts between interested parties are apparent at the outset of the decision making process, others may arise much later, for example during discussions in which the actual implications of alternative decisions are made explicit. All conflicts and their resolution in the decision making process should be documented [12].

5 Stewardship

5.1 Introduction

General guidance on and an introduction to stewardship are presented in Section 2.10. The aim of Section 5 is to present more detailed guidance on stewardship [16]: e.g., when to implement, what plans/actions should be carried out, etc.

After remediation has been completed, the degree, extent and duration of control, if any, ranging from monitoring and surveillance to restriction of access, should be reviewed and formalised with due consideration of the residual risk [14]. The organisation responsible for the surveillance and verification of activities should be clearly identified.

In the case of long term remedial actions, long term stewardship may start when the remedy is shown to be functioning properly and operating as designed. Large, complex sites may undergo remediation of portions of the site while other parts may continue to perform mission-related work. As a result, specific actions that would normally be associated with long term stewardship, such as monitoring the effectiveness of engineered controls, may start years before final closure of the site.

There are several possible end points for the remediation process [12]:

1. *Unristricted use of the area*. Before a site may be released for unrestricted use, a survey should be performed to demonstrate that the end point conditions have been met (see Section 3.3.10.6). If the chosen remediation process involved the removal of contamination, and if the site meets the required remediation end criteria, it may be released without further restrictions. In this situation, the prevailing conditions should be considered to be the residual background conditions for a new practice or for use of the site for habitation [12].

   For example, for the remediation of the site for any new practice, the contribution to individual doses from an eventual remediation of the new practice should not exceed an additional dose of 300 μSv/year over the new background level that resulted from any previous remediation activities following any previous practices (See Figure 2.4 in Section 2.2.2.4). However, the sum of all possible combinations of doses to members of the public due to exposures from all subsequent practices should not exceed an additional dose of 1 mSv/year over the original background level before the first practice started.

   Further, consideration should be given that even after free release a site may become the source of contamination, hence:

   > *"Consideration should be given to the potential circulation of material coming from future modification of the buildings, including demolition after site release. Materials originating from the site, after the site is released from regulatory control, need to comply with the national requirements for radiation protection... This should be an integral part of the optimization analysis of the clean-up process. Scenarios for exposure to sites released for unrestricted use should be realistic and consider the potential uses of the materials from the released site" [6].*

2. *Restrictued use of the area*. The term 'restricted use' means that some types of use will be allowed while others will not; for example, in certain cases the use of a site for forestry may be possible but its use for agriculture may be prohibited [12]. Where a significant part of the exposure due to residual contamination may arise from the food chain, the use of agricultural countermeasures should be considered. Similarly, the use of a site for recreational, industrial or certain agricultural purposes may be appropriate, but its residential use may not be. Impacts of the residual contamination on aquifers should also be considered in this evaluation.

In cases where all reasonable remediation options are insufficiently protective or in cases where the optimised remediation options do not include the removal of the contamination, specific restrictions on the future uses of a contaminated site may be imposed. Specific restrictions may also be established for controlling the removal of material from such sites or the use of such material.

An appropriate programme, including any necessary provisions for monitoring and surveillance, should be established to verify the long-term effectiveness of the remedial measures, and should be continued until it is no longer necessary [14].

A mechanism should be established for periodically reviewing the conditions in remediated areas and amending or removing any restrictions imposed. If surveillance and maintenance are required after remediation is completed, a surveillance and maintenance plan should be prepared which should be periodically reviewed. The plan should be subject to the approval of the competent authority.

Interested parties (e.g., stakeholders, etc.) should be informed of any restrictions and of the results of all monitoring and surveillance programmes, and should be invited to participate in decision making after the remediation.

3. *Restricted access to the area*. Access to the area may need to be restricted and measures may need to be put into place to enforce this.

Restriction of access to contaminated sites and/or institutional control may be required to be maintained in cases of serious residual contamination [12]. Specific restrictions should be established for the following purposes [14]:

- To control the removal of radioactive material from contaminated sites or the use of such material, including its use in commodities;
- To control access to contaminated sites;
- To control the future uses of contaminated sites, including use for the production of foodstuffs and water use, and to control the consumption of foodstuffs from contaminated sites.

The degree of any such restrictions should be determined by the competent authority. In case institutional control is seen to be necessary, post remedial activities should occur in a controlled context and may include [3]:

- Monitoring the long term stability and performance of barriers which isolate or contain residual radioactively contaminated materials; depending on the type and levels of residual contamination, access control measures may vary from the placing of warning signs to fencing of various types and guarded control stations; site control personnel should have the legal authority to deny access to the site, if required;
- Monitoring environmental indicators within and down gradient of the remediated site;
- Maintenance of barriers and other protection systems;
- Prevention of intrusion;
- Adherence to licensing conditions that may have been imposed;
- Regulation and administration of administrative controls;
- Assembly, distribution, and safekeeping of all project and post-remediation period data;
- Analyses and records.

In each case, further surveillance and monitoring may be required to confirm the long term effectiveness of a performed programme of remediation, and additional controls may need to be imposed on the basis of the monitoring results.

The degree, extent and duration of control, if any, ranging from monitoring and surveillance to restriction of access, should be reviewed and formalised with due consideration of the residual risk at the remediated site.

So, long term stewardship results from the need to address the reality that ‘clean-up’ of facilities can not in all cases achieve conditions deemed acceptable for unrestricted use and will therefore require some form of management far into the future.

5.1.1 Assessment criteria for establishing short term or long term stewardship

Long term stewardship results from the need to address the reality that ‘clean-up’ of facilities can not in all cases achieve conditions deemed acceptable for unrestricted use and will therefore require some form of management far into the future.

Principal drivers for needing long term stewardship at a site may be a combination of:

- *Priorities* - Owner, local, federal priorities may not support funding for clean-up to free-release levels.
- *Long-lived contaminants* - Radionuclides, chemicals, and metals may not be easily or quickly broken down to safe constituents.
- *Lack of technology* - No further environmental benefit from remediation may be attainable with existing technology or asymptotic levels have been reached, e.g., groundwater and vadose zone.
- *Risk* – Short term human health or environmental risks of conducting remedial activities may outweigh the benefits of remediation.

The technical needs for dealing with long term stewardship may be identified as discussed in the following paragraphs.

5.1.2 Scope and objective of long-term stewardship

While removal of radioactively contaminated soil and groundwater is obviously a permanent solution for the site in question itself, the chosen disposal site may have to be subject to a stewardship programme. Any engineered solution to contain contaminants or to reduce exposures, whether on-site or at the chosen disposal facility, will only have a limited period of useful life. Natural forces will gradually degrade structures such as liners, barriers or cappings. Modelling predictions, based on historical experience and observed parameter values, allow an estimate to be made of how long an engineered near surface structure is likely to perform according to intentions. However, experience in recent times with floodwater defences has shown that our events database extending some 100 years into the past may be insufficient to capture the whole parameter range required for, say, a 1000 year lifetime. This uncertainty over the long term effectiveness of remediation solutions requires provisions for monitoring, periodic performance assessment, and, if required, maintenance; hence the establishment of a stewardship programme. It is this uncertainty that creates the need for long term stewardship. While making remediation decisions, it is important to consider long term stewardship issues and obligations explicitly when comparing remedial alternatives and implementing a final remedy [138].

Stewardship, and by inference the steward’s responsibilities, must be defined at a practical implementing level, that is from the bottom up. For stewardship to be understandable and affordable, a narrow definition of stewardship is recommendable [139].

Stewardship plans cannot be static but have to be adapted to the development of a site, with respect to both its physical state and its use. Periodic revision of the stewardship plans will be necessary.

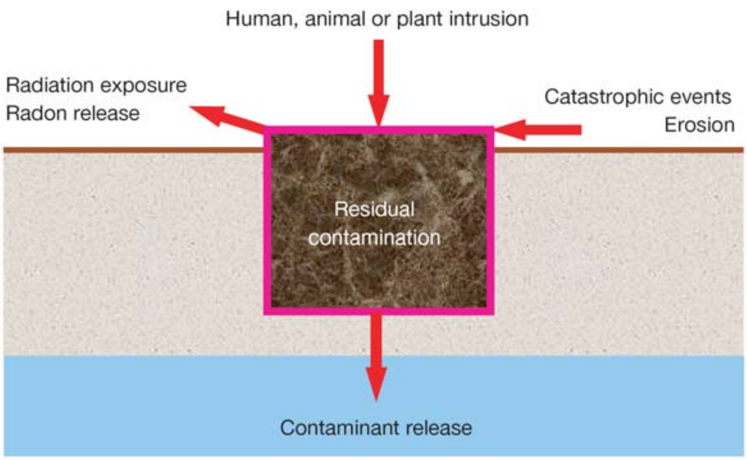


Figure 5.1 Stewardship challenges

The objectives of long term stewardship should be to ensure adequately long-lived institutional controls, monitoring, engineering controls, maintenance activities and information management for the related radioactively contaminated sites and/or groundwater, and surveillance to restriction of access to the site.

Plans dealing with these topics should be proposed by the operator of the site on the basis of a graded approach and in consideration with 'the components of stewardship' (see Section 5.2). The restrictions proposed by the operator should be enforceable by the regulatory body and the clean-up/remediation plan should specify which entity will ensure that the proposed restrictions are maintained.

The societal aspects of long term stewardship may present several important challenges, such as building trust, communicating the nature of the risks and of the remediation and stewardship options, reconciling economic, management and technical issues with considerations of public values and beliefs, resolving ethical questions and engaging stakeholders in the decision making process, and thereafter retaining stakeholder commitment.

Many regulations assign authority and responsibility for environmental contamination into the foreseeable future, i.e., decades, but residual contamination at facilities or sites may remain hazardous for a very long time.

5.1.3 Life cycle management and stewardship

In recent years a slow change in paradigms has occurred: awakening awareness of long term ecological problems has led to a move away from treating environmental problems only after they have occurred. The goal is to avoid environmental impacts from the beginning in the life cycle of a human activity. This life cycle management aims to treat each stage in the life of a facility or site not as an isolated event but as one phase in its overall life. Thus, the planning does not only cover each stage but is also a continuing activity, taking into account actual and projected developments. As a consequence, a more forward looking integrated management of human activities was introduced into the legislation in many countries.

5.1.4 Regulatory framework

The objectives and outcomes of remedial actions have a direct and lasting effect on the level of long term stewardship required at a site. The International Commission on Radiological Protection (ICRP) stipulates that:

'Remediation measures shall be justified by means of a decision aiding process requiring a positive balance of all relevant attributes relating to the contamination. In addition to the avertable annual doses, both individual and collective, other relevant attributes shall be assessed' [154].

The prime objectives for remediation actions are the abatement of environmental impacts and the reduction of risks to human and other receptors. According to [14]:

'Remediation shall (a) reduce the doses to individuals or groups of individuals being exposed; (b) avert doses to individuals or groups of individuals that are likely to arise in the future; (c) prevent and reduce environmental impacts from the radionuclides present in the contaminated area'.

The criteria for the release of sites from regulatory control upon the termination of practices have been formulated recently in an IAEA Safety Guide [6], see Section 2.5. Though strictly speaking this guide applies only to the decommissioning of authorized practices, sites where past practices or accidents have led to contamination in the ground would have to comply with most of the criteria set out there. The preferred option, according to this IAEA Safety Guide, is unrestricted release provided the site meets the appropriate release criteria developed for a reasonable set of possible future uses (see also Section 5.2.10.5).

In the case of restricted use,

'The restrictions should be designed and implemented to provide reasonable assurance of compliance with the dose constraint for as long as they are necessary... Therefore, existing regulatory limits on the institutional control time frames should be taken into consideration in deciding whether to release a site for restricted use'.

The scope of a stewardship program is outlined implicitly in Section 5.1.2, while the actual regulatory framework will vary from country to country. Even after free release, a site may become the source of contamination, hence:

'Consideration should be given to the potential circulation of material coming from future modification of the buildings, including demolition after site release. Materials originating from the site, after the site is released from regulatory control, need to comply with the national requirements for radiation protection ... This should be an integral part of the optimization analysis of the remediation process. Scenarios for exposure to sites released for unrestricted use should be realistic and consider the potential uses of the materials from the released site' (see Section 2.5 and [6]).

5.2 Components of long term stewardship

Many aspects of long term stewardship are intended to maintain the long term protectiveness of the remedy. The treatment of these aspects is placed in perspective by putting stewardship into the larger context of life cycle management. Components of long term stewardship therefore should include:

- *Management (see Section 5.2.1).* It should be clear, that during the life cycle of site management, the stewardship will encompass an extremely broad range of issues and activities. Some of these may be relatively transient in character (e.g., a time frame of a few years), others will specifically envisage timescales of centuries or even millennia (e.g., performance hopes for containment under prevailing environmental conditions).
- *Institutional/Administrative controls (see Section 5.2.2).* Control exposure to hazardous substances by establishing (governmental) controls and providing legal enforcement tools. It is recommended that institutional control activities defined for a remediated site where restrictions are maintained after remediation has been completed should be included in a monitoring and surveillance plan that should be subject to periodical review and to approval by the competent authority, including:

- * Governmental controls,
  * Proprietary controls,
  * Physical/Engineered controls implemented to treat or stabilize contamination, to physically contain or isolate waste, or to prevent access.
- *Maintenance (see Section5.2.3).* Support maintenance of engineered controls to guide decisions on when and how to modify long term stewardship activities.
- *Monitoring (see Section 5.2.4).* Ongoing environmental monitoring to determine the effectiveness of the remedy, improve understanding of the contaminant interactions with the site.
- *Information and knowledge management (see Section 5.2.5).* Maintenance of environmental data, knowledge and other information relevant to the remedy including public communication. When sites make the transition from clean-up to long term stewardship, site stewards and stakeholders should be given detailed information about the location and the nature of residual hazards, the processes that generated these, and the engineered and institutional controls that are part of the remedy.
- *Periodic review of the remedy and, if needed, alteration of the remedy (see Section 5.2.6)*. At regular intervals, for example, every five years, a review should be conducted to evaluate the implementation and performance of a remedy in order to determine if the remedy is or will be protective of human health and the environment.
- *Site access*. Restriction of access to contaminated sites and/or institutional control may be required to be maintained in cases of serious residual contamination.
- *Removal of restriction of site access (see Section 5.2.7)*. If the monitoring and surveillance programme has verified the long term effectiveness of the remedial measures in eliminating unacceptable risks to human health and the environment, consideration should be given to removing any restrictions applied to the site and ending or reducing the extent of the monitoring and surveillance.
- *Economic and funding (see Section 5.2.10).* In terms of the economic context, the implementation of a stewardship program should follow a split time frame concept.

Next to the above components long term stewardship has to deal also with societal and ethical aspects (see Section 5.2.8), such as:

- Building trust at the stakeholders. Stakeholders in the specific case of long term stewardship may be different as during the remediation of the site and should be identified.
- Communicating the nature of the risks and stewardship.
- Defining societal criteria for defining and implementing stewardship strategies.
- Managing ethical questions and engaging stakeholders in the decision making process and thereafter retaining stakeholder commitment [155].
- Keeping stakeholders involved (see Section 5.2.9).
- Reconciling economic, management and technical issues with considerations of public values and beliefs.

Contaminated sites are socially constructed risks. As in the case of most socially mediated risks, the significance - and hence the acceptability - to an individual, to members of a community or to a society, of exposure (or a danger of exposure) to a dose, depends on how, by whom and why the dose has been produced. Correspondingly, in order to assess to what extent or on what basis the members of a society will judge acceptable (or not) a given strategy for management of high level long lived radioactive residues, it is necessary also to consider the meanings and relationships (in social, economic, cultural and symbolic terms) that alternative remediation and stewardship strategies might establish between the people -

individuals, classes, interest groups, succeeding generations and whole nations - implicated in the site stewardship process.

5.2.1 Management

5.2.1.1 Management within multiple time frames

Some management studies on the topic of stewardship propose separating 'nearer term' and 'longer term' challenges as a pragmatic way of developing a comprehensible and affordable long term stewardship programme. However, expressions such as nearer term (or short term) and longer term (or long term, etc.) can be and are given a wide spectrum of usages. It may be helpful to distinguish between different strategic planning horizons on the basis of the actors involved (viz. present versus future generations) and on the basis of hypotheses about system stability and change.

Regarding the actors involved, it is useful to follow the sustainability literature, where it is now commonplace to distinguish between present and future generations. This distinction is not associated with a specific period (is a generation 15, 25 or 35 years?), rather it is based on a question of agency: of actions by some people, on behalf of or for others. In reality, it is the responsibility of the present generation of policy makers and stakeholders to determine the ways in which the interests of future generations (and, by extension, of other species and ecosystems) are to be provided for.

Provision for the needs of future generations can be assured only through principled choices of resource use (investment and protection decisions) whose stewardship intent is to maintain and enhance the opportunities and security of future generations. Stewardship actions must be viable and acceptable to the present day stakeholders, at the same time as being motivated with respect to future generations.

Regarding system durability, there are important time horizons related to the stability and finiteness of stewardship strategies. This applies to institutional matters and also to engineering solutions. Institutional arrangements, including financial conditions, workforce and legal frameworks, can change quite quickly (on a scale of a few years) even when clear and 'binding' agreements have been made. The prevailing frameworks of government and of governance can also change rapidly (the rise and fall of political regimes) but in a deeper sense change more slowly (the rise and fall of civilizations). Therefore, the durability of stewardship for the longer term will depend on rooting the stewardship function in cultural values, purposes and understanding. This may be referred to as the archeological time frame.

Technological solutions (such as near surface containment), when put in place with attention to environmental and geological conditions and with a view to durability, can be proposed reliably for time horizons ranging from decades to hundreds of years. The longer the time horizon, the greater the extent to which performance is associated with the properties of natural systems and is, therefore, dependent on these. Therefore, in the longer term, a scientific characterization of natural processes is the determinant, and there is inevitably an element of indeterminacy associated with the long term evolution of natural processes. This may be referred to as the geological time frame.

These various considerations lead to the recognition of three time frames as being complementary for stewardship functions:

- One generation (approximately 30 years);
- Archaeological spans (of the order of 100 - 1000+ years);
- Geological spans (e.g., 1000 - 10 000+ years).

The main challenges for stewardship relate to the transitions in the planning horizon between one generation (the present period of activity) and the archaeological and geological horizons.

The ‘nearer term’ stewardship challenges are more likely to gain support from stakeholders, because they will probably be based upon existing and proven methodologies. These challenges may be economic (discussed further in Section 5.2.10), technical or institutional ones, or may involve ownership or measurability of success. While there is always the likelihood that technology will advance over time, there will be less confidence in institutional or financial stability, as the recent past shows only too well.

Convincing stakeholders to accept a stewardship programme when the longer term issues are less developed will be a challenge in itself. The way in which the longer term challenges (responsibilities and obligations, etc.) are framed may have a substantial bearing on the acceptance, or non-acceptance, of the immediate ‘steps’ (or nearer term solutions). The mechanisms of involving stakeholders are very country and culture specific (e.g., see [45] and references therein).

It will, therefore, be important to incorporate within the longer term process a mechanism that will allow a reappraisal of the control measures and financial provision on a regular basis (this may be a 25 or 50 year period, for example).

For the longer term issues, although very real and significant, satisfactory answers may not be attainable. The pursuit of those answers will probably be very expensive, and demonstrating progress on an annual basis might be difficult. A lack of demonstrable progress for the resources expended can undermine a programme’s credibility in general. Therefore, it was suggested to pursue the longer term issues by a different means. The very act of continuing nearer term activities is likely to clarify actual longer term needs. It must be noted, however, that with this approach, while circumventing the possible paralysing effect of having to design for millennia, there may be no guarantee that the nearer term activities are continued for any length of time beyond, say, one generation. Such a separation allows, at least, a definition of stewardship to be made from the bottom or from an implementation viewpoint. The danger in defining stewardship from the top down and building a stewardship programme in this way is that the definition and resultant programme to fulfil the responsibilities of a top-down definition must be excessively broad and all-encompassing to be capable of handling every conceivable eventuality. While there may be no direct solutions to maintaining the ability to manage long term stewardship for thousands of years, focusing on shorter term (100 years or so) solutions will keep people involved at the site, which will allow for evaluation of the changes required over time. If too much energy is spent on trying to solve the problems of 2234 with today’s knowledge, opportunities may be lost to take the best decisions for the short term and unreasonable or unrealistic solutions may be recommended for the long term.

5.2.1.2 Management of trust, constancy and learning

Three management challenges for long term stewardship are recognized and are:

- Obtaining and maintaining public trust;
- Achieving institutional constancy or ensuring continuity of long term stewardship activities over many generations;
- Learning from past and ongoing experience as technological and management means for implementing long term stewardship are developed.

Further, there is also some relevant experience in the operation of high reliability organizations as well as in the management of natural resources. Organizational tasks requiring high reliability, such as air traffic control, require high levels of trust, both within the operating organization and in its social environment. A central finding of studies of organizations that need to demonstrate high reliability is that public confidence in them reflects the way in which the operations of the organization are carried out. Not only is the substance of long term stewardship affected by choices made in the clean-up process but so also is the social setting in which long term stewardship will be conducted. That setting is critically important to the ability of stewards to discharge their responsibilities. By several organizations it has been recognized the importance of trust, constancy and learning in long term stewardship as indicated in a recent report [56], which contains advice about means for maintaining and enhancing public trust, characteristics associated with institutional constancy and recommendations on institutional learning.

5.2.1.3 Management decision making in the presence of large uncertainties

There are several management questions arising specifically from the long term character of stewardship. These include, on the one hand, the presence of large uncertainties about physical system stability and change and, on the other hand, the impossibility of resolving in advance the socio-economic and institutional dimensions, such as identification of stakeholders, funding mechanisms, communication, and retention and management of records, over very long time periods.

The conclusions for decisions taken in the present are usually based on monitoring and/or observations. However, for the future, decisions are model based and bound to a range of uncertainties. The potential failures resulting from uncertainties may imply or result in a range of 'active decisions' by the steward.

Two main types of uncertainty can be distinguished according to the time frame:

- Uncertainties about the result of the assessment after remediation under normal conditions, leading to the decision in the present (e.g., data gaps in the inventory, insufficient site characterization or insufficient engineering quality).
- Uncertainties about the future. These cover both the nature and the range of natural phenomena/'events' in the future and the influence of the passage of time on the internal evolution of the designed structures/processes.

All models are back-calibrated to observations made of phenomena during the past few centuries or even just decades, which is a limited period of time compared with the long term for which predictions are to be made. This problem has become obvious in recent years when, for example, predictions of 200 or 1000 year flood events in Central Europe naturally failed because the underlying database only spans 150 years at most.

Some of these uncertainties in our knowledge of a site's properties and behaviour are discussed in more detail.

5.2.1.4 Identification of possible stewardship organizations

A stewardship organization must be a long-lived entity. This increases the probability that the steward will exist long enough to perform the stewardship responsibilities during the mandated institutional control period. On the basis of this premise, a corporate entity may not be an appropriate long term steward because site integrity could be jeopardized by profit driven decisions to transfer title and responsibility for a site, or by dissolution of the corporation.

In general, the majority of projects on establishing stewardship programmes tacitly assume that national governments continues to exist indefinitely as an entity. Therefore, in the case of failure of institutional control, it is assumed that there is always a higher level organization that is capable of taking corrective action. Thus, stewardship is reduced to providing for the necessary mechanism of making these 'higher' authorities aware of any violation. If the past is an indication of future development, this might be a correct assumption for the next two hundred years or so. However, many places in the world have seen substantial changes in governance since the late 1700s and such assumptions may not be valid at all. It is for these types of concern that designs that minimize the need for long term stewardship and that are likely to function whether governmental structures are available or not are preferred.

A number of institutions have survived a considerable length of time and are still functioning more or less in the same way. Examples include the papacy/Vatican (around 2000 years), Mecca (close to 1400 years), the Royal Society of United Kingdom and Académie Française (about 350 years) and the British Museum (270 years). In addition, there are various monuments and other examples of civil engineering that are know to have been in operation (or are still in operation) for hundreds of years, including Roman public baths and water supply systems, the Forbidden City in Beijing (about 600 years) and the Taj Mahal (about 350 years). Some states have survived for remarkable periods of time, if not in territorial integrity, at least as a concept, including the Kingdom of Egypt, the Chinese Empire, the Roman Empire, the Holy Roman Empire and some modern states in Europe such as Spain, France and The Netherlands.

At some stage, museums were claimed to be candidate institutions, but they must be active and 'living' museums, such as the British Museum. However, the second world war and recent events in, for example Iraq, show that museums are by no means safe. It may be worthwhile to review the properties that made these institutions survive 200+ years. Retaining momentum in public interest appears to be one of the properties required, and is particularly associated with religious institutions. There must be a sustained interest in the services of or values represented by an institution. Thus, longevity is linked to cultural or spiritual values. Conversely, there are many institutions or civil engineering structures that were intended for eternity but that have not survived or which do not fulfil their function any more, for example, the Egyptian pyramids, where the societal context ceased to exist. Some civil engineering structures, on the other hand, seem to have attained a new spiritual value, for example certain megalithic structures, that ensures their continued preservation.

In essence, the longevity of institutions appears to be linked to the relationship built between them and the society, or succession of societies, to which they belong. Similarly, the fact that certain human-made structures have survived in a well preserved and maintained state appears to be linked to society maintaining an active interest in these.

It should be noted that such interest can be both positive and negative, that it can be something that is sought after or something that is to be avoided.

5.2.2 Institutional/Administrative controls

Institutional controls or provisions may be provisions designed to control future uses of land or resources by limiting development and/or restricting public access to a site which has residual contamination. The IAEA defines institutional control as 'control of a waste site by an authority or institution designated under the laws of a country'.

These controls and provisions can be active and passive. They may include property controls such as easements and covenants; governmental controls such as zoning, permits, restrictions on land and water use, and excavation permit requirements; informational devices like deed notifications and restrictions and title transfers; and legal enforcement tools such as administrative orders and consent decrees. These controls are administrative in nature and are often implemented or enforced by off-site land use authorities.

Institutional controls also limit activities and/or access to land, groundwater, surface water, and waste disposal areas to prevent or reduce exposure to hazardous substances. These kinds of controls may be used in conjunction with other stewardship measures such as engineered controls to provide an extra layer of protection. In general, institutional controls are not intended to reduce the quantity, toxicity, or mobility of hazardous substances in the environment. They may provide for temporary or permanent restrictions.

It is recommended that institutional control activities defined for a remediated site, where restrictions are maintained after remediation has been completed, should be included in a monitoring and surveillance plan. This plan should be subject to periodical review and to approval by the competent authority.

The extent of such a monitoring and surveillance plan should be based on the residual risks and their degrees of uncertainty and on the need to verify the long term stability of the radiological conditions. Referring to foregoing considerations, monitoring and surveillance programmes may include, as necessary, environmental monitoring (of dose rates, activity concentrations in soil, water and air, biological indicator species and foodstuffs), whole body monitoring (if applicable) and dose assessment.

Decisions regarding the routine maintenance of such monitoring and surveillance programmes should be documented in the remediation plan. The results of the monitoring and surveillance programmes should be documented and made readily available to interested parties to assist in maintaining public confidence. An invitation to interested parties to participate in the decision making is recommended also in the post-remediation phase.

5.2.2.1 Governmental controls

Governmental controls are generally applied through the traditional powers invested in the police by the government and enforced on its citizens. Governmental controls are essentially regulatory in nature. Examples of these would be zoning, permits and ordinances, for example, groundwater use permits:

- Special zoning, for instance, may be established to prevent contaminated groundwater from being extracted.
- Enforcing certain types of land use can provide a degree of control if the user of the land is likely to be an entity that will continue in existence. In addition, if the land use is very site specific (e.g., a golf course or a horse race course) then changes to land use are unlikely to be brought about without being brought to the attention of the steward.
- To maintain this restriction, an inspector would check the site and determine, for example, whether water is being extracted. A review of developments around the site to consider pressures that will probably affect changes in usage over time may be useful.

Amongst the major issues facing regulators is how institutional control can be maintained over times exceeding a few decades, i.e., the question of how the ‘rules’ can be enforced. Acceptability of, and compliance with, institutional controls is a socio-cultural question.

Strategies aimed at ensuring institutional control face two challenges: unintentional and intentional breaches of institutional control. There seems to be general agreement that little can be done about intentional breaches. Experience in many countries shows that warning signs are ignored, fences are ripped down, sites are misused and impounded material is taken away without authorization. However, education of stakeholders and building a relationship (Section 5.2.9) might work towards reducing such incidences.

Regulators have to be aware, however, that from a stakeholder perspective the cost-benefit balance may be tipped in favour of a breach; there may be, for instance, pressing economic reasons to reuse fencing and other materials or to occupy restricted sites. It may be expedient to address the underlying reasons for such possible breaches rather than the breaches themselves.

Stakeholders may advocate the complete removal of contamination in order to achieve free release of a site or to have a problem removed from their ‘backyard’. However, it is important to remember that a disposal site for radioactive residues has to be found or newly constructed. In particular, in the latter case, a reasonable balance between the stewardship needs for the site with residual contamination remaining and the stewardship needs for the site receiving the removed contaminants has to be found.

Institutional control is a broader concept than regulatory control (i.e., institutional control may be thought of as a form of regulatory control applied after completion of remediation). In particular, institutional control measures may be passive, they may be imposed for reasons not entirely related to protection or safety, they may be applied by organizations that do not meet the definition of a regulatory body, and they may apply in situations that do not fall within the scope of facilities and activities. As a result, some form of institutional control may be considered more likely to endure further into the future than regulatory control.

5.2.2.2 Proprietary controls

Proprietary controls are often placed on deeds. They involve restricting the use of and through an ownership interest in the property.

Provisions under institutional control may preclude the construction of a building on a specific property. This restriction could be placed on the deed of a property to ensure that future owners will also be restricted from building a house on the property.

To maintain this restriction, the steward has to periodically visually inspect the property and management location (e.g., land register or cadastre) to verify that the restriction is still in force. In addition, the steward (if not the previous proprietor) has to make any new owner aware of such restrictions and if necessary take action to enforce them.

5.2.2.3 Physical/engineered controls

Engineered controls should be designed to treat or stabilise contamination and/or to physically contain or isolate contaminated materials or other residual hazards. The IAEA defines physical/engineered controls as ‘controls intended to limit or prevent access or exposure to contaminations at a site or parts thereof’, for example buried waste.

Common types of engineered controls are an instrument of institutional control aimed at minimizing the need for active control measurements; however, regular surveillance and maintance shall still be required.

Physical/engineered controls may include periodically inspection of the in-situ stabilisation; integrity of caps or covers on residual contamination; and vaults, repositories, or engineered landfills designed to isolate contaminated materials. Contaminated water may be addressed by controls such as groundwater barriers (e.g., slurry walls, pilings), groundwater treatment systems (e.g., pump and treat, permeable reactive barriers), and surface water diversions (e.g., dams, ponds, and ditches).

Physical controls should prevent access to contaminated areas or preclude specific uses. Options may include:

- Fencing, walls, and other barriers;
- Locks (on wellheads, buildings, fences);
- Guards and security patrols; and
- Signs, markers, or monuments.

5.2.3 Maintenance /long term behaviour of engineering solutions

Engineered and physical controls will need periodic inspection and maintenance to ensure continued performance. Engineered control systems have finite design lives; as a result, periodic monitoring of engineered controls should be necessary to alert for breakdowns of controls and hazardous substance releases. Maintenance of engineered controls should include routine repairs and replacement; these should be documented in operation and maintenance plans for individual engineered controls or for the site as a whole. Similarly, physical controls may require periodic inspection and maintenance in the form of replacing signs, mending fences, etc.

Maintenance protocols should be specified in documents and the effectiveness of maintenance activities may be a major part of regular remedy reviews.

5.2.4 Monitoring

5.2.4.1 Introduction

Many of the concepts applied to the assessment and remediation of contaminated sites were developed in the past century, and were built on established traditions of applied science and engineering. Implicit and often tacit assumptions prevalent at that time included that:

- Clean-up can be effectuated to near zero residual concentrations.
- Clean-up can be performed against a fixed set of standards/parameters.
- Permanent solutions can be applied, and the change over time of both the site itself and the engineered structures, such as barriers, can be largely ignored.
- Generic solutions can be site independent, and are also independent of the particular economic and social context.
- The systems in question can be captured by deterministic parameters.

In recent years the validity of these assumptions and their efficiency is being questioned. Emerging new concepts include acceptance of fundamental uncertainties and the appropriateness of risk based clean-up criteria, comprehensive multi-criteria analyses incorporating social as well as technical performance criteria, and acknowledgement of the fact that any engineered structure has only a finite lifetime (see Sections 5.2.1.1 and 5.2.1.4), that a site interacts with its surrounding environment, and hence insistence on an open ended or evolutionary perspective on stewardship. Advances in knowledge permit more and more sophisticated interventions in the functioning of environmental systems. Going far beyond macroscopic intervention in materials (such as building a dam), it is now possible to intervene on the scales of atoms (nuclear fission and fusion), molecules and cellular structures. However, these forms in which matter is organized are dynamic (e.g., change in ecosystems, hydrological cycles and atmospheric circulation), and some of the components introduced into the environment have long lifetimes (toxic organic compounds and radionuclides).

Science and technology applications can sometimes solve, or at least mitigate, the emerging problems inherited from the (recent or distant) past. However, given that the systems in question are complex and will naturally continue to change, there is always the possibility that undetermined changes (including unintended side effects of engineering interventions) can come to dominate design goals.

Leading available techniques in general and the specific remediation techniques applied to (radioactively) contaminated sites in particular are described in Sections 3 and 4 [3], [7], [9], [43], [156]. While they have been implemented worldwide with varying degrees of success, it will be important to assess and ultimately prove their potential against the specific characteristics of the site or sites considered.

Taking into consideration the discussion above, a number of technological challenges for long term management of sites emerge. These technological challenges are within and complementary to the societal framework highlighted in this and other sections.

5.2.4.2 Objectives

Monitoring is usually performed as part of the institutional control measures [157]. This is to verify that the site functions as designed, that regulations are complied with, and that certain aspects of institutional control are still in place and functioning. The legal basis for the requirement to monitor, and the extent of the monitoring, arises from regulations on radiation protection, regulations on environmental protection and, in the case of mining involving radioactive materials, mining regulations designed to ensure orderly closure of mines and mining sites. In addition, there may be requirements arising from relevant legislation on public safety. The sustained performance of a monitoring programme may be one of the core tasks of a steward.

For new practices, remediation planning commences with the development of a site and continues through the operations on the site; major parts of the post-closure monitoring systems usually develop from the programme of monitoring during operation. Assuming that a licensed operation would have a well developed monitoring system, the closure of the operation and the transition to long term monitoring may justify a modification and even a reduction of the extensive monitoring system operated during the operational phase. There may also be a greater focus on environmental compartments rather than on monitoring releases and discharges. Long term monitoring is a relatively new discipline, and it can be assumed that future monitoring experiences and monitoring data will show the values and shortcomings of current monitoring systems.

The characteristics and state of a site after closure and/or remediation determine the type and scope of monitoring required. In the case of mining and milling sites, on-site residues typically include covered waste rock heaps and stabilized tailings ponds. In addition there may be slightly contaminated and covered sites. Any surface structures would have been decommissioned and demolished, with contaminated debris and scrap being buried on-site if it could not be recycled or sent for disposal at a licensed facility.

Monitoring is an essential element of the long term management programme for a closed and remediated site and may need to be undertaken for a number of purposes, for instance for environmental or socio-economic reasons. Programmes typically cover all pathways for exposure of the critical group for all identified contaminants of concern. The scope and nature of monitoring programmes will differ between sites, depending on the level of restriction for land use applied by the regulators [157].

There are three major aspects to monitoring in relation to long term stewardship and management:

1. Monitoring the implementation of a stewardship programme;
2. Monitoring the performance of engineered remediation solutions;
3. Monitoring as an essential instrument of quality assurance and quality control (QA/QC).

For all cases, data quality objectives (DQOs) have to be formulated. These help to identify the questions to be addressed and then ways in which the required information can be obtained. The process is designed to ensure that all parties involved decide during the planning phase what specific decisions will be made using the data collected and what the action levels are for those decisions. In addition, the costs and tolerances of making the wrong decision are quantified so that the statistical design of the monitoring programme can be scaled appropriately. The lower the tolerance for making the wrong decision the more data are needed, and consequently the higher the cost of the programme. Once a monitoring system has been designed, the data quality objectives process has to cycle back through the decisions with all the parties involved, to gain agreement [158].

Visible monitoring programmes and their associated QA/QC systems are valuable tools for enhancement of public confidence [158]. The data from monitoring programmes can be a significant element in a public information and education programme. The data can be made available in a variety of forums and media. An important consideration is to ensure timely dissemination of the information. This can be achieved, for instance, through use of the Internet, where data may be displayed in real time if necessary. In addition, the provision of interpretive comments and control charts enable stakeholders to become aware of the most recent data and their significance. Data may also be distributed through newsletters, notice boards and public displays (including closed circuit TV images of a site), as well as being presented at regular meetings. All of these mechanisms may be used in combination.

Ownership can be created by involving the stakeholders in the monitoring programme. When drawing up the monitoring programme, the steward may need to ensure that a holistic approach is used that will encompass all the relevant issues. For example, sites may be monitored by regularly collecting certain data as well as through inspections. In addition, it may be necessary to check other sources, such as land title registers, to ensure that land use requirements or other essential conditions have not been altered. Again, the reader is referred to IAEA Safety Report No. 27 [157], which contains comprehensive examples of the methods and systems that may be used for these tasks.

5.2.4.3 The scope of monitoring programmes

Monitoring requirements are usually science based but also need to take into account stakeholder requirements in respect of the timing or frequency, range of parameters studied and proposed duration of a programme. Programmes are, therefore, risk based and include social and political risks.

There is a need to reassess programmes periodically to ensure that the level of monitoring activity is appropriate and continues to provide sufficient data of the correct quality to enable the programme objectives to be met, i.e., that it meets the data quality objectives. Reviews usually include issues of compliance with regulatory requirements, as well as an assessment of ongoing performance of the remediation work and ongoing assurance to the community.

The media to be monitored need to cover all pathways relevant to identified contaminants of concern. These will be water (possibly both surface water and groundwater), soil and vegetation; atmospheric monitoring is carried out for gases and particulates.

There may be a need to identify specific targets of concern and also to consider the natural environment as well as humans and the human-made environment. For example, one of the primary requirements of a capping design is to limit percolation of water into the impounded materials. Therefore, monitoring will focus on indicators of the performance of those elements of the capping system that are designed to prevent percolation of water, namely the hydraulic head in the drainage layer. It would need to be known whether the elements perform according to design and, if not, an early warning of potential problems would be desirable. As an example of such a targeted programme, the monitoring system parameters chosen for the cover at the Fernald (Ohio, USA) environmental management project are given in Table 5.1.

Table 5.1 Fernald (Ohio, USA) on-site disposal facility monitoring parameters [159]

Parameter	Critical elements	Technology
Differential settlement	Condition of barrier layer, maintenance of drainage	Topographic survey with settlement plates, ground penetrating radar targets
Head in drainage layer	Stability of cover system	Pressure transducers
Drainage layer temperature, barrier temperature	Stability of cover system, frost protection of barrier layers	Thermistor embedded in a transducer
Root zone status; vegetative soil layer status,	Erosion control	Water content reflectometers, heat dissipation units
Vegetation health and coverage	Erosion control	Topographic and vegetation surveys, webcam, remote sensing

5.2.4.4 Long-term stewardship monitoring activities and technical uncertainties

Monitoring should provide the information needed to track conditions at the site, determine whether the selected remedies remain effective over time, provide information to decide whether remedies should be altered, and guide decisions on when to stop individual stewardship activities. Environmental elements that may require monitoring include surface water, groundwater, air, and ecological features.

Surface water may be monitored to ensure that water quality, especially water leaving a site, meets the applicable standards. Surface water monitoring can focus on dam integrity and operations, inflows to ponds, stream flows, water quality leaving the site, off-site water quality, and remedy performance.

The primary objectives of groundwater monitoring systems should be to establish contaminant concentration trends, monitor the effects of remedial actions, and provide groundwater flow data for use in water balance and groundwater modelling.

Air monitoring systems may be needed to measure ambient air quality, effluent air, project performance, and meteorological data.

Facilities and structures may also require monitoring. Though the usual approach to physical structures is one of remediation through deactivation, decommissioning, decontamination and dismantlement, certain structures may present a situation in which the short-term human health or environmental risks of conducting remedial activities outweigh the benefits of remediation. In such cases, long-term stewardship, possibly combined with stabilisation, may be an option, and monitoring or some form of modified surveillance becomes necessary. Table 5.2 highlights some examples of long term stewardship activities and technical uncertainties.

Table 5.2 Examples of long term stewardship activities and technical uncertainties

Media potentially subject to stewardship	Possible stewardship activities	Examples of technical uncertainties
Water		
All contaminated groundwater and surface water sediments that cannot or have not been remediated to levels appropriate for unrestricted release.	Verification and/or performance monitoring. Use restriction, access controls (comprehensive site land use plan). Periodic review requirements. Resources management to minimize potential for exposure.	What is the likelihood that residual contaminants will move towards or reach a current or potential potable water resource? Are dense non-aqueous phase liquids (DNAPLs), heavy metals or long-lived radionuclides present in concentrations and/or locations different from those identified? Will treatment, containment and monitoring remain effective and adequate? Will ambient conditions change significantly enough to diminish the effectiveness of the selected remediation strategy?
Soils		
All surface and subsurface soils where residual contamination remains, or where wastes remain under engineered caps.	Institutional controls to limit direct contact or food chain exposure. Maintenance of engineered controls or markers. Periodic review requirements.	What is the likelihood of future contaminant migration if ambient conditions change? How will changes in land use affect the barriers in place to prevent contaminant migration and potential exposure? What is the likelihood of cap failure occurring sooner than expected? What is the effect of contaminant caused degradation of remediation strategy components?
Engineered structures		
All land based disposal units with engineered controls.	Monitoring and inspections, by agreements, orders or permits. Institutional controls, including restricted land use. Maintenance, including repairing caps. Periodic review requirements. Land and resources use planning to minimize the potential for exposure.	What is the effect of contaminant caused degradation of remediation strategy components? At what point in time will the remediation solution require significant repair or reconstruction? Is the monitoring system robust enough to detect remediation failure?

5.2.4.5 Monitoring techniques versus regulatory requirements and social ethical challenges

In addition to the monitoring challenges imposed by nature on a given solution, changing circumstances, such as regulatory requirements and standards as well as changing public opinion, may continue to give rise to new questions about the chosen or applied solution.

A long term monitoring and surveillance project has often to identify the following aspects in need of monitoring or surveillance:

- The ecological system associated with the vegetative cover and the 'buffer' area (i.e., the surrounding area);
- Physical changes in the cover system and the buffer area;
- The effectiveness of institutional controls.

Various monitoring, technological developments and improved scientific understanding might make a chosen solution appear inadequate in hindsight, potentially in both the short and the long term. For this reason, new technologies, techniques, sensors and data logging are being developed, for example, in-situ sensors, sensors acting as sentinels against event related phenomena. Therefore, it is important that regulatory requirements reflect current scientific understanding in order to arrive at the best leading solution for the short term as the long term.

It is also important that evidence of changing large scale or global scale boundary conditions (e.g., in climatology, weather patterns and sea levels) and design bases (e.g., regional water tables and drainage patterns) be reflected in the licensing and other regulatory requirements.

Monitoring protocols should be specified in documents and the effectiveness of monitoring activities may be a major part of regular remedy reviews.

5.2.4.6 Example: monitoring at former mining sites

Issues of concern

Large quantities of residues possibly containing radionuclides remaining at or near the surface and mine workings that may remain open are typical of former mining sites. Potential contaminant sources that require monitoring include areas not remediated to free release, surface and underground workings, tailings ponds and waste rock piles.

Increased surface areas underground, the opening of airflow pathways and the lowering of the groundwater table may allow radon to migrate from radionuclide bearing rocks into buildings above the mine site, thus possibly creating a radiological problem. As long as the mine ventilation is operating, the concentrations are kept below levels of concern and the radon is vented in a way that avoids significant exposures. Without ventilation, the radon concentration in dwellings on the surface may increase significantly. Radon levels may need to be monitored and appropriate management strategies introduced.

Monitoring at waste rock piles and tailing ponds

After remediation, monitoring of seepage water for aqueous contaminants, air for radon and engineered structures, such as covers, for their stability will be required to prove the long term effectiveness of the remediation measures and to provide the necessary reassurance to the public. The duration of the performance verification monitoring phase is usually determined by the licensing authorities in consultation with the operators, taking into account the overall management plan. Inspections may be timed so as to efficiently capture any potential change and may be as far apart as several decades. The measurements mainly relate to the:

- Quality of seepage water and groundwater; the monitoring of the chemical composition may extend over considerable periods of time, possibly 20 years or more.

- Radon exhalation and the radon concentration of the air close to the ground over a sufficiently long time to gain confidence that stable conditions have been achieved; such measurements may need to be continued for a considerable number of years. Owing to changing seasonal exhalation conditions, two measurements per annum, one in winter and one in summer, are typically needed.
- Soil mechanical parameters of covers and other engineered structures in order to detect unfavourable changes in water content, porosity, density, soil fabric, etc.

Measurements are usually carried out by the operator or the site steward and are periodically reviewed by the regulatory authorities.

Monitoring at closed mines

Closed mines present a special category of objects requiring monitoring, particularly concerning the chemistry of any discharging mine water. Acid mine drainage is a common problem, which is exacerbated in some (uranium) mines by residual fluids from in-situ leaching operations.

A reliable model based forecast of the mine water development can provide a good reference for the scope, frequency and likely duration of monitoring activities. The contaminants to be monitored depend very much on the specific situation, but commonly involve radioactive components, non-radioactive contaminants, such as arsenic and heavy metals, and major constituents. Comparison of measured concentrations with modelled forecasts gives an indication of how long any water treatment and monitoring may be needed.

In deep mines, depending on the mine geometry, the main processes that maintain concentration gradients are convection and diffusion. The water volumes to be treated under a stewardship programme depend on the respective recharge rates in the area and the ensuing water balance in the mine. Mine water volume streams can be as high as 500 - 1000 m^3/h.

Underground mines typically extend below the water table, and restoring the water table to pre-mining levels or another suitably defined operational level is part of a decommissioning and stewardship programme. The objectives of the flooding are to:

- Stop oxidation processes;
- Minimize water treatment costs and emissions and maximize the radiation protection of the workers by suitable controls of the flooding.

A stepwise flooding scheme, whereby the monitoring results provide data for corrective actions if the system does not behave as predicted or envisaged, is recommendable.

Safe mine closure requires a thorough understanding of the hydrogeology and hydraulics of the mine and the surrounding environment. Meaningful monitoring points are the basis for a model developed with this understanding, which is by no means trivial. A more detailed discussion of the respective requirements, however, is outside the scope of this report.

Scope of monitoring versus land use

Revegetation of covered waste rock piles is commonly allowed, or rather cannot easily be prevented in temperate or tropical climates. Other uses usually require a more involved permit procedure and appropriate monitoring. In order to determine the scope - from a radiological point of view - of potentially allowable site uses, expected exposures of critical groups or individuals are calculated for each use. The monitoring programmes are then designed to suit the site use chosen. Recreational uses with short term occupancy such as a golf course or an airfield for model aircraft, on waste rock piles, may be preferable, for instance, to industrial or residential developments.

5.2.5 Information and knowledge management

5.2.5.1 Introduction

When sites make the transition from clean-up to long term stewardship, site stewards and stakeholders should be given detailed information about the location and the nature of residual hazards, the processes that generated them, and the engineered and institutional controls that are part of the remedy.

There is a general notion that future generations will command more knowledge and capability than the present generation. However, as is evident from many archaeological mysteries, such as the true purpose and design objectives of the Egyptian pyramids, and lost production technologies, such as the composition of some medieval stained glass, knowledge and insight might also be lost. Another example is the loss of knowledge, technology, infrastructure and institutional control associated with the decline and fall of the Roman Empire. It took nearly a millennium and a half to again reach the same level of sophistication in some areas. It is interesting to note that knowledge was slowly recovered through decentralized and redundant record keeping: much of the writings of the ancient Greek and Roman authors was preserved in the Arab world and fed back into the Western world.

It should also be noted here that the majority of texts on related subjects, such as knowledge management, are concerned with the preservation of knowledge as a corporate (or group, such as the nuclear industry as a whole) asset. In this sense, it is about ensuring that the knowledge of an individual is shared with others and about making this knowledge available at any time. In the present context the time horizon is much longer and may go well beyond the lifetime of individuals or corporations, even beyond the duration of a society.

Site specific knowledge and information is much more vulnerable to loss than are generic knowledge and capabilities. An example here may be the ancient city of Troy, where knowledge of its exact location was lost but general awareness of its former existence remained, due to written sources. Eventually modern archaeological science was able to re-establish its location by inter-relating a variety of decentralized sources of information. There are similar examples from other parts of the world.

Long term knowledge management and the intentional transmission of information will have to address four main issues:

1. How to transmit knowledge over long periods of time;
2. The kind of knowledge to be stored;
3. The types of data and information needed;
4. The types of storage media.

The first of the above issues is the most important and the most difficult to resolve.

In Section 2.11, record keeping is treated extensively for all phases of the live cycle of an industry and its site.

5.2.5.2 Knowledge forms and knowledge sharing

A multicultural panel on science and sustainable development, held at the sixth session of the Commission for Sustainable Development (CSD) of the United Nations in New York, considered issues such as these and made the following recommendation:

> *'... every possible effort should be made to improve the processes of generating, sharing and utilizing science for sustainable development, and that this will need to include a commitment to overcome the communication gaps within the scientific community and between scientists, policy makers and the general public'.*

The panel statement suggested that appropriate elements of quality assurance, science communication and public policy processes will include:

> *'... new institutions and public procedures for the social evaluation of science advances; technology transfer seen in the framework of reciprocal learning and capacity building; and a reassessment of the forms and locations of the 'centres of excellence' capable of contributing knowledge and judgement needed for sustainability'.*

Mobilizing knowledge for sustainable development and stewardship requires attention to the forms of knowledge sharing, including their institutional, technical, economic, linguistic and cultural preconditions. Social trust and partnerships are constructed through dialogue and cooperation - among scientists and technical experts with policy makers, implementers and stakeholders - including experts with site specific (local) knowledge that complements methodological and coordination expertise. Knowledge as a resource must be accessible to the actors and pertinent to the context of their action [160].

Following these arguments, it is important to adopt a pluralistic approach to building the knowledge base. Science (understood as the activity of technical experts) needs to be considered as an important part of the relevant knowledge base that needs to be developed and mobilized in order to provide evidence in a decision or policy process. However, the ideal of rigorous scientific quality assurance is complemented by a commitment to open public dialogue. Citizens and stakeholders have a fundamental role in a knowledge partnership process.

The strength and relevance of scientific evidence is amenable to assessment by citizens, who contribute to the framing of the issues and to judgements about the acceptability of proposed solutions. In this perspective, all parties come to the dialogue ready to learn. Through this co-production of knowledge, the extended peer community creates a (deliberative) democracy of expertise.

The 'post-normal' model of science practice, developed by risk assessment experts Funtowicz and Ravetz [161], [162], [163], places the emphasis on quality assurance through extended participation. A pluralistic, participatory and democratic view is developed of the knowledge and judgement base for policy actions:

- The old distinction between hard facts and soft values is replaced by a soft facts/hard values framework - admitting the complexity of emergent system properties (and hence uncertainties, etc.), and admitting the plurality of quality and legitimating criteria (e.g., there are different definitions of a problem, different ways of selecting and conceiving its relevant aspects, as well as different definitions of goals, depending not only on conflicts of interest but also on cultural factors).
- The highly asymmetrical distinction between experts and non-experts is reframed. In a sense, when facing a post-normal problem, all stakeholders are experts: in different ways, from different points of view and with regard to different aspects of the problem. Thus, it is necessary to extend the number and type of actors, both individual and collective, legitimated to intervene in the definition of problems as well as the selection and implementation of the connected policies. This extension does not only fulfil the requirements of democratic decision making but also improves the quality of decisions. The way of conducting a decision process dramatically influences its results. The dialogue between different actors is essential for quality, credibility and legitimacy, and hence the prospects of success of policy implementation.

The efforts to extend the time window for understanding ecosystem behaviour through recourse to what has become known as traditional ecological knowledge may serve as an example of formal and informal knowledge. Traditional ecological knowledge can be defined as any cumulative body of knowledge and beliefs, often partly tacit and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment.

An attribute of many societies with historical continuity in resource use practices is that they are non-industrial or less technologically advanced, many of them indigenous or tribal. There is little doubt that traditional ecological knowledge can be valuable for developing long term time horizons for system stewardship. Both the habits of thought and the substantive environmental knowledge can be sources of wisdom. Records of traditional ecological knowledge may be helpful in reconstructing the ecological history of a given area, thus extending our design base over longer time spans. Better supported predictions of future developments might be possible in conjunction with modern system analytical and modeling techniques. As this 'knowledge' typically combines digested experience with myth and has no established time frame, it is difficult to deduce the time period for which it would be valid.

However, it should not be assumed that 'traditional' practices and the knowledge and values that they embody are automatically aligned to contemporary site stewardship needs. Some commentators convey the idea that indigenous populations living on the basis of traditional ecological knowledge always do/did so in a sustainable way. This is not necessarily the case. While some behavioural patterns may have been aimed at conservation of resources, for instance those arising from hunting taboos, the lack of baseline data and a detailed analysis of the ecosystems in question make a proper judgement difficult. Historical evidence also shows that traditional ecological knowledge is not always very resilient and adaptive to changes in the ecosystem if the rate of change is too fast. It could even be argued that modern western thinking developed in response to challenges by the surrounding ecosystem. Apparently there were important incentives and drivers for such a development and they outweighed the loss of 'sustainability' [164].

Observations of indigenous populations are generally based on a rather short timescale, the observation times typically not extending beyond a few decades into the past. For a given ecosystem and indigenous population, the situation may appear stable over the observation time and the changes induced by the human population may be too small to observe. It is also important to remember that every continent (exept Antartica) once had an 'indigenous' population that, over time, showed itself to be able to shape its environment beyond recognition.

5.2.5.3 Selection of records for retention

A major challenge in record keeping anywhere is the decision about which records to retain and which records could be disposed of. As has been discussed above, the importance that is attached to a certain record may change with time and depend on the stakeholder concerned.

A categorisation of records according to levels of importance, such as critical, necessary or useful, might be helpful in deciding which material requires most attention and in focusing resources on its preservation. A road map that indicates in which way the importance of a certain record changes with time might be a useful management instrument.

The timescale of retention of individual records would be determined by the needs of the stewardship programme. Certain records would be reclassified as time progresses; for instance, operational records would become historical records. A risk assessment may need to be undertaken in more complex cases to achieve a balance between the possible cost arising from no longer having certain records available and the cost of storing these records. It may actually be cheaper to store all records indiscriminately than to scrutinise them and make selections - with the risk of destroying some that may later be deemed valuable. For certain types of records there may be legal requirements to retain them for a specified period of time; for example, tax offices may require that documentation supporting tax returns be kept for a certain number of years, or a contractor may be required to retain certain records for warranty purposes.

In addition to the operator and their successors, for example the steward, the regulator may also have collected various types of records. Often, these duplicate records may have been generated or held by the operator and may provide a certain redundancy. Different rules and regulations for retention may apply for the regulator and other government authorities. Some governments may have a well established system for assessing and retaining records. The regulator may require the operator to prepare a summary report on records held.

5.2.6 Periodic review

At regular intervals, for example, every five years, a review should be conducted to evaluate the implementation and performance of a remedy in order to determine if the remedy is or will be protective of human health and the environment. Key questions for the review may be:

- Is the remedy functioning as intended by the decision documents?
- Are the exposure assumptions, toxicity data, clean-up levels, and remedial action objectives used at the time of the remedy still valid?
- Has any other information come to light that could question the protectiveness of the remedy?

Site-specific information to be reviewed may include results from monitoring activities, operation and maintenance reports or other documentation of remedy performance, and previous five-year review reports. Changes that affect the validity of clean-up levels (e.g., standards identified as applicable or relevant and appropriate requirements and assumptions about contaminant characteristics and potential exposure) should also be considered. Nearby communities and stakeholders should be notified when a five-year review is conducted or even be involved in its compilation. The results of the review should be archived for future referencing.

5.2.7 Removal of restrictions of site access

If the monitoring and surveillance programme has verified the long term effectiveness of the remedial measures in eliminating unacceptable risks to human health and the environment, consideration should be given to removing any restrictions applied to the site and ending or reducing the extent of the monitoring and surveillance. If the option of ending or reducing these services is considered, the value of the monitoring and surveillance in promoting and maintaining public confidence should be taken into account. In considering the long term effectiveness of remedial measures, the environmental influence of physical, chemical, geological and other factors should be evaluated. In particular, contamination of groundwater may not become apparent for some time and may do so at some distance from the source of the contamination. Such considerations should be documented in the remediation plan.

5.2.8 Societal and ethical challenges relating to long term stewardship

The societal aspects of long term stewardship may present several important challenges, such as building trust, communicating the nature of the risks and of the remediation and stewardship options, reconciling economic, management and technical issues with considerations of public values and beliefs, resolving ethical questions and engaging stakeholders in the decision making process, and thereafter retaining stakeholder commitment [155].

5.2.8.1 Stakeholder involvement; partnership building and purpose

Stakeholder involvement in the decision making process on long term management strategies has gained importance in many countries. One of the key elements in stakeholder involvement is the provision of and the use of information as a basis for decision making. Decisions in question may range from initial choices of remediation and stewardship strategy, to all the related issues of financial resource management, record keeping and management, and monitoring to assess the requirements for stewardship or intervention as time goes on.

Contaminated site stewardship decisions may involve complex judgements about how people (a community) will live with, cope with or get along with inconveniences and risks that have their origins in the past. In some cases of major misfortunes or accidents, the people most directly concerned, or their descendants may live with memories, scars and the pain of things lost, and must confront the uncertainties of building a new life. Public policy in such situations must contribute to repairing, revitalising and rebuilding communities. What are the human factors that permit people, in the face of economic loss, environmental adversity, damage to their health or other misfortunes, to recover and again become purposeful and enthused in their efforts in society?

These challenges of partnership building and (sometimes) rebuilding will be important even when - as with the majority of mining and industrial exploitation activities - site stewardship is not associated with past accidents or traumas. First, there may be the requirements of memory associated with the requirements of monitoring and eventual intervention at different types of contaminated sites whose risks extend decades, centuries or, in some cases, even millennia into the future. Second, there may be the problem of community and partnership building in the face of adversity. This may be partly an economic resources problem but it is also a cultural and political problem of purposes and meanings.

5.2.8.2 Communicating the nature of the risk and stewardship

Contaminated sites are socially constructed risks. As in the case of most socially mediated risks, the significance - and hence the acceptability - to an individual, to members of a community or to a society, of exposure (or a danger of exposure) to a dose, depends on how, by whom and why the dose has been produced. Correspondingly, in order to assess to what extent or on what basis the members of a society will judge acceptable or trust (or not) a given strategy for the management of high level long-lived radioactive residues, it is necessary also to consider the meanings and relationships (in social, economic, cultural and symbolic terms) that alternative remediation and stewardship strategies might establish between the people - individuals, classes, interest groups, succeeding generations and whole nations - implicated in the site stewardship process.

Trust may be characterised as the willingness of a person, group or community to make themselves vulnerable in the expectation (or hope) of a benefit coming from association with others that would not otherwise be forthcoming [155]. The conditions of trust in government, as in a commercial enterprise, as in scientific and technological advances more generally, all relate, on the one hand, to hopes of benefits and, on the other hand, to confidence in the capacity and will of society leaders and innovators, and other potential partners, to ensure the sharing of those benefits. Successful stewardship, like successful diplomacy, will arise from effective dialogue leading to confidence in the prospects for a worthwhile common future.

The ‘appropriation’ of a problem by local stakeholders, and their identification of a concept for a solution that is acceptable to them, may be among the key ingredients for the economic, social and political viability of a solution. Equally necessary is the engagement of the relevant national authorities, establishing a political and economic partnership that will unite the complementary local and national resources and forms of authority. From a societal point of view, this suggests the identification of three key components for a viable solution to a contaminated site stewardship problem:

1. *Technical and scientific expertise*: the development, application and maintenance of scientific knowledge and technical competence to measure and to control the present and eventual exposure of living beings to radioactivity.
2. *Building social/societal relationships with the site*: the envisaging and invention, in social and symbolic terms, of how the relevant community (or communities) will relate to and interact with the sites, the risks, the residues and the records.

3. *Political and economic partnership*: a means to permit mobilisation of the relevant knowledge and resources for the implementation of an agreed societal strategy for stewardship.

5.2.8.3 Defining societal criteria for defining and implementing stewardship strategies

The second and third of the above components (see Section 5.2.8.2) underlie in various ways operational considerations such as management, economics and financing, and records and information systems. The societal components are also interdependent with the effectiveness of technical and scientific expertise. The building and maintenance of the necessary political and economic partnerships depend basically on the relationships that the different stakeholders develop and maintain among each other and with the site. Without these ongoing partnerships, the relevant knowledge for stewardship will not be mobilised or renewed, and the motivation for long term engagement will be fragile. Therefore, it is important to consider stakeholder participation for designing the stewardship solution, or for formulating and evaluating options, as well as for roles in the operational stages. No individual or institution holds a complete knowledge base for 'what should be done'. The participation of stakeholders is necessary for the mobilisation of existing wisdom and purposefulness, and for the regular renewal of this.

Radiology science and engineering should address the ways and means of controlling the exposure of present and future generations to radiation, relative to what is considered safe or otherwise satisfactory. Technical expertise (drawing on various aspects of physics and chemistry, biology, epidemiology, etc.) plays a crucial role in determining what should be considered a safe level of exposure and on the effectiveness of different engineering and institutional strategies for the present and possible future levels of exposure associated with a site. However, technical expertise, on its own, cannot answer the societal question of what should be done.

In a situation where there is a consensus that the enduring presence of hazardous wastes is troublesome and requires a societal response, but, precisely because this potential risk is not easily forgotten, a solution that inspires confidence should engage a permanent process of vigilance in which concerned stakeholders are directly involved. This may involve stewardship procedures whereby an economically active community, in partnership with overall regulatory authorities, is living close to (or even within) and maintaining a watch over the site. This is an example of a social (rather than a technical) criterion for acceptability.

Generalising from this example, a set of questions might be useful for identifying broad social criteria for the acceptability of stewardship strategies proposed for a given site. The questions should be formulated in descriptive language, considering the current situation or features of the proposed solution. As a function of circumstance, and of stakeholder point of view, these questions may be modified with normative or prescriptive language, i.e., to function as criteria for acceptability, as suggested in italics:

1. Is there official recognition of a waste, residual risk or contamination problem at the site? (*Should there be official recognition of a waste, residual risk or contamination problem?*)
2. If yes, is there, or is there planned to be, active stewardship of the site? (*Should there be active stewardship of the site?*)
3. Is there, or is there planned to be, an ongoing public interaction with the site as a dimension of the stewardship process? (*Should there be an ongoing public interaction with the site?*)
4. If yes, is the 'historical liability' made a feature of the site's new public identity or use? (*Should the historical liability be made into a feature of the site's new identity and use?*)

5. If yes, what types of activity are mainly associated with the contamination features, for example, activities for the public good such as education, training and research, or private benefit activities such as recreation and tourism? (*What types of activities should be associated with the contamination or waste features?*)
6. What type of socio-economic status and prestige should be accorded to the stewardship process? (*What type of socio-economic profile, prestige or importance should be associated with the stewardship process?*)

Examples of stewardship concepts that may emerge from different sequences or combinations of 'Yes'/ 'No' answers to the above questions may be:

1. The response to the first question might be 'No', with an ongoing controversy about whether or not there is a significant danger associated with a site.
2. The sequence 'Yes' to the first question, 'No' to the second question would imply identification of an 'orphan' site, and therefore lead to the question of the acceptability of this orphan status.
3. The sequence 'Yes' to the first question, 'Yes' to the second question, 'No' to the third question would lead to concepts of a segregated or isolated site, with restricted access. Appropriate analogies might be a dangerous natural site, a rubbish dump, a warehouse for storing dangerous goods, a mausoleum or a nursing home. Answers to question six would permit a characterisation of the socio-economic status of the stewardship activity for the site.
4. The sequence 'Yes' to the first question, 'Yes' to the second question, 'Yes' to the third question, 'No' to the fourth question would lead to suggestions for 'ordinary' uses of the site, for example, industrial or forestry production, or recreational activities (such as a golf course) that do not in any way rely on or 'exploit' the stewardship status of the site. These activities will, however, be under regulatory control, and answers to question five and question six would highlight whether or not a stigma is associated with the site.
5. The sequence 'Yes' to the first question, 'Yes' to the second question, 'Yes' to the third question, 'Yes' to the fourth question would lead, by contrast, to suggestions for uses of the site that specifically rely on or 'exploit' the historical liability as a distinctive feature of the site. This could include ordinary commercial uses of the site, such as tourist and recreational activities, and ones that specifically make use of the identity of the site or installations such as shrines or temples, museums and educational facilities.

The purpose of this typology process is to highlight the qualitative range of different models that can be, and have been, envisaged for stewardship of contaminated sites. Each category of solution has its appropriate analogies and metaphors, and thus highlights different aspects of social life, different types of prestige and status, different communities or different relationships. Specific technical, financial, management, record keeping, monitoring and communication procedures must all be framed with recognition of these qualitative societal and institutional choices.

Suppose, for example, that there are jobs attached to the long term site stewardship activity and salaries to be paid. In what terms will the job of site wardens be advertised? Who will be recruited (the question of job opportunities for locals)? What types of skill will be required? What will the salary scale be? What will be the relation of the site wardens to others in the local community (if there is a local community), and the perception of their role by the rest of society?

a. In the context of high level radioactive waste disposal, variations of the shrine/temple concept have been offered for some years by many commentators. The concept has appeal partly because it evokes the 'eternal' character of the guardianship task. It might also have appeal because, by the establishment of a high prestige guardian task, the stewardship roles could offer reasonable prospects for highly trained nuclear engineers. Generation after generation of guardians could be imagined, each generation handing down, by algorithm, ceremony and song, a unique competence to those that follow, maintaining an eternal vigil.

b. The contrasting nursing home concept brings a quite different set of connotations: patience, compassion, meticulous care, weariness, perhaps even mourning, anger and sadness with the pain of a long condemnation to watch over the ageing residents of the nursing home.

c. The theme park option brings once again a distinct set of job profiles and social relations.

5.2.8.4 Managing ethical questions

The prime objectives for remediation actions are the abatement of actual health risks and environmental impacts and the reduction of risks to human and other receptors in the longer term. Site stewardship is a prolongation of these goals [155].

In recent years, a key reference point has been adherence to sustainability principles. Sustainable development seeks to reconcile present day needs with the requirements of future generations. Other definitions of sustainability put to the fore the maintenance of biosphere life support systems, species diversity, economic justice between developed and developing nations, political self-determination, and tolerance of diversity in cultural and political conventions.

However, application of sustainability principles is not always straightforward. The management of long term radiological liabilities is associated with scientific uncertainties and also with moral, political and economic dilemmas. What principles should be applied to the distribution of inconveniences and risks that are the ‘downstream’ legacy of benefits gained? What is, and what should be, our attitude about the possibly adverse consequences imposed on others (elsewhere or in the future) by present day production and consumption decisions?

Some sectors of the public may effectively demand a reduction to zero impact and zero risk. This is in contrast to the fact that society in general has received benefits from the site activities resulting in these impacts and risks. Perceptions, however, may be shaped by the fact that the groups of society affected are not necessarily identical to those receiving the benefits. It may be pointed out that in almost all cases the demand for zero impact and zero risk will only result in a transfer of risk from one community to another. For instance, removal of radioactive residues to an engineered repository off-site will result in a net reduction of risk, but at the same time move the risk from one community to another.

The acceptability of residual risks is in general a function of a wide variety of sociological, economic and political factors. It may vary over time for individuals or certain groups of individuals. The acceptability typically evolves, among others, as a balance between the perceived risk and the actual inconvenience imposed by institutional control measures. Inconvenience here is understood to encompass, for example, the restrictions on site use imposed. The higher the perceived risk, the more acceptable become institutional controls.

What does the current generation owe future generations in terms of the legacy wastes from nuclear materials and weapons production? One answer is nothing, arguing that future generations are likely to have more knowledge and capability than exists now, and will be quite able to look after themselves, so that attempts at help from the current generation would be considered, from a far vantage point, as merely quaint. However, it is advisable if possible to prevent their stumbling, through ignorance or accident, on what may be harmful to them.

It is undesirable to leave unresolved problems for future generations, although it is also undesirable to deprive future generations of certain options because of actions taken by the present generation. Some moral philosophers, however, claim that this argument would quickly lead to a justification of no action being taken by the current generation on many issues, and that pre-emption of future options is acceptable ethically, provided that the current action is well motivated and reasonable in the light of current knowledge.

An example of these dilemmas is the controversy about the principle of precaution as a guideline in regulatory policy. The spectrum of attitudes within our societies towards technological progress can be highlighted by two contrasting positions around the question of the 'burden of proof' associated with innovations or engineering exercises whose outcomes are uncertain. Those evoking the traditional discourses of progress will argue that 'the future can look after itself'. Those evoking a precautionary attitude will argue that absence of proof of danger is not the same as proof of absence of danger and that, where great uncertainty and possibly grave dangers reside, risks should not be taken. In the Rio Declaration, for instance, it is stated that: 'Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost effective measures to prevent environmental degradation' [155].

This precautionary principle can be justified by a variety of arguments in terms of duty or responsibility, respect or esteem for others (notably future generations) as members of an extended community [155]. The idea is that actions carrying a possible (but as yet undemonstrated) risk of serious and long lasting damage to future human interests should not be permitted. It is clear that the principle is founded on specific ethical considerations that gain force where science and technological progress are no longer regarded as ordinarily beneficial and where outcomes cannot be determined fully (or at all) in advance, i.e., where powerful forces of natural and technological change are being engaged under conditions of inability to exercise mastery over eventual outcomes.

How far should the precautionary attitude be taken? Answers to such questions hinge on notions of responsibility, including the definition of intergenerational equity. The controversy around precaution as a principle for orientating social choices thus highlights the dilemmas of action and decision in risky domains. It is interesting to note the peculiarity of the ethical notions of holding ourselves responsible for the detriments caused by past generations, relative to the ethical premises that have guided industrial and scientific developments in the past. It may also be affirmed that, despite some inconveniences from contamination and long-lived wastes, future generations will nonetheless enjoy accumulated benefits from previous generations. It can therefore be argued that each generation should also carry some of the burden incurred by their predecessors. Hence, we could ask ourselves, whether we really need to find 'permanent' solutions, or whether we should not be able to leave some legacy to future generations, as these will profit from our technological developments.

The definition of what constitutes a residual risk is subject to scientific developments and subsequent changes in regulatory systems. A stewardship programme may need to have provisions for accommodating such changes in the regulatory system. While the legal framework usually ensures that the criteria do not change, the regulator may deem it necessary to reassess risks. Such reassessment may result in changes to the institutional control measures that in turn require changes in the stewardship arrangements. A mechanism should be available to furnish (additional) resources.

Engineering interventions within complex systems cannot overcome all risks and cannot avoid contributing to uncertainties that have been called virtual or hypothetical risks, i.e., conceivable (and undesirable) outcomes characterised by complex causation networks, time lags and severity of impacts (e.g., a nuclear meltdown or a toxic waste containment system failure caused by an earthquake), whose investigation by any kind of laboratory testing is logically impossible or involves costs that are prohibitive. These 'virtual' risks are often unproven - or un-quantified - until they materialise, but at that point they cannot be managed - they may be accommodated in various ways, but only at significant economic and social costs. For those upon whom the misfortune falls, the perceived uneven, unfair and un-negotiated imposition of disadvantages, damage and burdens (including future clean-up costs or enduring health problems) is likely to be resented and un-forgiven - and hence of much greater social and political weight than any notion of a net benefit to society.

There are also risks of an essentially human character. One example is the potential that if significant concentrations of contamination are left in the ground at any particular site, the extraction of such material could prove to be an enticement for extremists wishing to create chaos or terror in the world. This type of material, while not in a suitable form to construct nuclear weapons, may nonetheless in theory be used to make so-called dirty bombs or similar devices. It is therefore important to ensure that any stewardship programme takes the security question into consideration. A similar issue will clearly be prevalent for radioactive waste disposal sites.

These scientific, moral and political dilemmas cannot be eliminated; decision making and stewardship must accept them. What remains is that it is the responsibility of the present generation's policy makers and articulate members of the public to affirm, by proxy, the 'entitlements' (if any) of, for example, future generations, vulnerable persons, endangered species and ecosystems. In effect, provision for the needs of future generations (as for all other forms of diversity) can be assured only through generous choices of resource use (investment and protection decisions) with the intent to maintain and enhance the opportunities and environmental security of others, including future generations.

Stewardship is a commitment towards future generations that is given practical effect through communal and political choices for the investment of time, labour and economic resources in environmental remediation and monitoring. The stewardship activity is thus interwoven with many other features of economic life, including:

1. Investment in infrastructure and durable public assets;
2. Provision for extensive and ongoing community involvement in decision making processes;
3. Educational investments aimed at fostering an ethics of care and environmental interest;
4. Investments in research and technological development intended to furnish understanding, information and practical know-how that may simultaneously enhance the economic opportunities and environmental security of future generations.

In practice, there must be an evaluation of options with reference to multiple criteria. The ethical dimension of management consists, in fact, of the articulation of the different principles that may underlie operational criteria. The spectrum of stewardship strategies may be considered as being, from some perspectives, ethically principled actions, i.e., actions that satisfy or respond to particular criteria of good or sound practice that are suggested by members of the community. For the domain of radioactivity stewardship, current examples of ethical criteria include:

1. Have the responsibilities of existing parties been appropriately assigned? For example:
    a. Has the principle of national autonomy/responsibility (for countries to take care of their own wastes at the national level) been applied?
    b. Has the principle that 'the polluter pays' been applied?
    c. Is due respect shown for local, national and international regulatory conditions?
2. Have responsibilities towards other parties been adequately addressed in the short term? For example:
    a. Have measures been taken to ensure the health security of workers and the public on or close to the site?
    b. Is there security against attack from external or internal sources of aggression?

3. Have responsibilities towards other parties been adequately addressed in the longer term? For example:
   a. Has the sustainability principle for intergenerational responsibility (not passing on problems to future generations that cannot be coped with in the present) been applied?
   b. Has some version of the principle of precaution been applied?
   c. Is the necessary knowledge base for competent stewardship stable in the long term?
4. Have available technical know-how and systems science been used? For example, are standards of best practice (technical reliability, simplicity, etc.) being applied?
5. Is the solution economically viable? For example:
   a. Are the immediate costs of stewardship affordable with the available resources?
   b. Are there major financial costs postponed to the future?
   c. Are there reasonable prospects of acquiring resources for the forecast stewardship costs in the longer term?
6. Does the solution enhance the prestige of the host communities or other stakeholder groups closely associated with the residue/waste site?

Each distinct stakeholder group will bring a different balance of pre-conceptions to the evaluation process. The general idea is that a comparative evaluation of the stewardship scenarios should take place from a variety of different points of view corresponding to distinct pre-conceptions. Each stakeholder group may express different criteria of adequacy or quality in relation to each of the governance issues. Where tensions, conflicts of interest, uncertainties and dissent emerge (e.g., among scientists as well as decision makers, administrators and stakeholders from different areas of commercial activity and civil society), these can be documented. The reasons for dissent can then be discussed in a transparent way, which sometimes opens up prospects for consensus or novel strategies.

5.2.9 Keeping stakeholders involved

Even if all conceivable groups of stakeholders have been identified, individuals may (have to) set for themselves priorities other than to become actively involved in the decision making process [155]. There may be sound economic and social reasons for such priority setting, as active involvement commonly has to take place during people's leisure time. Most social groups do not have the opportunity to become involved during the time they earn their livelihood or follow other social activities. Active participation and actively seeking involvement is commonly associated with certain kinds of social disposition and cannot be taken for granted. However, the decision making processes, in order to adequately reflect the interest of all groups, have to sample the views of those who cannot, or do not want to, actively participate.

The development of a 'this is not my problem' attitude among potential stakeholders is often observed in the context of complex decision making problems. This essentially affects all parties concerned with the development of stewardship plans. It may be due to a relative distance from the problem, or simply related to the fact that the site is not actually visible to the individual/community. It is most prevalent in situations where the implications or issues associated with a project are too complex for an individual, or a community, to comprehend. This effect has obvious implications when communicating and consulting with potential stakeholders.

Loss of interest, even by key activists, along a lengthy decision making and implementation process may also seriously undermine the diversity, effectiveness and credibility of public participation programmes.

Maintaining and enhancing transparency in the long term stewardship programme and traceability of records and decisions are factors that may influence the level of interest of stakeholders in the programme. Transparency implies that the decision-making process be well documented (including a clear and comprehensive synthesis of the bases for decisions) and available to all stakeholders in the programme. In addition, all documents should be readily retrievable and should be easily understood by all interested parties. Policy and technical considerations should be clearly differentiated; for instance, a statement of intent and rationale behind each stage and decision should be developed and tested for understandability and then broadly publicised to stakeholders. To improve transparency (and auditing), it is also valuable to ensure that key information is not buried in a surfeit of less relevant information. Transparency creates the basis for a dialogue among the implementer, regulator, external review bodies and stakeholders.

Responsiveness to stakeholder feedback is a further incentive to maintain stakeholder involvement. Responsiveness requires that the agency implementing the long term stewardship programme seeks, acknowledges and acts on new information and on inputs from other stakeholders in a timely fashion. Schedules should be planned to allow timely integration of new knowledge into decision making and to include the time to implement changes responding to newly acquired information. This phased approach to stewardship allows the implementing agency to integrate lessons learned from prior stages and stakeholder feedback, and to plan for future stages.

Finally, trust in the institution implementing long term stewardship is essential to involve and maintain the interest of stakeholders. Trust in the institution implies integrity, for example, carrying out agreed actions. For all decisions, all uncertainties, assumptions and indeterminacies should be identified and labelled as such. Technical results should be accurately and objectively reported and placed in context at each stage. The applicability and limitations of data should remain openly acknowledged. All relevant results, including those offered by external parties, should also be incorporated into the decision making process.

From the point of view of stakeholders, the success of a long term stewardship programme should be measured in terms of public participation. The following seven items may be identified as the basis for successful stewardship programmes:

1. Acceptance of the responsibility for long term stewardship of contaminated areas;
2. Development of a (national) policy on stewardship;
3. Establishment of a legal mandate for funding stewardship activities separate from remediation funding;
4. Development of a better understanding of the trade-offs and relationship between clean-up and stewardship;
5. Development of guidance for site specific stewardship plans;
6. Involvement of stakeholders in stewardship planning, oversight and review;
7. Establishment of information systems (e.g., databases and permanent markers) designed for use by future generations.

While some of these items simply reflect the demand for good practice and the call for a decisive political will to take on long term commitments, others may pose a serious technological challenge.

5.2.9.1 Keeping stakeholders involved in the specific case of long term stewardship

As suggested above, identification of an appropriate stewardship strategy may depend partly on technical considerations and partly on societal concerns [155]. However, who speaks for society and who are the key stakeholders for stewardship decisions?

Stakeholders in the specific case of long term stewardship may typically be those individuals or organisations that may have an interest in stewardship being executed properly or who are affected by programmes. Although identification of stakeholders is difficult, consideration of the following questions may provide some insight:

- Who has the information and the expertise that might be helpful?
- Who has been involved or has wanted to be involved in similar risk situations before?
- Who may be affected, with or without their knowledge, by the remediation planning?
- Who may be mobilised to act or angered if they are not included?

There is no single delineation of the public and the stakeholder that is straightforward and applicable to all situations, and so no definition is universally accepted. Many analyses start from distinctions between public and private sectors of economic activity, for example, government and business, and then refer also to civil society. Some typologies include research and technical experts as a distinct category. In some contexts, tribal, ethnic or local community membership may be more significant than field of economic activity. Any individual can be both a member of the general public and a stakeholder with a business, government or other specific identity, depending on the private, political or professional aspects of their life that are touched upon.

Typically, the public is everybody and also includes all stakeholders such as affected citizens and civic organisations, environmental groups, labour organisations, schools and universities, representatives of business interests (e.g., chambers of commerce), representatives of government (e.g., local, regional and national government), and the scientific and technical expert community (e.g., academia, professionals' organisations and government departments).

Whichever the groupings retained neither each member of these groups nor all groups may be necessarily affected in a direct way by the contamination in question and the related remedial and stewardship activities. The question of whether all concerned citizens or only those directly affected should be given standing as stakeholders in the context of stewardship remains unresolved to date and is probably irresolvable - because different answers refer to distinct models and beliefs about justice, knowledge and political processes.

Figure 5.2 Typical stakeholders involved in remediation programmes

For example, the question of the roles and legitimacy of non-government organisations has often been a matter of debate. These organisations (citizens' associations, incorporated societies, networks, etc.) may vary tremendously in type and style of activities. There is no doubt that in some cases their activities have had a positive effect on the quality of decision making and site management. Acting as voices for the local community, environmental quality and the interests of less influential societal groups, they often play mediating roles between the public, local communities and regulatory agencies (the government). However, it is also noted that non-government organisations may develop distinctive profiles, with their own perceptions and agendas that may be at variance with the perceptions of those actually affected and whom these organisations claim to represent.

The activists within non-government organisations may, by design or effect, work to impose their own perspectives on locals (and also on regulatory agencies), as they may seek to expand their influence and to establish their indispensability as mediators.

Figure 5.2 indicates potential actors, or affected parties, as identified within a remediation programme. Their typical interests are outlined in Table 5.3. It should be noted that the diagram and the table are for purposes of illustration only, and are by no means comprehensive.

Table 5.3 Functions of interested parties in remediation projects

Parties	Interests
Problem holders	Cost effectiveness Functionality of environmental media Efficient decision making
Authorities	Multi-functionality of soil Minimisation of residual environmental load Consistent policy Efficient decision making Maintenance/improvement of tax revenues through viable economy
Consultants	Interests of their clients (problem holders or competent authorities) Efficient decision making Shareholder benefits
Contractors	Interests of their clients Efficient decision making Shareholder benefits
Public	Risk reduction Minimal limitations of use Minimal nuisance Efficient decision making Maintenance/improvement of socioeconomic conditions

5.2.9.2 Procedures for stakeholder based decisions in the specific case of long-term stewardship

Stakeholder participation may contribute to all aspects of stewardship activities, including record keeping, monitoring, communication, investment and site maintenance [155]. Following, the focus will be on the idea of stakeholders as partners with regulatory agencies and technical experts, through looking at the basis for decisions made about stewardship strategies.

A standard economics approach to decision making is to seek to establish a ‘rational’ justification for a choice between actions on the basis of relations of preference. If action C is preferred over action B, and action B is preferred over action A (etc.), then action C is the highest valued action. However, whenever the span of choices involves and will have consequences for more than one person, judgements typically may differ as to which is preferable. Each option for site management will produce distinct types and differing distributions of benefits, costs and risks that will be looked at differently by each of the individuals or sectors of society concerned. Not only will the different protagonists concerned have divergent views about what is their interest, their right or their due; they may also propose quite different principles for resolving this problem of social choice.

The particular difficulties of contaminated site stewardship as a problem of social choice may be summarised by the following four points:

1. The choices relate to complex entities, processes or outcomes (involving geological, biological and social systems), each option being characterised by a range of

attributes. Comparison of stewardship options means comparing a vector of attributes with a wide variety of concepts, units of measure and criteria. It is not always easy to pass from a multiple criteria appraisal to a ranking of alternatives along a single scale.

2. The consequences of decisions are distributed in time, and often different aspects of outcomes (good and bad, as perceived by different constituencies) will have distinctive time profiles, for example: vegetation cover; diffusion or dilution of dangerous substances in water, rock and soil; financial costs of monitoring; financial benefit streams including stewardship salaries and eventual site use.
3. There are various degrees of uncertainty due partly to the complexity of natural systems and partly to social indeterminacies such as decisions not yet made or the consequences of which are not yet known or future interest in the site.
4. Many reasons or principles may be put forward as justifications for the acceptability, or not, of different outcomes (including perceived uncertainties and risks, distribution of benefits and costs across different constituencies within society, or across generations through time). It may not be possible to respect all principles simultaneously (this may be the case for the judgements offered by a single person, or for the judgements offered by a range of sectors). Because the principles may be 'irreducible' (i.e., incomparable, in the sense of being grounded in qualitatively different considerations), choice may be characterised by dilemmas and the need to make sacrifices of principles, rather than mere trade-offs on quantitative terms.

These complexities account for the importance of consultations with stakeholders, for example through processes of dialogue and of structured deliberations about site management issues and options. Stakeholder dialogues may be used to help build up a clear picture about the merits and de-merits of site stewardship alternatives that present themselves to the relevant authorities and stakeholders in the society. In general, three points should be addressed in order to build a structured stakeholder dialogue process:

1. There should be an explicit identification of the relevant stakeholders, and the establishment of an institutional framework within which exchange of information and opinions can take place.
2. There should be a clear picture of the relevant site management options. For example, remediation and long-term site stewardship issues and options may be explored in terms of a small number of scenarios each of which expresses distinct technological, economic and governance features. Stakeholders may sometimes be solicited to contribute to the framing of these scenarios.
3. There should be a clear expression of the criteria for the selection of the stewardship strategies, with a variety of different criteria reflecting the full diversity of societal concerns.

If these conditions are met, then stakeholder dialogue may be organised as an evaluation of the different stewardship solutions or scenarios, within a multiple criteria framework that covers a full range of governance issues. The distinct stakeholder perspectives become visible through the contrasting judgements made in relation to each option or scenario. As systems analyst Rittel has remarked [165]:

> '*A policy maker or analyst in this sort of situation needs to be more like a 'midwife of problems' than a provider of determinate and uncontroversial solutions. Decision making has to be understood as an argumentative or deliberative process, one of raising questions and issues towards which you can assume different positions, and with the evidence gathered and arguments built for and against these different positions'*.

Quite often, a constructive stakeholder interaction may permit the emergence of novel ideas for solutions, including compromises between different performance criteria. These processes of information sharing and debate may also be effective in building goodwill, respect and trust. Differences of view are not to be feared. Commitment to a stewardship role, or to cooperating with site stewards, may emerge alongside and partly through misunderstandings, disputes and conflicts.

Well structured participatory processes [166] may help with:

1. Identification and development of elements of common problem definition and common language for all the parties concerned;
2. Understanding of the assumptions underlying expert solution proposals and evaluation techniques, of the terms in which these techniques can contribute to reasoned decisions, and limitations to their application;
3. Sharing of the reasons and justifications brought by the different social groups to the deliberation process;
4. Status and respect given to participation by both professionals and lay persons in the deliberation processes.

Multi-stakeholder deliberation requires information, and may certainly be aided by good inputs from experts and by systems of indicators at appropriate scales. However, stakeholders do not just receive and exchange information. They may interact in a variety of formal and informal ways, sometimes being in conflict and sometimes cooperating. Working together to produce a well structured and transparent evaluation of stewardship options, with inputs from different sectors of the affected communities, may contribute significantly to the confidence and shared understanding needed to build a common future together.

5.2.9.3 Political and economic partnership

Partnership building (the third component identified, see Section 5.2.8.2) has emerged worldwide as a pragmatic response by public authorities (and, sometimes, by nuclear industry exponents themselves) confronted by the ineffectiveness of the standard technical expertise model for viable waste management decisions [155]. In many countries directly concerned with an obligation for radioactive waste management, there has been an incontestable deficit of stakeholder confidence regarding the decisions proposed by the established expert and government bodies for the long term disposal of radioactive waste, resulting in abandonment of envisaged programmes and/or a major reconstruction of the institutional and policy framework. Confronted by public disquiet about the risks, and the very long time frames involved in monitoring sites, the authorities have turned to various forms of stakeholder consultation.

Attention to the question of the nature of the relationships to be established and maintained by society with the sites and the radioactive materials (the second component, as identified above) is less in evidence. The reason for this is that this issue has been treated more implicitly than explicitly. A specific answer to the question of what type of ‘relationship’ is envisaged has dominated in the technical and regulatory literature, without really being made the subject of a focused discussion. In effect, the concepts of containment and of provisional and permanent ‘disposal’ of wastes through the competent action of an authority are based on a principle that can be summarised as ‘out of the public’s sight, out of the public’s mind’. The comfort and safety of the public are to be assured by technological means, implemented by a delegated authority, to achieve the segregation of the noxious elements outside the main part of society. Because the waste or contaminated site is placed ‘off limits’ the general public no longer has any relationship to it, and so the problem has disappeared.

Much of the current controversy about radioactive waste disposal and site stewardship arises because this solution concept - based on the principle of containment and segregation, ‘out of the public’s sight, out of the public’s mind’ - does not have widespread social acceptance. The historical record of controversies shows that many people are not willing to believe that wastes will remain where they are (for thousands and thousands of years), and many people are also not willing to trust experts when they say that, suitably contained, wastes will indeed remain where they are.

This lack of confidence undoubtedly arises from many factors, some of which are related to technical factors and some of which are related to non-technical factors. One relevant factor may be the accumulation of experience with nuclear energy, radiation and spent nuclear fuel, revealing the meticulous and costly character of achieving long term and secure containment. Another factor may be the growing general awareness about the problems of waste management in modern societies (extending far beyond radioactive wastes) and about the spectrum of side effects, often unpredictable and sometimes long lasting, of contemporary technologies. Another, certainly, is the heritage of suspicion about official cover-ups of accidents and risks, and hence perceptions of the unreliability of government agencies in risk management matters.

Whatever the reasons that might be identified, it is clear that the 'containment and segregation model' of the relation to be established between the society and the risk (the waste disposal or contaminated sites) does not inspire wide public trust. This does not necessarily mean that people are generally irrational about radioactivity. Rather, it suggests that certain features of the model 'out of the public's sight, out of the public's mind' are felt to be inappropriate - and hence unacceptable - for some classes of contaminated site problem. The challenge is to identify the factors that might affect a solution's acceptability, in order that an appropriate strategy may be explored for the underlying problem.

5.2.10 Economic context

While in the near term each country will have its own existing and proven institutional and financial mechanisms, there is no guarantee that these will continue in the longer term [155]. Priorities are likely to be vastly different from current ones; and even though public interest may call for significant stewardship programmes, there may be economic constraints to achieving this. It is important, therefore, to reappraise the mechanisms for financial provision on a relatively regular basis. Some areas worthy of further consideration for developing the protocols that future generations may demand are:

- Funding mechanisms;
- Life cycle costing;
- Planning for new and operational installations;
- Management of legacy sites;

5.2.10.1 Funding mechanisms

While the need for long term stewardship has become more widely accepted, major issues remain about how to best fund (or pay for) the required activities and in many cases about who will be responsible to ensure these activities are funded and implemented.

In response to the question of who is responsible, many countries today have adopted the principle that the polluter pays. This means that the originator of a contamination is responsible for covering the cost of adequate remediation measures as well as the long term stewardship of the site in question. The thus defined responsible party may be the company that is implementing/operating the installation and profiting from it or it may be the final consumer who is benefiting from the goods or services rendered by it. In many cases the originator of the damage may have ceased to exist, or it is difficult, even impossible, to attribute a contamination to a certain agent, owing to multiple contamination events, thus resulting in 'orphan' contamination with no identifiable responsible party. Even when the responsible party is clearly identifiable, it may not have set options to ensure adequate funding to meet long term stewardship requirements, in which case an alternative funding mechanism has to be put in place. Contaminated areas are often located in zones that are in need of economic revitalisation for other reasons.

Assuming that long term stewardship will require funding for an unprecedented length of time (hundreds or thousands of years), innovative (or innovative adaptations of familiar) financial solutions will be required.

The funding options for nearer term challenges may be different from those for the longer term. Five basic criteria may be considered when financing long term stewardship:

1. Financial security;
2. Clear rules, roles and responsibilities;
3. Public information;
4. Enforceability;
5. Permanence.

These criteria can also be used to consider the strengths and weaknesses of other funding approaches. It should be emphasised that the raising of funds is only one of the issues to be contemplated when dealing with long term liabilities. The adequate treatment of these will require the implementation of a system capable of integrating in a coordinated way the technical, legal, financial and managerial (decision making and follow-up) aspects towards addressing long-term liability issues in their broader dimensions.

5.2.10.2 Life cycle costing

Traditional costing approaches normally take into consideration the so-called conventional costs, i.e., direct and indirect cost items that cannot be avoided by the organisation undertaking a certain project: capital costs, equipment, energy, utilities and supplies.

Life cycle management requires the adoption of broader costing concepts in which all costs involved in the implantation of the project, from the initial planning phase to the decommissioning and stewardship phases have to be taken into account (Figure 5.3). This life cycle costing concept is a key issue when developing financial instruments to cover long term liabilities including stewardship.

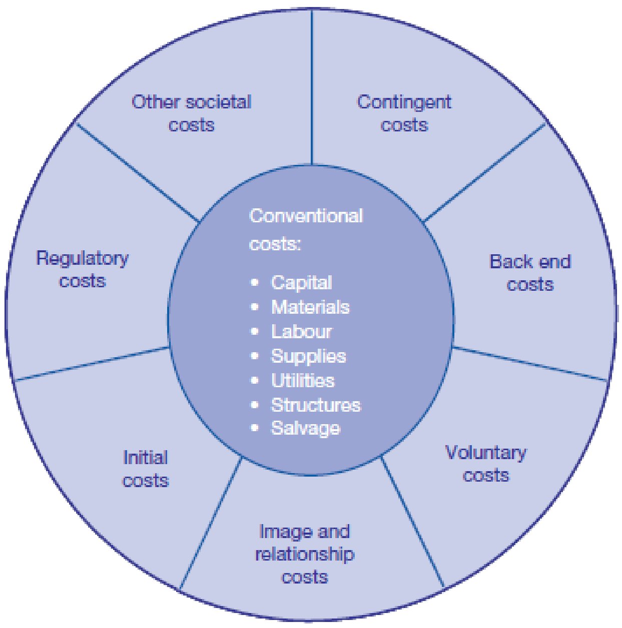


Figure 5.3 Life cycle costs

In the case of a privately owned installation aimed at generating profit, the fact has to be taken into account that the installation will produce revenues for only a certain period of time. However, the costs involved in the correct management of environmental and societal issues may extend in time far beyond the operational period of the installation. As a consequence, a concept similar to that of a pension plan needs to be developed to cover the costs that will be incurred after the installation ceases operation. The concept is similar to that of a personal pension fund in the way in which provisions are made during the period in which a person is generating income to cover the final period of life. In fact, the same concept can be applied to all kinds of installations, whether private or public.

5.2.10.3 Planning for new and operational installations

Sources of funds

New installations are best planned to follow the concept of life cycle costing from their very early phases, in order to provide adequate financial coverage to meet future liabilities and to promote the identification of the actual environmental costs, encouraging greater efficiency in the use of resources.

In the case of installations already in their operational phase, it would be beneficial to carry out life cycle cost planning for their residual life, not only because that necessitates a thorough environmental audit and risk assessment of the installation but also because it allows for planning of the financial and technical requirements to meet all future liabilities, including those previously unrecognised.

In both cases there is the possibility to set up funds on the basis of current income streams. The provision of funds for long term liabilities needs to be planned in such a way that when the installation stops operating and income generation ceases, the present value of the funds accumulated to that date is equivalent to the present value of the cost to be incurred until the end of the life of the installation (including the stewardship phase) under a life cycle costing perspective. Many countries now make long term liability funds a prerequisite for the issuance of licences for new installations.

Fund structuring

Six principles may be quoted that should be observed when structuring a financial guarantee vehicle to cover long term liabilities (Table 5.4).

Table 5.4 Financial guarantee principles

Principle	Requirements
Life cycle costs after operations cease	Financial guarantees must cover all the installation’s costs, including those incurred after the end of operations.
Liquidity	All forms of financial guarantee should be reasonably liquid.
Accessibility	Financial assurance should be readily accessible, dedicated and only released with the specific assent of the regulatory authority or other decision making body.
Financially robust guarantors	Regulators must carefully screen the financial health of guarantors before accepting any form of assurance.
Public involvement	The public should be given notice and an opportunity to comment both before the setting up of the fund and before any decision on whether to release resources from the fund.
Lack of a substitute	Any financial guarantee should not be regarded as a surrogate for the company’s legal environmental liability.

One of the methods that have been identified as a useful approach to ensure funds are available is known as a trust fund. A trust can provide a mechanism to ensure that the funds necessary to fulfil long term responsibilities are available.

Management of funds

In addition to the fund raising process, appropriate management of funds is a key issue for the effectiveness of the long term management strategy. A number of roles have to be accomplished by various agents in this management process. The main roles to be accomplished in any system designed to correctly manage environmental liabilities are:

a. Identification of environmental liabilities (life cycle costs that have to be covered by the fund to be put in place);

b. Provision of resources to cover the environmental liabilities (which typically is the task of the 'problem holder');

c. Administration of funds in order to ensure their soundness in the long term (a typical asset management function);

d. Making of decisions about the use of funds for environmental remediation actions, and follow-up on the efficacy of these actions;

e. Implementation of remedial and stewardship activities (actions to reduce environmental liabilities);

f. Regulation and auditing of the system (to ensure its overall efficacy and effectiveness).

These roles can be carried out by the different agents potentially involved in the process. Typical agents that may be involved in one or more roles are:

a. Owners of installations;

b. Governments;

c. Final site users;

d. Financial management companies;

e. Fund management boards;

f. Contractors (companies responsible for remediation actions).

Different systems may be devised to combine the roles to be performed by the potential agents involved. It is important to note that although the roles listed above must be performed in any conceptual system, not all the agents actually have to be involved. According to these conditions various systems may be devised, from simpler ones (in which many roles are played by each agent) to more complex ones (in which responsibility is distributed among several independent agents). Figure 5.4, Figure 5.5 and Figure 5.6 illustrate three potentially feasible systems for the administration of funds for liabilities.

In the case of closed installations and legacy sites, the funds cannot normally be raised from the revenue streams of the operations. Governments might be presumed to be the first candidates as a source of funds for these cases. However, unless the liability was originated directly by governmental activities at the site, in which case the government is the actual holder of the liability, the government may not be prepared to assume this role.

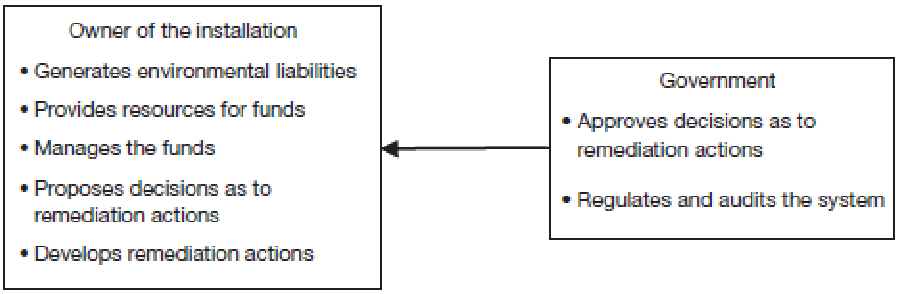


Figure 5.4 A liability management system with two agents

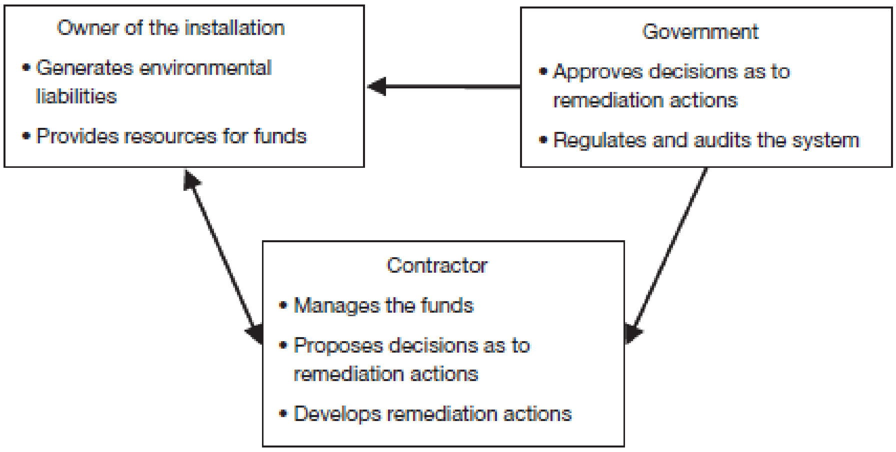


Figure 5.5 A liability management system with three agents

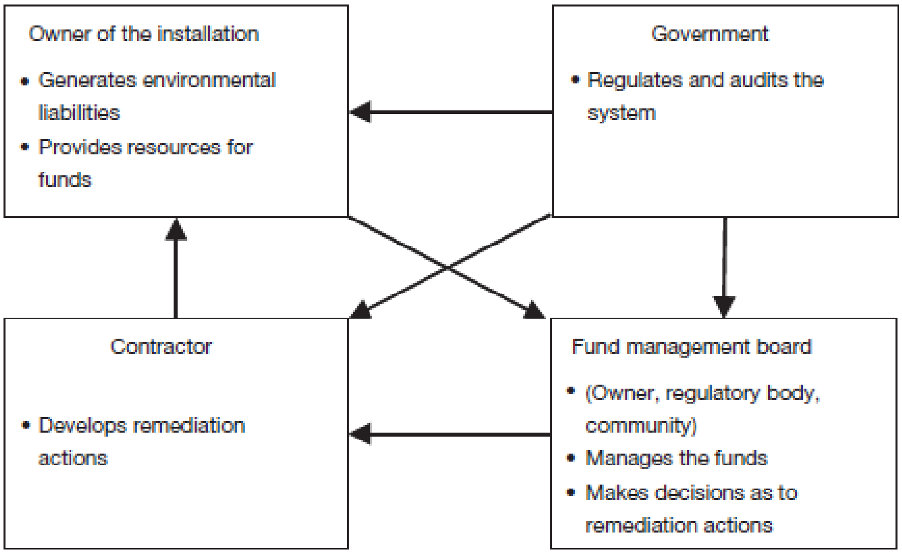


Figure 5.6 A liability management system with four agents

5.2.10.4 Management of legacy sites

In general, all those that could potentially be held liable would be investigated, such as current site owners/operators, former site owners/operators, owners/operators of neighbouring sites that might have (had) an influence on the site in question and local/regional government bodies. In these cases, it is possible to compel the potentially liable party to respond to the damage in question. This normally should follow a three stage process:

1. The first stage should involve identification and characterisation of the potential liability holder(s);
2. The second stage should comprise the demonstration of the legal obligation of this party or these parties for the liability;
3. Finally, the third stage should involve the enforcement of the liability holder's duty to pay for the necessary environmental recovery actions or to conduct them according to a plan approved by the regulatory authority.

For many instances of uranium mining, the responsible party is in fact the government or the responsibility has been accepted by the government since the operation has been in the national interest. In circumstances where it is impossible to make the original owner undertake the remediation, it is likely that the government will be required to manage the situation. It is not rare, however, that the needs in terms of resources for site remediation exceed by far the (annual) budget available. Some form of prioritisation of activities will be unavoidable. A particular problem inherent to government budgeting is the usual short cycle of a few years at best, which makes it difficult to provide for long term commitments such as stewardship needs.

In some cases, it is possible for the government to recover part of the costs incurred through an increase in land value after site remediation by selling the site for reuse. A variant on this, but applicable mostly in urban areas with an active property market, is to transfer the land to private investors with a binding obligation to remediate the land according to prescribed standards and, if needed, to provide for long term stewardship. The financial incentive for the investors is the difference between their expenditure for remedial and stewardship activities and the resulting land value. Various combinations of taxpayer and privately funded remediation and stewardship plans (public-private partnerships) can be imagined provided they are adapted to the situation in hand.

5.2.10.5 Future land use

In some countries, there is an ever increasing tendency towards avoiding further exploitation of green field sites and restricting new developments to sites with a previous industrial history. Redevelopment potential can be a key factor in ensuring the viability of a remediated site and the associated long term stewardship programme. Redevelopment of the land, however, requires that the land has been remediated to residual levels of contamination that are compatible with its intended use. It is likely that in many non-accident scenarios only restricted releases will be feasible and that the stewardship process will need to cover the management of the future land use. Controlled reuse of a site may generate sufficient revenue to finance the cost of the necessary institutional control and may also prevent or minimise misuse that might jeopardize the institutional controls.

Reuse may come in a number of guises, for example, housing, new industries, recreational facilities, museums or even authorised disposal facilities. Monitoring of the site will need to be an ongoing process and may at a later date find that a breach of the containment system has occurred. A mechanism, therefore, needs to be in place that will allow a re-evaluation of the site's status, because the original judgement will have been made on the basis of environmental risk assessment work at that time.

If the individuals who are actually benefiting from the reuse within the stewardship process are involved, this may increase the probability of continuity and orderly records management, as they may have a vested interest in the process. The objective is to create a sense of ownership in the use scenarios that are compatible with the stewardship requirements.

The development potential of a redundant site is often dependent on one or two key assets left over from the operating life of these sites (experience from the mining industry). These assets can provide an important catalyst to a particular kind of development or serve to improve the attractiveness of the site as an investment proposition for developers.

Example 5.1: Identification of a key asset

In one example, the key asset was a high quality sports and social club built in traditional style and with excellent facilities. It was originally provided for employees and their families on the edge of the production site but served as the basis for redeveloping the site as a leisure park, also making use to the mine waster as the focal point of a new golf course.

An important step in exploring the redevelopment potential of a site is to identify these potential key assets and assess their relevance to future development scenarios. Once identified these assets need to be protected from deterioration during the transition from the previous use to the new use with stewardship requirements. A particular threat is the paradigm shift from operation to remediation and reuse that often results in neglect of infrastructure by previous owners or their agents.

The (re)drawing of site boundaries and the disposition of certain features, such as impoundments for contaminated residues, will have a strong influence on the usability and the redevelopment potential of a site. It is of great advantage if these factors can already be considered during the decommissioning and remediation phase, or even better when worked into the original operational plan. Features to consider include ease of access, convenient shape of plots, as well as connections to services and other infrastructure such as roads, railways, sewerage systems, drinking water supply and the electric grid.

There may also be certain protected uses that could be explored, for example cemeteries. In some cultures, certain persons (e.g., priests or medicine men) may impose taboos on sites or particular uses of sites. However, the longevity of such restrictions is difficult to predict. On the other hand, socio-cultural development in some parts of the world may make these societies more conducive to the earlier instruments of institutional control.

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Appendix A: Development of a decision rule and specification of the limits on decision errors

A.1 Development of a decision rule

The purpose of this step is to define the parameter of interest, specify the action level (or DCGL), and integrate previous DQO outputs into a single statement that describes a logical basis for choosing among alternative actions.

There are three activities associated with this step:

- Specifying the statistical parameter that characterizes the parameter of interest.
- Specifying the action level for the study.
- Combining the outputs of the previous DQO steps into an 'if...then...' decision rule that defines the conditions that would cause the decision maker to choose among alternative actions.

Certain aspects of the site investigation process, such as the historical site assessment (HAS), are not so quantitative that a statistical parameter can be specified. Nevertheless, a decision rule should still be developed that defines the conditions that would cause the decision maker to choose among alternatives.

The expected outputs of this step are:

- The parameter of interest that characterizes the level of residual radioactivity.
- The action level.
- An 'if...then...' statement that defines the conditions that would cause the decision maker to choose among alternative actions.

The parameter of interest is a descriptive measure (such as a mean or median) that specifies the characteristic or attribute that the decision maker would like to know about the residual contamination in the survey unit.

The mean is the value that corresponds to the 'centre' of the distribution in the sense of the 'centre of gravity'. Positive attributes of the mean include:

- It is useful when the action level is based on long-term, average health effects.
- It is useful when the population is uniform with relatively small spread.
- It generally requires fewer samples than other parameters of interest.

Negative attributes include:

- It is not a very representative measure of central tendency for highly skewed distributions.
- It is not useful when a large proportion of the measurements are reported as less than the detection limit.

The median is also a value that corresponds to the 'centre' of a distribution, but where the mean represents the centre of gravity the median represents the 'middle' value of a distribution. The median is that value such that there is the same number of measurements greater than the median as less than the median. The positive attributes of the median include:

- It is useful when the action level is based on long term, average health effects.
- It provides a more representative measure of central tendency than the mean for skewed populations.

- It is useful when a large proportion of the measurements are reported as less than the detection limit.
- It relies on few statistical assumptions.

Negative attributes include:

- It will not protect against the effects of extreme values.
- It is not a very representative measure of central tendency for highly skewed distributions.

The non-parametric statistical tests discussed in Section 3.10 are designed to determine whether or not the level of residual activity uniformly distributed throughout the survey unit exceeds the $DCGL_W$. Since these methods are based on ranks, the results are generally expressed in terms of the median. When the underlying measurement distribution is symmetric, the mean is equal to the median. The assumption of symmetry is less restrictive than that of normality because the normal distribution is itself symmetric. If, however, the measurement distribution is skewed to the right, the average will generally be greater than the median. In severe cases, the average may exceed the $DCGL_W$ while the median does not. For this reason, EURSSEM recommends comparing the arithmetic mean of the survey unit data to the $DCGL_W$ as a first step in the interpretation of the data.

The action level is a measurement threshold value of the parameter of interest that provides the criterion for choosing among alternative actions. EURSSEM uses the investigation level, a radionuclide-specific level of radioactivity based on the release criterion that results in additional investigation when it is exceeded, as an action level. Investigation levels are developed for both the elevated measurement comparison (EMC) using scanning techniques and the statistical tests using direct measurements and samples.

The mean concentration of residual radioactivity is the parameter of interest used for making decisions based on the final status survey. The definition of residual radioactivity depends on whether or not the contaminant appears as part of background radioactivity in the reference area. If the radionuclide is not present in background, residual radioactivity is defined as the mean concentration in the survey unit. If the radionuclide is present in background, residual radioactivity is defined as the difference between the mean concentration in the survey unit and the mean concentration in the reference area selected to represent background. The term *1-sample case* is used when the radio-nuclide does not appear in background, because measurements are only made in the survey unit. The term *2-sample case* is used when the radionuclide appears in background, because measurements are made in both the survey unit and the reference area.

The decision rule for the 1-sample case is: ‘If the mean concentration in the survey unit is less than the investigation level, then the survey unit is in compliance with the release criterion’. To implement the decision rule, an estimate of the mean concentration in the survey unit is required. An estimate of the mean of the survey unit distribution may be obtained by measuring radionuclide concentrations in soil at a set of n randomly selected locations in the survey unit. A point estimate for the survey unit mean is obtained by calculating the simple arithmetic average of the n measurements. Due to measurement variability, there is a distribution of possible values for the point estimate for the survey unit mean, δ. This distribution is referred to as $f(\delta)$, and is shown in the lower graph of Figure A.1. The investigation level for the Sign test used in the 1-sample case is the $DCGL_W$, shown on the horizontal axis of the graph.

If $f(\delta)$ lies far to the left (or to the right) of the $DCGL_W$, a decision of whether or not the survey unit demonstrates compliance can be easily made. However, if $f(\delta)$ overlaps the $DCGL_W$, statistical decision rules are used to assist the decision maker. Note that the width of the distribution for the estimated mean may be reduced by increasing the number of measurements. Thus, a large number of samples will reduce the probability of making decision errors.

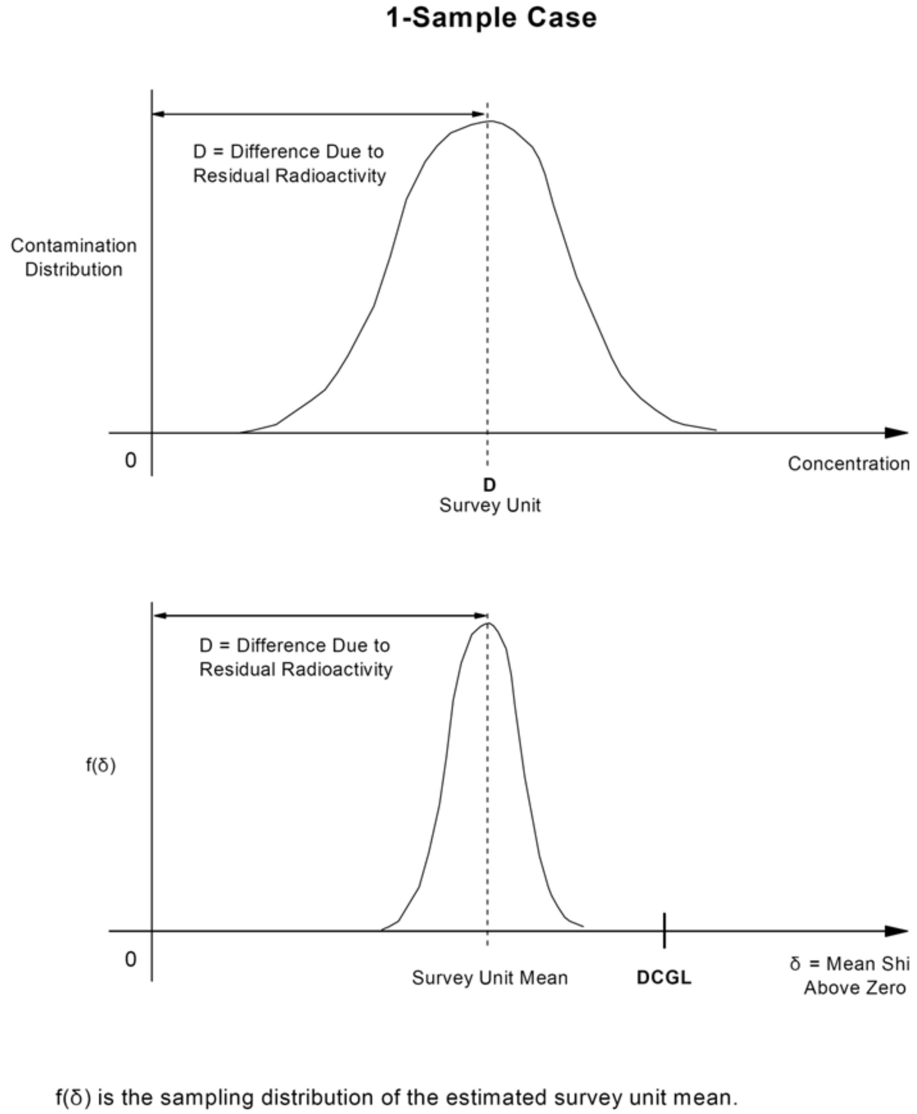

Figure A.1 Example of the parameter of interest for the 1-Sample Case

Figure A.2 shows a simple, hypothetical example of the 2-sample case. The upper portion of the figure shows one probability distribution representing background radionuclide concentrations in the surface soil of the reference area, and another probability distribution representing radionuclide concentrations in the surface soil of the survey unit. The graph in the middle portion of the figure shows the distributions of the estimated mean concentrations in the reference area and the survey unit. In this case, the parameter of interest is the difference between the means of these two distributions, D, represented by the distance between the two vertical dotted lines.

The decision rule for the 2-sample case is: 'If the difference between the mean concentration in the survey unit and the mean concentration in the reference area is less than the investigation level, then the survey unit is in compliance with the release criterion'. To implement the decision rule, an estimate of the difference is required. This estimate may be obtained by measuring radionuclide concentrations at a set of 'n' randomly selected locations in the survey unit and 'm' randomly selected locations in the reference area. A point estimate of the survey unit mean is obtained by calculating the simple arithmetic average of the n measurements in the survey unit. A point estimate of the reference area mean is similarly calculated. A point estimate of the difference between the two means is obtained by subtracting the reference area average from the survey unit average.

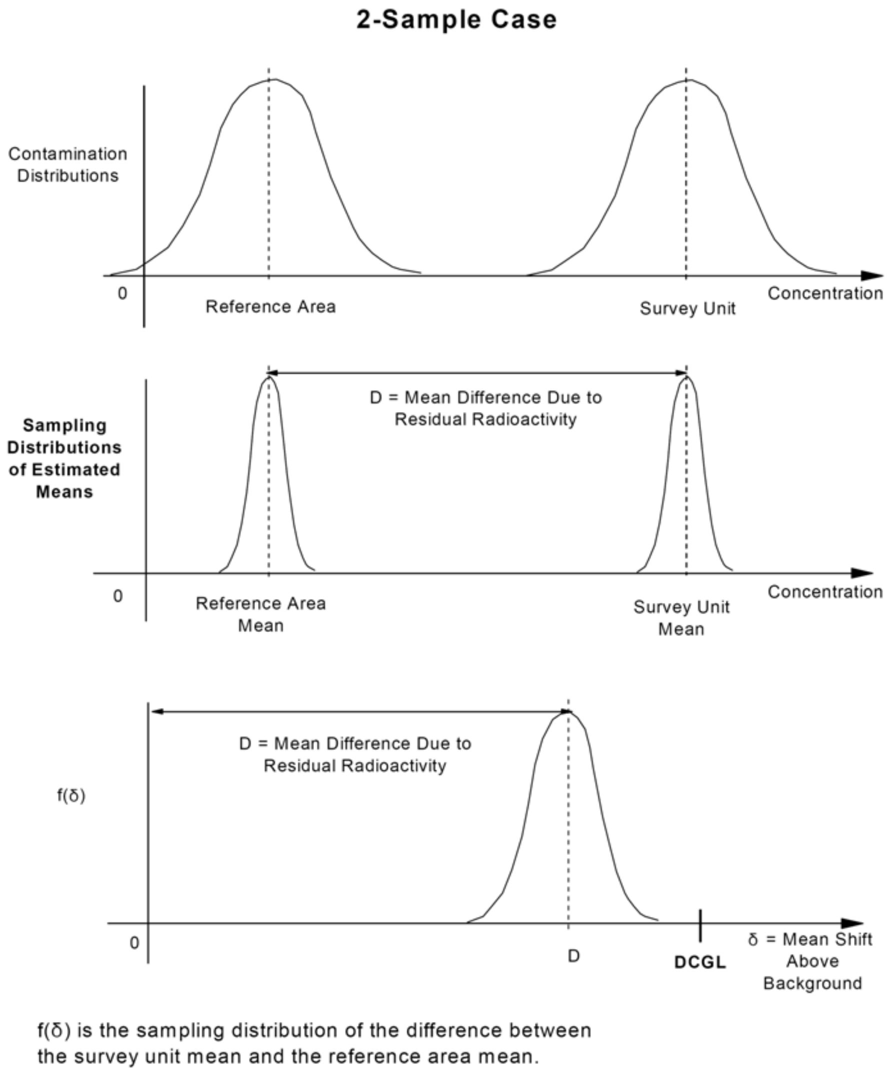

Figure A.2 Example of the parameter of interest for the 2-Sample Case

The measurement distribution of this difference, f(δ), is centred at D, the true value of the difference. This distribution is shown in the lower graph of Figure A.2.

Once again, if f(δ) lies far to the left (or to the right) of the $DCGL_W$, a decision of whether or not the survey unit demonstrates compliance can be easily made. However, if f(δ) overlaps the $DCGL_W$, statistical decision rules are used to assist the decision maker.

A.2 Specifications of limits on decision errors

Decisions based on survey results can often be reduced to a choice between 'yes' or 'no', such as determining whether or not a survey unit meets the release criterion. When viewed in this way, two types of incorrect decisions, or decision errors, are identified:

- Incorrectly deciding that the answer is 'yes' when the true answer is 'no', and
- Incorrectly deciding the answer is 'no' when the true answer is 'yes'.

The distinctions between these two types of errors are important for two reasons:

- The consequences of making one type of error versus the other may be very different, and
- The methods for controlling these errors are different and involve trade-offs.

For these reasons, the decision maker should specify levels for each type of decision error.

The purpose of this section is to specify the decision maker's limits on decision errors, which are used to establish performance goals for the data collection design. The goal of the planning team is to develop a survey design that reduces the chance of making a decision error.

While the possibility of a decision error can never be totally eliminated, it can be controlled. To control the possibility of making decision errors, the planning team attempts to control uncertainty in the survey results caused by sampling design error and measurement error. Sampling design error may be controlled by collecting a large number of samples. Using more precise measurement techniques or field duplicate analyses can reduce measurement error. Better sampling designs can also be developed to collect data that more accurately and efficiently represent the parameter of interest. Every survey will use a slightly different method of controlling decision errors, depending on the largest source of error and the ease of reducing those error components.

The estimate of the standard deviation for the measurements performed in a survey unit (σ_s) includes the individual measurement uncertainty as well as the spatial and temporal variations captured by the survey design. For this reason, individual measurement uncertainties are not used during the final status survey data assessment. However, individual measurement uncertainties may be useful for determining an *a priori* estimate of σ_s during survey planning. Since a larger value of σ_s results in an increased number of measurements needed to demonstrate compliance during the final status survey, the decision maker may seek to reduce measurement uncertainty through various methods (*e.g.*, different instrumentation). There are trade-offs that should be considered during survey planning. For example, the costs associated with performing additional measurements with an inexpensive measurement system may be less than the costs associated with a measurement system with better sensitivity (*i.e.*, lower measurement uncertainty, lower minimum detectable concentration). However, the more expensive measurement system with better sensitivity may reduce σ_s and the number of measurements used to demonstrate compliance to the point where it is more cost effective to use the more expensive measurement system. For surveys in the early stages of the Radiation Survey and Site Investigation Process, the measurement uncertainty and instrument sensitivity become even more important. During scoping, characterization, and remedial action support surveys, decisions about classification and remediation are made based on a limited number of measurements. When the measurement uncertainty or the instrument sensitivity values approach the value of the DCGL, it becomes more difficult to make these decisions. From an operational standpoint, when operators of a measurement system have an *a priori* understanding of the sensitivity and potential measurement uncertainties, they are able to recognize and respond to conditions that may warrant further investigation - *e.g.*, changes in background radiation levels, the presence of areas of elevated activity, measurement system failure or degradation, *etc.*

The probability of making decision errors can be controlled by adopting a scientific approach, called hypothesis testing. In this approach, the survey results are used to select between one condition of the environment (the null hypothesis, H_0) and an alternative condition (the alternative hypothesis, H_a). The null hypothesis is treated like a baseline condition that is assumed to be true in the absence of strong evidence to the contrary. Acceptance or rejection of the null hypothesis depends upon whether or not the particular survey results are consistent with the hypothesis.

A decision error occurs when the decision maker rejects the null hypothesis when it is true, or accepts the null hypothesis when it is false. These two types of decision errors are classified as Type I and Type II decision errors, and can be represented by a table as shown in Table A.1.

A Type I decision error occurs when the null hypothesis is rejected when it is true, and is sometimes referred to as a false positive error. The probability of making a Type I decision error, or the level of significance, is denoted by alpha (α). Alpha reflects the amount of evidence the decision maker would like to see before abandoning the null hypothesis, and is also referred to as the *size* of the test.

A Type II decision error occurs when the null hypothesis is accepted when it is false. This is sometimes referred to as a false negative error. The probability of making a Type II decision error is denoted by beta (β). The term (1-β) is the probability of rejecting the null hypothesis when it is false, and is also referred to as the *power* of the test.

Table A.1 Example representation of decision errors for a final status survey

H_a/ The residual Activity in the Survey Unit Exceeds the Release Criteria				
		DECISION		
		Reject H_0 (Meets Release Criterion)	Accept H_0 (Exceeds Release Criterion)	
TRUE CONDITION OF SURVEY UNIT	Meets Release Criterion	(No decision error)	Incorrectly Fail to Release Survey Unit (Type II)	
	Exceeds Release Criterion	Incorrectly Release Survey Unit (Type I)	(No decision error)	

There is a relationship between α and β that is used in developing a survey design. In general, increasing α decreases β and vice versa, holding all other variables constant. Increasing the number of measurements typically results in a decrease in both α and β. The number of measurements that will produce the desired values of α and β from the statistical test can be estimated from α, β, the $DCGL_W$, and the estimated variance of the distribution of the parameter of interest.

There are five activities associated with specifying limits on decision errors:

- Determining the possible range of the parameter of interest. Establish the range by estimating the likely upper and lower bounds based on professional judgement.
- Identifying the decision errors and choosing the null hypothesis.
    - Define both types of decision errors (Type I and Type II) and establish the true condition of the survey unit for each decision error.
    - Specify and evaluate the potential consequences of each decision error.
    - Establish which decision error has more severe consequences near the action level. Consequences include health, ecological, political, social, and resource risks.
    - Define the null hypothesis and the alternative hypothesis and assign the terms ‘Type I’ and ‘Type II’ to the appropriate decision error.
- Specifying a range of possible parameter values, a gray region, where the consequences of decision errors are relatively minor. It is necessary to specify a gray region because variability in the parameter of interest and unavoidable imprecision in the measurement system combine to produce variability in the data such that a decision may be ‘too close to call’ when the true but unknown value of the parameter of interest is very near the action level.
- Assigning probability limits to points above and below the gray region that reflect the probability for the occurrence of decision errors.
- Graphically representing the decision rule.

The expected outputs of this step are decision error rates based on the consequences of making an incorrect decision. Certain aspects of the site investigation process, such as the historical site assessment (HSA), are not so quantitative that numerical values for decision errors can be specified. Nevertheless, a ‘comfort region’ should be identified where the consequences of decision errors are relatively minor.

In the above section, ‘Development of a decision rule’, the parameter of interest was defined as the difference between the survey unit mean concentration of residual radioactivity and the reference area mean concentration in the 2-sample case, or simply the survey unit mean concentration in the 1-sample case. The possible range of values for the parameter of interest is determined based on existing information (such as the historical site assessment or previous surveys) and best professional judgement. The likely lower bound for f(δ) is either background or zero. For a final status survey when the residual radioactivity is expected to meet the release criterion and a conservative upper bound might be approximately three times $DCGL_W$.

Hypothesis testing is used to determine whether or not a statement concerning the parameter of interest should be verified. The statement about the parameter of interest is called the null hypothesis. The alternative hypothesis is the opposite of what is stated in the null hypothesis. The decision maker needs to choose between two courses of action, one associated with the null hypothesis and one associated with the alternative hypothesis.

To make a decision using hypothesis testing, a test statistic is compared to a critical value. The *test statistic*[26] is a number calculated using data from the survey. The critical value of the test statistic defines a rejection region based on some assumptions about the true distribution of data in the survey unit. If the value of the test statistic falls within the rejection region, the null hypothesis is rejected. The decision rule, developed in Appendix A, is used to describe the relationship between the test statistic and the critical value.

EURSSEM considers two ways to state H_0 for a final status survey. The primary consideration in most situations will be compliance with the release criterion. This is shown as Scenario A in Figure A.3. The null hypothesis is that the survey unit exceeds the release criterion. Using this statement of H_0 means that significant evidence that the survey unit does not exceed the release criterion is required before the survey unit would be released.

In some situations, however, the primary consideration may be determining if any residual radioactivity at the site is distinguishable from background, shown as Scenario B in Figure A.4. In this manual, Scenario A is used as an illustration because it directly addresses the compliance issue and allows consideration of decision errors.

For Scenario A, the null hypothesis is that the survey unit does not meet the release criterion. A Type I decision error would result in the release of a survey unit containing residual radioactivity above the release criterion. The probability of making this error is α. Setting a high value for α would result in a higher risk that survey units that might be somewhat in excess of the release criterion would be passed as meeting the release criterion. Setting a low value for α would result in fewer survey units where the null hypothesis is rejected. However, the cost of setting a low value for α is either a higher value for β or an increased number of samples used to demonstrate compliance.

For Scenario A, the alternative hypothesis is that the survey unit does meet the release criterion. A Type II decision error would result in either unnecessary costs due to remediation of survey units that are truly below the release criterion or additional survey activities to demonstrate compliance. The probability of making a Type II error is β. Selecting a high value for β (low power) would result in a higher risk that survey units that actually meet the release criterion are subject to further investigation. Selecting a low value for β (high power) will minimize these investigations, but the trade-off is either a higher value for α or an increased number of measurements used to demonstrate compliance. Setting acceptable values for α and β, as well as determining an appropriate gray region, is a crucial step in the DQO process.

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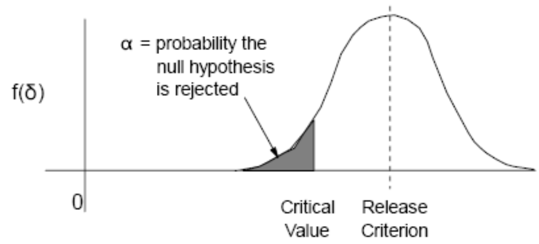
26 The test statistic is not necessarily identical to the parameter of interest, but is functionally related to it through the statistical analysis.

SCENARIO A

Assume as a null hypothesis that the survey unit exceeds the release criterion. This requires significant evidence that the residual radioactivity in the survey unit is less than the release criterion to reject the null hypothesis (and pass the survey unit). If the evidence is not significant at level α, the null hypothesis of a non-complying survey unit is accepted (and the survey unit fails).

HYPOTHESIS TEST	
H_0: Survey unit does not meet release criterion H_a: Survey unit does meet the release criterion	Survey unit passes if and only if the test statistic falls in the rejection region.



This test directly addresses the compliance question.

The mean shift for the survey unit must be significantly below the release criterion for the null hypothesis to be rejected.

With this test, site owners face a trade-off between additional sampling costs and unnecessary remediation costs. They may choose to increase the number of measurements in order to decrease the number of Type II decision errors (reduce the chance of remediating a clean survey unit for survey units at or near background levels.

Distinguishability from background is not directly addressed. However, sample sizes may be selected to provide adequate power at or near background levels, hence ensuring that most survey units near background would pass. Additional analyses, such as point estimates and/or confidence intervals, may be used to address this question.

A high percentage of survey units slightly below the release criterion may fail the release criterion, unless large numbers of measurements are used. This achieves a high degree of assurance that most survey units that are at or above the release criterion will not be improperly released.

Figure A.3 Possible statement of the null hypothesis for the final status survey addressing the issue of compliance

In the EURSSEM framework, the gray region is always bounded from above by the DCGL corresponding to the release criterion. The *lower bound of the gray region* (LBGR) is selected during the DQO process along with the target values for α and β. The *width* of the gray region, equal to (DCGL - LBGR), is a parameter that is central to the non-parametric tests discussed in this manual. It is also referred to as the *shift,* Δ. The absolute size of the shift is actually of less importance than the *relative shift* Δ/σ, where σ is an estimate of the standard deviation of the measured values in the survey unit. The estimated standard deviation, σ, includes both the real spatial variability in the quantity being measured, and the precision of the chosen measurement method. The relative shift, Δ/σ, is an expression of the resolution of the measurements in units of measurement uncertainty. Expressed in this way, it is easy to see that relative shifts of less than one standard deviation, $\Delta/\sigma < 1$, will be difficult to detect. On the other hand, relative shifts of more than three standard deviations, $\Delta/\sigma > 3$, are generally easier to detect. The number of measurements that will be required to achieve given error rates, α and β, depends almost entirely on the value of Δ/σ (see Section 3.5).

Since small values of Δ/σ result in large numbers of samples, it is important to design for $\Delta/\sigma > 1$ whenever possible. There are two obvious ways to increase Δ/σ. The first is to increase the width of the gray region by making LBGR small. Only Type II decision errors occur in the gray region. The disadvantage of making this gray region larger is that the probability of incorrectly failing to release a survey unit will increase. The target false negative rate β will be specified at lower residual radioactivity levels, i.e., a survey unit will generally have to be lower in residual radioactivity to have a high probability of being judged to meet the release criterion. The second way to increase Δ/σ is to make σ smaller.

One way to make σ small is by having survey units that are relatively homogeneous in the amount of measured radioactivity. This is an important consideration in selecting survey units that have both relatively uniform levels of residual radioactivity and also have relatively uniform background radiation levels. Another way to make σ small is by using more precise measurement methods. The more precise methods might be more expensive, but this may be compensated for by the decrease in the number of required measurements. One example would be in using a radio-nuclide specific method rather than gross radioactivity measurements for residual radioactivity that does not appear in background. This would eliminate the variability in background from σ, and would also eliminate the need for reference area measurements.

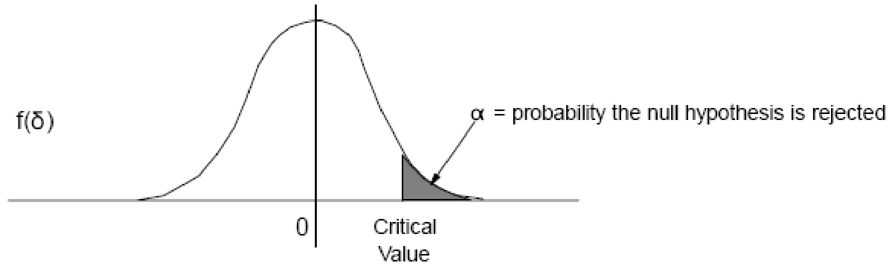
<table>
<tr><td colspan="2">SCENARIO B
Assume as a null hypothesis that the survey unit is indistinguishable from background. This requires significant evidence that the survey unit residual radioactivity is greater than background to reject the null hypothesis (and fail the survey unit). If the evidence is not significant at level α, the null hypothesis of a clean survey unit is accepted (and the survey unit passes).</td></tr>
<tr><td>HYPOTHESIS TEST
H_0: Survey unit is indistinguishable from background
H_a: Survey unit is distinguishable from background</td><td>Survey unit passes if and only if the test statistic falls in the rejection region.</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td colspan="2">Distinguishability from background may be of primary importance to some stakeholders.
The residual radioactivity in the survey unit must be significantly above background for the null hypothesis to be rejected.
Compliance with the DCGLs is not directly addressed. However, the number of measurements may be selected to provide adequate power at or near the DCGL, hence ensuring that most survey units near the DCGL would not be improperly released. Additional analysis, based on point estimates and/or confidence intervals, is required to determine compliance if the null hypothesis is rejected by the test.
A high percentage of survey units slightly below the release criterion will fail unless large numbers of measurements are used. This is necessary to achieve a high degree of assurance that for most sites at or above the release criterion the null hypothesis will fail to be improperly released.</td></tr>
</table>

Figure A.4 Possible statement of the null hypothesis for the final status survey addressing the issue of indistinguishability from background.

The effect of changing the width of the gray region and/or changing the measurement variability on the estimated number of measurements (and cost) can be investigated using the Decision Error Feasibility Trials (DEFT) software developed by EPA [135]. This program can only give approximate sample sizes and costs since it assumes that the measurement data are normally distributed, that a Student's t test will be used to evaluate the data, and that there is currently no provision for comparison to a reference area. Nevertheless, as a rough rule of thumb, the sample sizes calculated by DEFT are about 85% of those required by the one-sample non-parametric tests recommended in this manual. This rule of thumb works better for large numbers of measurements than for smaller numbers of measurements, but can be very useful for estimating the relative impact on costs of decisions made during the planning process.

Generally, the design goal should be to achieve Δ/σ values between one and three. The number of samples needed rises dramatically when Δ/σ is smaller than one. Conversely, little is usually gained by making Δ/σ larger than about three. If Δ/σ is greater than three or four, one should take advantage of the measurement precision available by making the width of the gray region smaller. It is even more important, however, that overly optimistic estimates for σ be avoided. The consequence of taking fewer samples than are needed given the actual measurement variations will be unnecessary remediations (increased Type II decision errors).

Once the preliminary estimates of Δ and σ are available, target values for α and β can be selected. The values of α and β should reflect the risks involved in making Type I and Type II decision errors, respectively.

One consideration in setting the false positive rate are the health risks associated with releasing a survey unit that might actually contain residual radioactivity in excess of the $DCGL_W$. If a survey unit did exceed the $DCGL_W$, the first question that arises is 'How much above the $DCGL_W$ is the residual radioactivity likely to be?' The DEFT software can be used to evaluate this.

For example, if the $DCGL_W$ is 100 Bq/kg (2.7 pCi/g), the LBGR is 50 Bq/kg (1.4 pCi/g), σ is 50 Bq/kg (1.4 pCi/g), $\alpha = 0.10$ and $\beta = 0.05$, the DEFT calculations show that while a survey unit with residual radioactivity equal to the $DCGL_W$ has a 10% chance of being released, a survey unit at a level of 115 Bq/kg (3.1 pCi/g) has less than a 5% chance of being released, a survey unit at a level of 165 Bq/kg (4.5 pCi/g) has virtually no chance of being released. However, a survey unit with a residual radioactivity level of 65 Bq/kg (1.8 pCi/g) will have about an 80% chance of being released and a survey unit with a residual radioactivity level of 80 Bq/kg (2.2 pCi/g) will only have about a 40% chance of being released. Therefore, it is important to examine the probability of deciding that the survey unit does not meet the release criterion over the entire range of possible residual radioactivity values, and not only at the boundaries of the gray region. Of course, the gray region can be made narrower, but at the cost of additional sampling. Since the equations governing the process are not linear, small changes can lead to substantial changes in survey costs.

As stated earlier, the values of α and β that are selected in the DQO process should reflect the risk involved in making a decision error. In setting values for α, the following are important considerations:

- In radiation protection practice, public health risk is modelled as a linear function of dose. Therefore a 10% change in dose, say from 15 to 16.5, results in a 10% change in risk. This situation is quite different from one in which there is a threshold. In the latter case, the risk associated with a decision error can be quite high, and low values of α should be selected. When the risk is linear, much higher values of α at the release criterion might be considered adequately protective when the survey design results in smaller decision error rates at doses or risks greater than the release criterion. False positives will tend to be balanced by false negatives across sites and survey units, resulting in approximately equal human health risks.
- The DCGL itself is not free of error. The dose or risk cannot be measured directly, and many assumptions are made in converting doses or risks to derived concentrations. To be adequately protective of public health, these models are generally designed to over predict the dose or risk. Unfortunately, it is difficult to quantify this. Nonetheless, it is probably safe to say that most models have uncertainty sufficiently large such that the true dose or risk delivered by residual radioactivity at the DCGL is very likely to be lower than the release criterion. This is an additional consideration for setting the value of α that could support the use of larger values in some situations. In this case, one would prospectively address, as part of the DQO process, the magnitude, significance, and potential consequences of decision errors at values above the release criterion. The assumptions made in any model used to predict DCGLs for a site should be examined carefully to determine if the use of site specific parameters results in large changes in the DCGLs, or whether a site-specific model should be developed rather than designing a survey around DCGLs that may be too conservative.

- The risk of making the second type of decision error, β, is the risk of requiring additional remediation when a survey unit already meets the release criterion. Unlike the health risk, the cost associated with this type of error may be highly non-linear. The costs will depend on whether the survey unit has already had remediation work performed on it, and the type of residual radioactivity present. There may be a threshold below which the remediation cost rises very rapidly. If so, a low value for β is appropriate at that threshold value. This is primarily an issue for survey units that have a substantial likelihood of falling at or above the gray region for residual radioactivity. For survey units that are very lightly contaminated, or have been so thoroughly remediated that any residual radioactivity is expected to be far below the DCGL, larger values of β may be appropriate especially if final status survey sampling costs are a concern. Again, it is important to examine the probability of deciding that the survey unit does not meet the release criterion over the entire range of possible residual radioactivity values, below as well as above the gray region.
- Lower decision error rates may be possible if alternative sampling and analysis techniques can be used that result in higher precision. The same might be achieved with moderate increases in sample sizes. These alternatives should be explored before accepting higher design error rates. However, in some circumstances, such as high background variations, lack of a radio-nuclide specific technique, and/or radio-nuclides that are very difficult and expensive to quantify, error rates that are lower than the uncertainties in the dose or risk estimates may be neither cost effective nor necessary for adequate radiation protection.

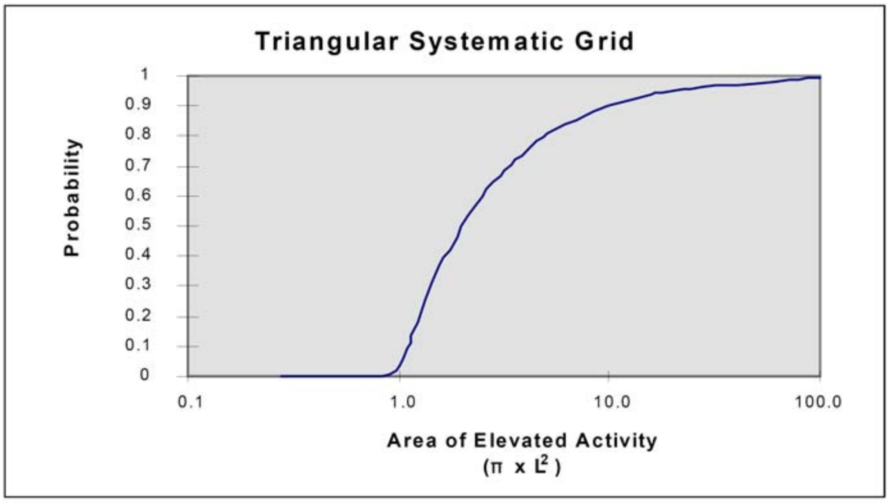
None of the above discussion is meant to suggest that under any circumstances a less than rigorous, thorough, and professional approach to final status surveys would be satisfactory. The decisions made and the rationale for making these decisions should be thoroughly documented.

For Class 1 survey units, the number of samples may be driven more by the need to detect small areas of elevated activity than by the requirements of the statistical tests. This in turn will depend primarily on the sensitivity of available scanning instrumentation, the size of the area of elevated activity, and the dose or risk model. A given concentration of residual radioactivity spread over a smaller area will, in general, result in a smaller dose or risk. Thus, the $DCGL_{EMC}$ used for the elevated measurement comparison is usually larger than the $DCGL_W$ used for the statistical test. In some cases, especially radio-nuclides that deliver dose or risk primarily via internal pathways, dose or risk is approximately proportional to inventory, and so the difference in the DCGLs is approximately proportional to the areas.

However, this may not be the case for radio-nuclides that deliver a significant portion of the dose or risk via external exposure. The exact relationship between the $DCGL_{EMC}$ and the $DCGL_W$ is a complicated function of the dose or risk modelling pathways, but area factors to relate the two DCGLs can be tabulated for most radio-nuclides, and site-specific area factors can also be developed.

For many radio-nuclides, scanning instrumentation is readily available that is sensitive enough to detect residual radioactivity concentrations at the $DCGL_{EMC}$ derived for the sampling grid of direct measurements used in the statistical tests. Where instrumentation of sufficient sensitivity (MDC, see Section 3.3.7) is not available, the number of samples in the survey unit can be increased until the area between sampling points is small enough (and the resulting area factor is large enough) that $DCGL_{EMC}$ can be detected by scanning. For some radio-nuclides (*e.g.*, ^3H) the scanning sensitivity is so low that this process would never terminate - *i.e.*, the number of samples required could increase without limit.

Thus, an important part of the DQO process is to determine the smallest size of an area of elevated activity that it is important to detect, A_{min}, and an acceptable level of risk, R_A, that it may go undetected. The probability of sampling a circular area of size A with either a square or triangular sampling pattern is shown in Figure A.5.



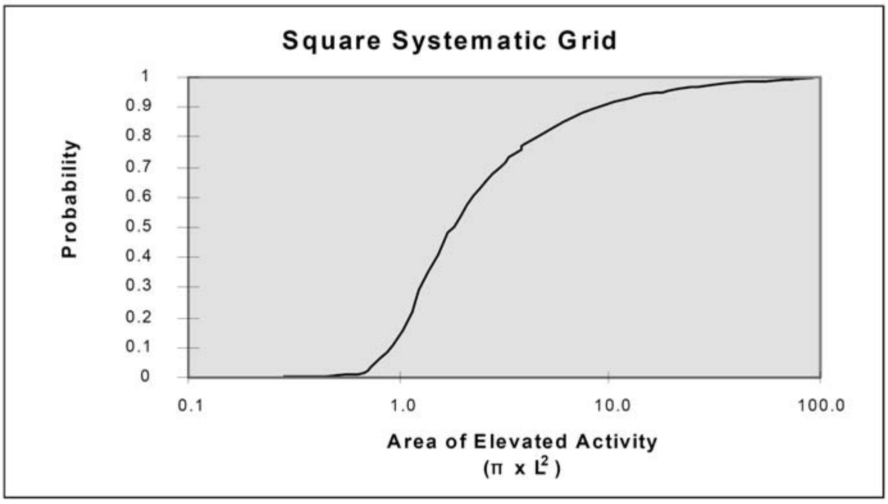


Figure A.5 Geometric probability of sampling at least one point of an area of elevated activity as a function of sample density with either a square or triangular sampling pattern

In this part of the DQO process, the concern is less with areas of elevated activity that are found than with providing adequate assurance that negative scanning results truly demonstrate the absence of such areas. In selecting acceptable values for A_{MIN} and R_A, maximum use of information from the historical site assessment and all surveys prior to the final status surveys should be used to determine what sort of areas of elevated activity could possibly exist, their potential size and shape, and how likely they are to exist. When the detection limit of the scanning technique is very large relative to the $DCGL_{EMC}$, the number of measurements estimated to demonstrate compliance using the statistical tests may become unreasonably large. In this situation an evaluation of the survey objectives and considerations should be performed. These considerations may include the survey design and measurement methodology, exposure pathway modelling assumptions and parameter values used to determine the DCGLs, historical site assessment conclusions concerning source terms and radio-nuclide distributions, and the results of scoping and characterization surveys. In most cases the results of this evaluation is not expected to justify an unreasonably large number of measurements.

A convenient method for visualizing the decision rule is to graph the probability of deciding that the survey unit does not meet the release criterion, *i.e.*, that the null hypothesis of Scenario A is accepted. An example of such a chart is shown in Figure A.6.

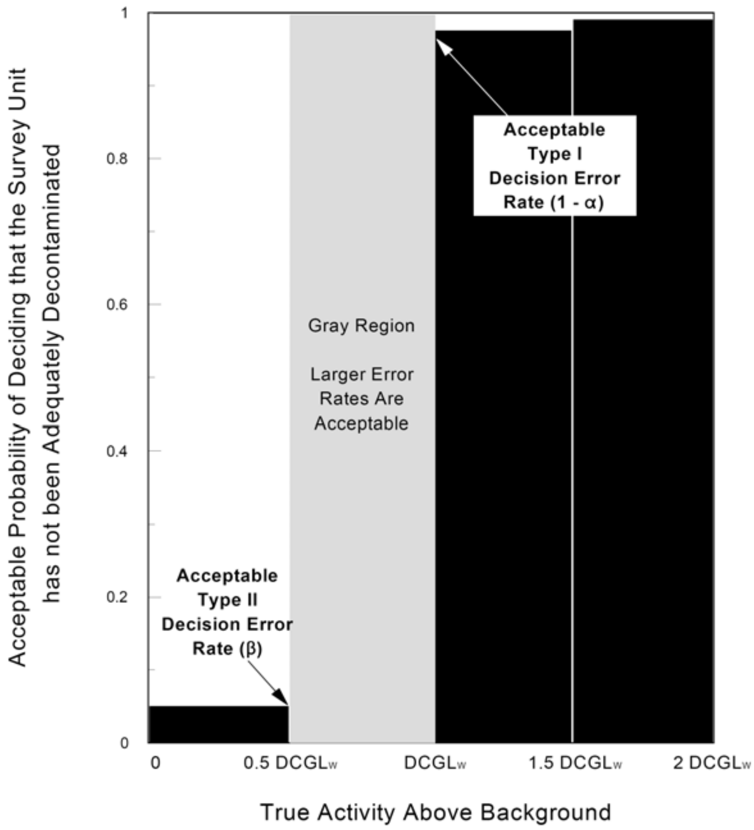


Figure A.6 Example of a power chart illustrating the decision rule for the final status survey

In this example α is 0.025 and β is 0.05, providing an expected power (1-β) of 0.95 for the test. A second method for presenting the information is shown in Figure A.7. This figure shows the probability of making a decision error for possible values of the parameter of interest, and is referred to as an error chart. In both examples a gray region, where the consequences of decision errors are deemed to be relatively minor, is shown. These charts are used in the final step of the DQO Process, combined with the outputs from the previous steps, to produce an efficient and cost-effective survey design. It is clear that setting acceptable values for α and β, as well as determining an appropriate gray region, is a crucial step in the DQO Process. Instructions for creating a prospective power curve, which can also be used to visualize the decision rule, are provided in 0.

After the survey design is implemented, the expected values of α and β determined in this step are compared to the actual significance level and power of the statistical test based on the measurement results during the assessment phase of the data life cycle. This comparison is used to verify that the objectives of the survey have been achieved.

Due the basic hypothesis testing philosophy, the null hypothesis is generally specified in terms of the *status quo* (*e.g.*, no change or action will take place if the null hypothesis is not rejected). Also, since the classical hypothesis testing approach exercises direct control over the Type I (false positive) error rate, this rate is generally associated with the error of most concern. In the case of the null hypothesis in which the residual radioactivity in the survey unit exceeds the release criterion, a Type I decision error would conclude that the residual activity was less than the release criterion when in fact it was above the release criterion. One difficulty, therefore, may be obtaining a consensus on which error should be of most concern (i.e., releasing a site where the residual activity exceeds the release criterion or failing to release a site where the residual activity is less than the release criterion). It is likely that the regulatory agency's public health-based protection viewpoint will differ from the viewpoint of the regulated party. The ideal approach is not only to define the null hypothesis in such a way that the Type I decision error protects human health and the environment but also in a way that encourages quality (high precision and accuracy) and minimizes expenditure of resources in situations where decisions are relatively "easy" (*e.g.*, all observations are far below the threshold level of interest or DCGL).

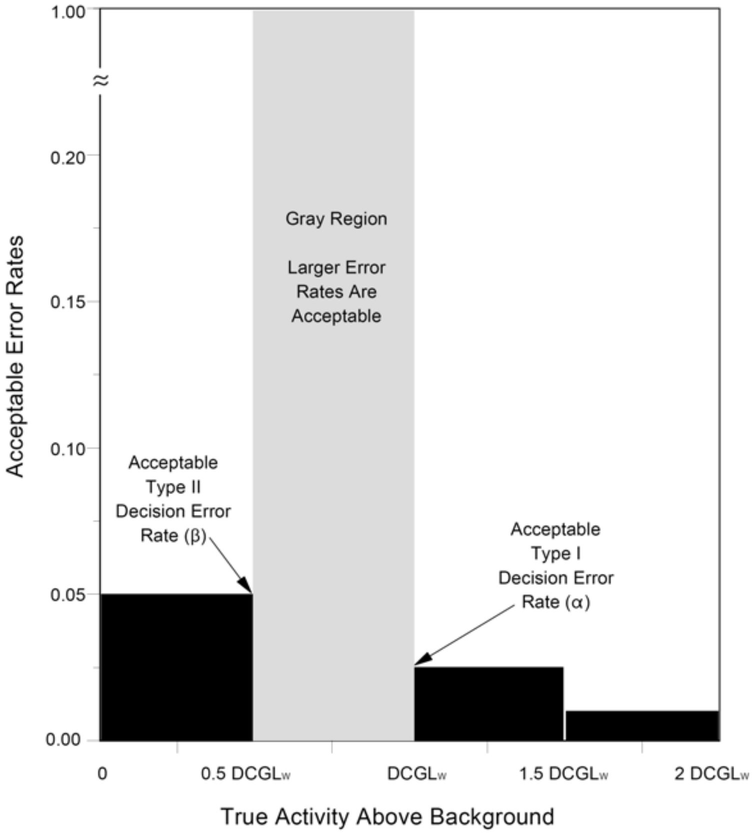


Figure A.7 Example of an error chart illustrating the decision rule
for the final status survey

To avoid excessive expense in performing measurements, compromises are sometimes necessary. For example, suppose that a significance level (α) of 0.05 is to be used. However, the affordable sample size may be expected to yield a test with power (β) of only 0.40 at some specified parameter value chosen to have practical significance. One possible compromise may be to relax the Type I decision error rate (α) and use a value of 0.10, 0.15, or even 0.20. By relaxing the Type I decision error rate, a higher power (*i.e.*, a lower Type II decision error rate) can be achieved. An argument can be made that survey designs should be developed and number of measurements determined in such a way that both the Type I (α) and Type II (β) decision error rates are treated simultaneously and in a balanced manner (i.e., $\alpha = \beta = 0.15$). This approach of treating the Type I and Type II decision error rates simultaneously is taken by the DQO Process. It is recommended that several different values for α and β be investigated before specific values are selected.

Appendix B: Field survey and laboratory analysis equipment for radioactive material concentrations and radiation levels

B.1 Introduction

This appendix provides information on various field and laboratory equipment used to measure radiation levels and radioactive material concentrations. The descriptions provide general guidance, and those interested in purchasing or using the equipment are encouraged to contact vendors and users of the equipment for specific information and recommendations. Although most of this equipment is in common use, a few specialty items are included to demonstrate promising developments.

The equipment is divided into two broad groupings of field survey and laboratory instruments, and each group is subdivided into equipment that measures alpha, beta, gamma, X-rays, neutron and radon. A single sheet provides information for each system and includes its type of use (field or lab), the primary and secondary radiation detected, applicability for site surveys, operation, specificity/sensitivity, and cost of the equipment and surveys performed.

The sheet contains the following sections:

- *Applicability for site surveys*. In this section it is discussed how the equipment is most useful for performing site radiological surveys.
- *Operation.* Herein basic technical information is provided on what the system includes, how it works, how to use it practically in the field, and its features.
- *Specificity/Sensitivity.* This section addresses the system's strengths and weaknesses, and the levels of radioactivity it can measure.
- *Cost.* The information obtained in this section has been obtained primarily from discussions with manufacturers, users, and reviews of product literature. The cost per measurement is an estimate of the cost of producing and documenting a single data point, generally as part of a multipoint survey. It assumes times for instrument calibration (primarily if conducted at the time of the survey), use, sample analysis, and report preparation and review. It should be recognized that these values will change over time due to factors like inflation and market expansion.

It is assumed that the user of this Appendix has a basic familiarity with field and laboratory equipment. Some of the typical instrument features and terms are listed below and may not be described separately for the individual instruments:

- **Field survey equipment** consists of a detector, a survey meter, and interconnected cables, although these are sometimes packaged in a single container.
- **The detector** or probe is the portion which is sensitive to radiation. It is designed in such a manner, made of selected materials, and operated at a high voltage that makes it sensitive to one or more types of radiation. Some detectors feature a window or a shield whose construction material and thickness make the detector more or less sensitive to a particular radiation. The size of the detector can vary depending on the specific need, but is often limited by the characteristics of the construction materials and the physics of the detection process.
- **The survey meter** contains the electronics and provides high voltage to the detector, processes the detector's signal, and displays the readings in analog or digital fashion. An analog survey meter has a continuous swing needle and typically a manually operated scale switch, used to keep the needle on scale. The scaling switch may not be required on a digital survey meter.
- **The interconnecting cables** serve to transfer the high voltage and detector signals in the proper direction. These cables may be inside those units which combine the meter

and detector into a single box, but they are often external with connectors that allow the user to interchange detectors.

- **Scanning and measuring surveys**. In a scanning survey, the field survey meter is operated while moving the detector over an area to search for a change in readings. Since the meter's audible signal responds faster than the meter display, listening to the built-in speaker or using headphones allows the user to more quickly discern changes in radiation level. When a scanning survey detects a change, the meter can be held in place for a more accurate static measurement.
- **Integrated readings.** Where additional sensitivity is desired, the reading can be integrated using internal electronics or an external scaler to give total values over time. The degree to which the sensitivity can be improved depends largely on the integration time selected.
- **Units of measure**. Survey meters with conventional meter faces measure radiation levels in units of counts, microRoentgen (μR), millirad (mrad), or millirem (mrem) in terms of unit time, *e.g.*, cpm or μR/hr. Those with SI meter faces use units of microSievert (μSv) or milliGray per unit time, *e.g.*, μSv/hr or mGy/hr.

B.2 Aspects to consider at the selection of field survey and laboratory equipment

Choose reliable instruments that are suited to the physical and environmental conditions at the site and capable of detecting the radiations of concern to the appropriate minimum detectable concentration (MDC). During survey design, it is generally considered good practice to select a measurement system with an MDC between 10-50% of the DCGL. Sometimes this goal may not be achievable based on site-specific conditions (*e.g.*, best available technology, cost restrictions).

The minimum detectable concentration is calculated based on a hypothesis test for individual measurements (see Section 3.3.7), and results below the minimum detectable concentration are variable and lead to a high value for σ (σ is defined as the standard deviation of the measurements in the survey unit) of the measured values in the survey unit or reference area. This high value for σ can be accounted for using the statistical tests described in Section 3 for the final status survey, but a large number of measurements are needed to account for the variability.

During scoping and characterization surveys, low MDCs help in the identification of areas that can be classified as non-impacted or Class 3 areas. These decisions are usually based on fewer numbers of samples, and each measurement is evaluated individually. Using an optimistic estimation of the MDC (see Section 3.11) for these surveys may result in the mis-classification of a survey unit and cleaning up an uncontaminated area or performing a final status survey in a contaminated area. Selecting a measurement technique with a well defined MDC or a conservative estimate of the MDC ensures the usefulness of the data for making decisions for planning the final status survey. For these reasons, EURSSEM recommends that a realistic or conservative estimate of the MDC be used instead of an optimistic estimate. A conservative estimate of the MDC uses reasonably conservative values for parameters with a high level of uncertainty, and results in a MDC value that is higher than a non-conservative or optimistic estimate.

The instrument should be calibrated for the radiations and energies of interest at the site. This calibration should be traceable to an accepted standards organization such as national institutes or qualified calibration services. Routine operational checks of instrument performance should be conducted to assure that the check source response is maintained within acceptable ranges and that any changes in instrument background are not attributable to contamination of the detector. If the radionuclide contaminants cannot be detected at desired levels by direct measurement (see Section 3.3.7), the portion of the survey dealing with measurements at discrete locations should be designed to rely primarily on sampling and laboratory analysis.

Assuming the contaminants can be detected, either directly or by measuring a key-nuclide or surrogate radio-nuclide in the mixture, the next decision point depends on whether the radionuclide being measured is present in background. Gross measurement methods will likely be more appropriate for measuring surface contamination in structures, scanning for locations of elevated activity, and determining exposure rates. Nuclide-specific measurement techniques, such as gamma spectrometry, provide a marked increase in detection sensitivity over gross measurements because of their ability to screen out contributions from other sources.

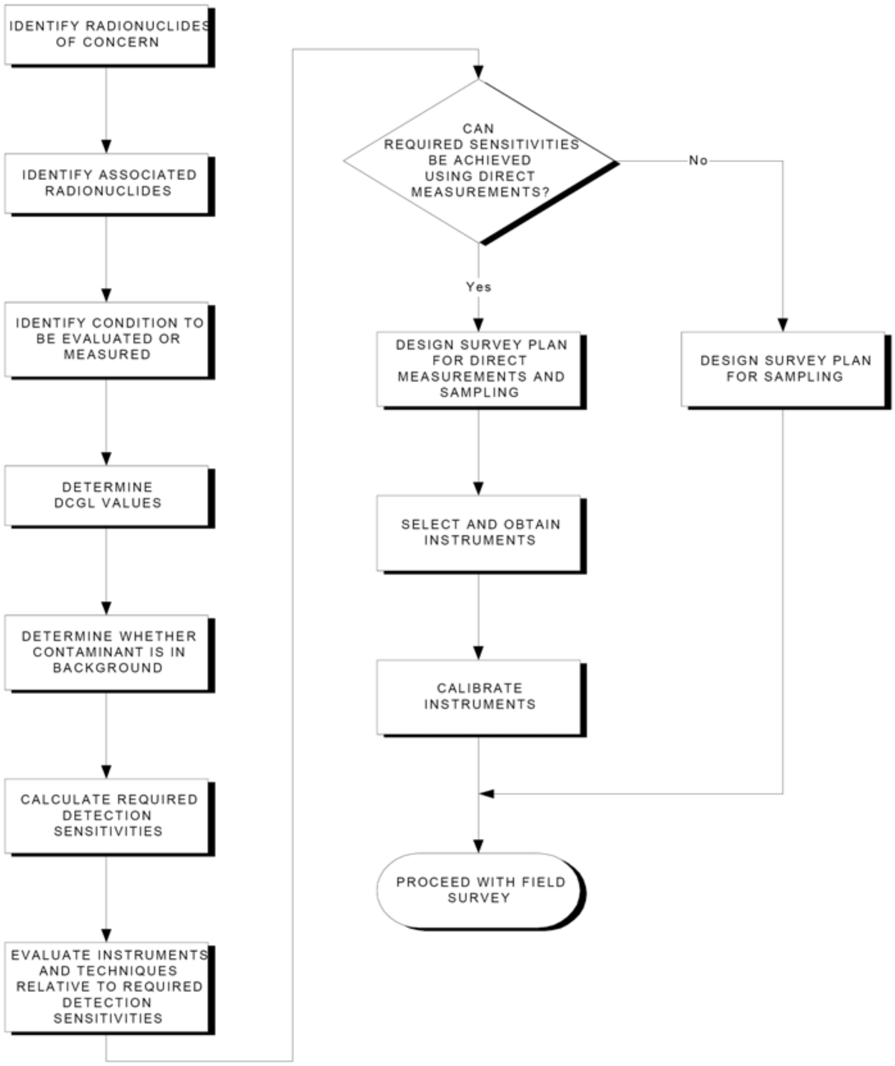


Figure B.1 Flow diagram for selection of field survey instrumentation for direct measurements and analysis of samples

Figure B.1 illustrates the sequence of steps in determining if direct measurement techniques can be applied at a particular site, or if laboratory analysis is more appropriate. Scanning surveys are typically performed at all sites. The selection of appropriate instruments for scanning, direct measurement, and sampling and analysis should be survey specific.

B.3 Advised sensitivity of direct measurement and scanning survey techniques

Direct measurement and scanning survey techniques should be capable of measuring levels below the established DCGLs - detection limits of 10-50% of the DCGL should be the target (see Section 3.3.7). Cost, time, best available technology, or other constraints may create situations where the above stated sensitivities are deemed impractical. Under these circumstances, higher detection sensitivities may be acceptable. Although service providers and instrument manufacturers will state detection limits, these sensitivities are usually based on ideal or optimistic situations and may not be achievable under site-specific measurement conditions. Detection limits are subject to variation from measurement to measurement, instrument to instrument, operator to operator, and procedure to procedure. This variation depends on geometry, background, instrument calibration, abundance of the radiations being measured, counting time, operator training, operator experience, self-absorption in the medium being measured, and interferences from radio-nuclides or other materials present in the medium. The detection limit that is achievable in practice should not exceed the DCGL. See section 3.3.7 for more detailed information.

B.4 Field survey equipment

B.4.1 Alpha particle detectors

System: ALPHA SCINTILLATION SURVEY METER
Lab/Field: Field
Radiation Detected:
Primary: Alpha
Secondary: None (in relatively low gamma fields)

Applicability to Site Surveys: The alpha scintillation survey meter is useful for determining the presence or absence of alpha-emitting contamination on nonporous surfaces, swipes, and air filters, or on irregular surfaces if the degree of surface shielding is known.

Operation: This survey meter uses an alpha radiation detector with a sensitive area of approximately 50 to 100 cm^2 (8 to 16 $in.^2$). The detector has a thin, aluminized window of mylar that blocks ambient light but allows alpha radiation to pass through. The detecting medium is silver activated zinc sulfide, ZnS(Ag). When the discriminator is appropriately adjusted, the meter is sensitive only to alpha radiation. Light pulses are amplified by a photomultiplier tube and passed to the survey meter.

The probe is generally placed close to the surface due to the short range of alpha particles in air. A scanning survey is used to identify areas of elevated surface contamination and then a direct survey is performed to obtain actual measurements. Integrating the readings over time improves the sensitivity enough to make the instrument very useful for alpha surface contamination measurements for many isotopes. The readings are displayed in counts per minute, but factors can usually be obtained to convert readings from cpm to dpm. Conversion factors, however, can be adversely affected by the short range of alpha particles which allows them to be shielded to often uncertain degrees if they are embedded in the surface. Systems typically use 2 to 6 ‘C’ or ‘D’ cells and will operate for 100-300 hours.

Specificity/Sensitivity: When the alpha discriminator is correctly adjusted, the alpha scintillation survey meter measures only alpha radiation, even if there are other radiations present. A scanning survey gives a quick indication of the presence or absence of surface contamination, while integrating the readings provides a measure of the activity on a surface, swipe, or filter. Alpha radiation is easily adsorbed by irregular, porous, moist, or over painted surfaces, and this should be carefully considered when converting count rate data to surface contamination levels. This also requires wet swipes and filters to be dried before counting. The minimum sensitivity is around 10 cpm using the needle deflection or 1 to 2 cpm when using headphones or a scaler. Some headphones or scalers give one click for every two counts, so the manual should be consulted to preclude underestimating the radioactivity by a factor of two.

Cost of Equipment: $1,000.

Cost per Measurement: $5.

System: ALPHA TRACK DETECTOR
Lab/Field: Field and Indoor Surfaces
Radiation Detected:
Primary: Alpha
Secondary: None

Applicability to Site Surveys: Alpha track detectors measure gross alpha surface contamination, soil activity levels, or the depth profile of contamination.

Operation: This is a passive integrating detector. It consists of a l mm-thick sheet of polycarbonate material which is deployed directly on the soil surface or in close proximity to the contaminated surface. When alpha particles strike the detector surface, they cause microscopic damage centres to form in the plastic matrix. After deployment, the detector is etched in a caustic solution which preferentially attacks the damage centres. The etch pits may then be counted in an optical scanner. The density of etch pits, divided by the deployment time, is proportional to the soil or surface alpha activity. The measurement may be converted to isotopic concentration if the isotopes are known or measured separately. The area of a standard detector is 2 cm^2 (0.3 in.2), but it may be cut into a variety of shapes and sizes to suit particular needs.

Specificity/Sensitivity: Alpha track detectors are relatively inexpensive, simple, passive, and have no measurable response to beta/gamma radiation. They provide a gross alpha measurement where the lower limit of detection is a function of deployment time. For surface contamination it is 330 Bq/m^2 (200 dpm/100 cm^2) @ l hour, 50 Bq/m^2 (30 dpm/100 cm^2) @ 8 hours, and 17 Bq/m^2 (10 dpm/100 cm^2) @ 48 hours. For soil contamination it is 11,000 Bq/kg (300 pCi/g) @ 1 hour, 3,700 Bq/kg (100 pCi/g) @ 8 hours, and 740 Bq/kg (20 pCi/g) @ 96 hours. High surface contamination or soil activity levels may be measured with deployment times of a few minutes, while activity down to background levels may require deployment times of 48-96 hours. When placed on a surface, they provide an estimate of alpha surface contamination or soil concentration. When deployed against the side of a trench, they can provide an estimate of the depth profile of contamination. They may also be used in pipes and under/inside of equipment.

For most applications, the devices are purchased for a fixed price per measurement, which includes readout. This requires that the detectors be returned to the vendor and the data are not immediately available. For programs having continuing needs and a large number of measurements, automated optical scanners may be purchased. The cost per measurement is then a function of the number of measurements required.

Cost of Equipment: $65,000.

Cost per Measurement: $5 to $10.

System: ELECTRET ION CHAMBER
Lab/Field: Field
Radiation Detected:
Primary: Alpha, beta, gamma, or radon
Secondary: None

Applicability to Site Surveys: An electret is a passive integrating detector for measurements of alpha- or beta-emitting contaminants on surfaces and in soils, gamma radiation dose, or radon air concentration.

Operation: The system consists of a charged Teflon disk (electret), open-faced ionization chamber, and electret voltage reader/data logger. When the electret is screwed into the chamber, a static electric field is established and a passive ionization chamber is formed. For alpha or beta radiation, the chamber is opened and deployed directly on the surface or soil to be measured so the particles can enter the chamber. For gammas, however, the chamber is left closed and the gamma rays incidenting on the chamber penetrate the 2 mm-thick plastic detector wall. These particles or rays ionize the air molecules, the ions are attracted to the charged electret, and the electret's charge is reduced. The electret charge is measured before and after deployment with the voltmeter, and the rate of change of the charge is proportional to the alpha or beta surface or soil activity, with appropriate compensation for background gamma levels. A thin mylar window may be used to protect the electret from dust. In low-level gamma measurements, the electret is sealed inside a mylar bag during deployment to minimize radon interference. For alpha and beta measurements, corrections must be made for background gamma radiation and radon response. This correction is accomplished by deploying additional gamma or radon-sensitive detectors in parallel with the alpha or beta detector. Electrets are simple and can usually be reused several times before recharging by a vendor. Due to their small size (3.8 cm tall by 7.6 cm diameter or l.5 in. tall by 3 in. diameter), they may be deployed in hard-to-access locations.

Specificity/Sensitivity: This method gives a gross alpha, gross beta, gross gamma, or gross radon measurement. The lower limit of detection depends on the exposure time and the volume of the chamber used. High surface alpha or beta contamination levels or high gamma radiation levels may be measured with deployment times of a few minutes. Much lower levels can be measured by extending the deployment time to 24 hours or longer. For gamma radiation, the response of the detector is nearly independent of energy from 15 to 1200 keV, and fading corrections are not required. To quantify ambient gamma radiation fields of 10 μR/hr, a 1000 ml chamber may be deployed for two days or a 50 ml chamber deployed for 30 days. The smallest chamber is particularly useful for long term monitoring and reporting of monthly or quarterly measurements. For alpha and beta particles, the measurement may be converted to isotopic concentration if the isotopes are known or measured separately. The lower limit of detection for alpha radiation is 83 Bq/m² (50 dpm/100 cm²) @ 1 hour, 25 Bq/m² (l5 dpm/100 cm²) @ 8 hours, and 13 Bq/m² (8 dpm/100 cm²) @ 24 hours. For beta radiation from tritium it is 10,000 Bq/m² (6,000 dpm/cm²) @ 1 hour and 500 Bq/m² (300 dpm/cm²) @ 24 hours. For beta radiation from ^{99}Tc it is 830 Bq/m² (500 dpm/cm²) @ 1 hour and 33 Bq/m² (20 dpm/cm²) @ 24 hours.

Cost of Equipment: $4,000 to $25,000 for system if purchased.

Cost per Measurement: $8-$25 for use under service contract.

System: GAS-FLOW PROPORTIONAL COUNTER
Lab/Field: Field
Radiation Detected:
Primary: Alpha, Beta
Secondary: Gamma

Applicability to Site Surveys: This equipment measures gross alpha or gross beta/gamma surface contamination levels on relatively flat surfaces like the floors and walls of facilities. It also serves as a screen to determine whether or not more nuclide-specific analyses may be needed.

Operation: This system consists of a gas-flow proportional detector, gas supply, supporting electronics, and a scaler or rate meter. Small detectors (~100 cm^2) are hand-held and large detectors (~400-600 cm^2) are mounted on a rolling cart. The detector entrance window can be < 1 to almost 10 mg/cm^2 depending on whether alpha, alpha-beta, or gamma radiation is monitored. The gas used is normally P-10, a mixture of 10% methane and 90% argon. The detector is positioned as close as practical to the surface being monitored for good counting efficiency without risking damage from the detector touching the surface. Quick disconnect fittings allow the system to be disconnected from the gas bottle for hours with little loss of counting efficiency. The detector operating voltage can be set to make it sensitive only to alpha radiation, to both alpha and beta radiation, or to beta and low energy gamma radiation. These voltages are determined for each system by placing either an alpha source, such as ^{230}Th or ^{241}Am, or a beta source, such as ^{90}Sr, facing and near the detector window, then increasing the high voltage in incremental steps until the count rate becomes constant. The alpha plateau, the region of constant count rate, will be almost flat. The beta plateau will have a slope of 5 to 15 percent per 100 volts. Operation on the beta plateau allows detection of some gamma radiation, but the efficiency is very low. Some systems use a spectrometer to separate alpha, and beta/gamma events, allowing simultaneous determination of both the alpha and beta/gamma surface contamination levels.

Specificity/Sensitivity: These systems do not identify the alpha or beta energies detected and cannot be used to identify specific radio-nuclides. Background for operation on the alpha plateau is very low: 2 to 3 counts per minute, which is higher than for laboratory detectors because of the larger detector size. Background for operation on the beta plateau is dependent on the ambient gamma and cosmic ray background, and typically ranges from several hundred to a thousand counts per minute. Typical efficiencies for un-attenuated alpha sources are 15-20%. Beta efficiency depends on the window thickness and the beta energy. For $^{90}Sr/^{90}Y$ in equilibrium, efficiencies range from 5% for highly attenuated to about 35% for un-attenuated sources. Typical gamma ray efficiency is < 1%. The presence of natural radio-nuclides in the surfaces could interfere with the detection of other contaminants. Unless the nature of the contaminant and any naturally-occurring radio-nuclides is well known, this system is better used for assessing gross surface contamination levels. The texture and porosity of the surface can hide or shield radioactive material from the detector, causing levels to be underestimated. Changes in temperature can affect the detector sensitivity. Incomplete flushing with gas can cause a non-uniform response over the detector surface. Condensation in the gas lines or using the quick disconnect fittings can cause count rate instability.

Cost of Equipment: $2,000 to $4,000.

Cost per Measurement: $2-$10 per m^2.

System: LONG RANGE ALPHA DETECTOR (LRAD)
Lab/Field: Field
Radiation Detected:
Primary: Alpha
Secondary: None

Applicability to Site Surveys: The LRAD is a rugged field-type unit for measuring alpha surface soil concentration over a variety of dry, solid, flat terrains.

Operation: The LRAD system consists of a large (1 m x 1 m) aluminium box, open on the bottom side, containing copper plates that collect ions produced in the soil or surface under the box, and used to measure alpha surface contamination or soil concentration. It is attached to a lifting device on the front of a tractor and can be readily moved to new locations. Bias power is supplied by a 300-V dry cell battery, and the electrometer and computer are powered by an automobile battery and DC-to-AC inverter. A 50 cm grounding rod provides electrical grounding. A notebook computer is used for data logging and graphical interpretation of the data. Alpha particles emitted by radio-nuclides in soil travel only about 3 cm in air. However, these alpha particles interact with the air and produce ions that travel considerably farther. The LRAD detector box is lowered to the ground to form an enclosed ionization region. The copper detector plate is raised to +300V along with a guard detector mounted above the detector plate to control leakage current. The ions are then allowed to collect on the copper plate producing a current that is measured with a sensitive electrometer. The signal is then averaged and processed on a computer. The electric current produced is proportional to the ionization within the sensitive area of the detector and to the amount of alpha contamination present on the surface soil.
Due to its size and weight (300 lb), the unit can be mounted on a tractor for ease of movement. All metal surfaces are covered with plastic to reduce the contribution from ion sources outside the detector box. At each site, a ground rod is driven into the ground. Each location is monitored for at least 5 min. After each location is monitored, its data is fed into a notebook computer and an interpolative graph of alpha concentration produced. The unit is calibrated using standard alpha sources.

Specificity/Sensitivity: The terrain over which this system is used must be dry, to prevent the shielding of alpha particles by residual moisture, and flat, to prevent air infiltration from outside the detector, both of which can lead to large errors. The unit can detect a thin layer of alpha surface contamination at levels of 33-83 Bq/m² (20-50 dpm/100 cm²), but does not measure alpha contamination of deeper layers. Alpha concentration errors are +74-740 Bq/kg (+2-20 pCi/g), with daily repeat accuracies of +370-3,700 Bq/kg (+10-100 pCi/g), depending on the contamination level. The dynamic measurement range appears to be 370-110,00 Bq/kg (10-3,000 pCi/g).

Cost of Equipment: $25,000 (estimate for tractor, computer, software, electrometer, and detector).

Cost per Measurement: $80 (based on 30 min per point and a 2 person team).

B.4.2 Beta particle detectors

System: ELECTRET ION CHAMBER
Lab/Field: Field
Radiation Detected:
Primary: Low energy beta (*e.g.*, tritium, ^{99}Tc, ^{14}C, ^{90}Sr, ^{63}Ni), alpha, gamma, or radon
Secondary: None

Applicability to Site Surveys: Applicability to site surveys: This system measures alpha- or beta-emitting contaminants on surfaces and in soils, gamma radiation dose, or radon air concentration, depending on how it is configured.

Operation: The system consists of a charged teflon disk (electret), open-faced ionization chamber, and electret voltage reader/data logger. When the electret is screwed into the chamber, a static electric field is established and a passive ionization chamber is formed. For alpha or beta radiation, the chamber is opened and deployed directly on the surface or soil to be measured so the particles can enter the chamber. For gammas, however, the chamber is left closed and the gamma rays incidenting on the chamber penetrate the 2 mm-thick plastic detector wall. These particles or rays ionize the air molecules, the ions are attracted to the charged electret, and the electret's charge is reduced. The electret charge is measured before and after deployment with the voltmeter, and the rate of change of the charge is proportional to the alpha or beta surface or soil activity, with appropriate compensation for background gamma levels. A thin mylar window may be used to protect the electret from dust. In low-level gamma measurements, the electret is sealed inside a mylar bag during deployment to minimize radon interference. For alpha and beta measurements, corrections must be made for background gamma radiation and radon response. This correction is accomplished by deploying additional gamma or radon-sensitive detectors in parallel with the alpha or beta detector. Electrets are simple and can usually be reused several times before recharging by a vendor. Due to their small size (3.8 cm tall by 7.6 cm diameter or l.5 in. tall by 3 in. diameter), they may be deployed in hard-to-access locations.

Specificity/Sensitivity: This method gives a gross alpha, gross beta, gross gamma, or gross radon measurement. The lower limit of detection depends on the exposure time and the volume of the chamber used. High surface alpha or beta contamination levels or high gamma radiation levels may be measured with deployment times of a few minutes. Much lower levels can be measured by extending the deployment time to 24 hours or longer. For gamma radiation, the response of the detector is nearly independent of energy from 15 to 1200 keV, and fading corrections are not required. To quantify ambient gamma radiation fields of 10 μR/hr, a 1000 ml chamber may be deployed for two days or a 50 ml chamber deployed for 30 days. The smallest chamber is particularly useful for long term monitoring and reporting of monthly or quarterly measurements. For alpha and beta particles, the measurement may be converted to isotopic concentration if the isotopes are known or measured separately. The lower limit of detection for alpha radiation is 83 Bq/m² (50 dpm/100 cm²) @ 1 hour, 25 Bq/m² (15 dpm/100 cm²) @ 8 hours, and 13 Bq/m² (8 dpm/100 cm²) @ 24 hours. For beta radiation from tritium it is 10,000 Bq/m² (6,000 dpm/cm²) @ 1 hour and 500 Bq/m² (300 dpm/cm²) @ 24 hours. For beta radiation from ^{99}Tc it is 830 Bq/m²(500 dpm/cm²) @ 1 hour and 33 Bq/m² (20 dpm/cm²) @ 24 hours.

Cost of Equipment: $4,000 to $25,000, for system if purchased.

Cost per Measurement: $8-$25, for use under service contract.

System: GAS-FLOW PROPORTIONAL COUNTER
Lab/Field: Field
Radiation Detected:
Primary: Alpha, Beta
Secondary: Gamma

Applicability to Site Surveys: This equipment measures gross alpha or gross beta/gamma surface contamination levels on relatively flat surfaces like the floors and walls of facilities. It would serve as a screen to determine whether or not more nuclide-specific analyses were needed.

Operation: This system consists of a gas-flow proportional detector, gas supply, supporting electronics, and a scaler or rate meter. Small detectors (~100 cm^2) are hand-held and large detectors (~400-600 cm^2) are mounted on a rolling cart. The detector entrance window can be < 1 to almost 10 mg/cm^2 depending on whether alpha, alpha-beta, or gamma radiation is monitored. The gas used is normally P-10, a mixture of 10% methane and 90% argon. The detector is positioned as close as practical to the surface being monitored for good counting efficiency without risking damage from the detector touching the surface. Quick disconnect fittings allow the system to be disconnected from the gas bottle for hours with little loss of counting efficiency. The detector operating voltage can be set to make it sensitive only to alpha radiation, to both alpha and beta radiation, or to beta and low energy gamma radiation. These voltages are determined for each system by placing either an alpha source, such as ^{230}Th or ^{241}Am, or a beta source, such as ^{90}Sr, facing and near the detector window, then increasing the high voltage in incremental steps until the count rate becomes constant. The alpha plateau, the region of constant count rate, will be almost flat. The beta plateau will have a slope of 5 to 15 percent per 100 volts. Operation on the beta plateau allows detection of some gamma radiation, but the efficiency is very low. Some systems use a spectrometer to separate alpha, and beta/gamma events, allowing simultaneous determination of both the alpha and beta/gamma surface contamination levels.

Specificity/Sensitivity: These systems do not identify the alpha or beta energies detected and cannot be used to identify specific radio-nuclides. Background for operation on the alpha plateau is very low, 2 to 3 counts per minute, which is higher than for laboratory detectors because of the larger detector size. Background for operation on the beta plateau is dependent on the ambient gamma and cosmic ray background, and typically ranges from several hundred to a thousand counts per minute. Typical efficiencies for un-attenuated alpha sources are 15-20%. Beta efficiency depends on the window thickness and the beta energy. For $^{90}Sr/^{90}Y$ in equilibrium, efficiencies range from 5% for highly attenuated to about 35% for un-attenuated sources. Typical gamma ray efficiency is < 1%. The presence of natural radio-nuclides in the surfaces could interfere with the detection of other contaminants. Unless the nature of the contaminant and any naturally-occurring radio-nuclides is well known, this system is better used for assessing gross surface contamination levels. The texture and porosity of the surface can hide or shield radioactive material from the detector, causing levels to be underestimated. Changes in temperature can affect the detector sensitivity. Incomplete flushing with gas can cause a non-uniform response over the detector surface. Condensation in the gas lines or using the quick disconnect fittings can cause count rate instability.

Cost of Equipment: $2,000 to $4,000.

Cost per Measurement: $2-$10 per m^2.

System: GM SURVEY METER WITH BETA PANCAKE PROBE
Lab/Field: Field
Radiation Detected:
Primary: Beta
Secondary: Gamma and alpha

Applicability to Site Surveys: This instrument is used to find and measure low levels of beta/gamma contamination on relatively flat surfaces.

Operation: This instrument consists of a flat 'pancake' type Geiger-Mueller detector connected to a survey meter which measures radiation response in counts per minute. The detector housing is typically a rigid metal on all sides except the radiation entrance face or window, which is made of mylar, mica, or a similar material. A steel, aluminium, lead, or tungsten housing surrounds the detector on all sides except the window, giving the detector a directional response. The detector requires approximately 900 volts for operation. It is held within a few cm of the surface to minimize the thickness of air shielding in between the radioactive material and the detector. It is moved slowly to scan the surface in search of elevated readings, then held in place long enough to obtain a stable measurement. Radiation entering the detector ionizes the gas, causes a discharge throughout the entire tube, and results in a single count being sent to the meter. The counts per minute meter reading is converted to a beta surface contamination level in the range of 1,700 Bq/m^2 (1,000 dpm/100 cm^2) using isotope specific factors.

Specificity/Sensitivity: Pancake type GM detectors primarily measure beta count rate in close contact with surfaces to indicate the presence of contamination. They are sensitive to any alpha, beta, or gamma radiation that enters the detector and causes ionization. As a result, they cannot determine the type or energy of that radiation, except by using a set of absorbers. To be detected, beta particles must have enough energy to penetrate through any surface material that the contamination is absorbed in, plus the detector window, and the layer of air and other shielding materials in between. Low energy beta particles from emitters like ^{3}H (17 keV) that cannot penetrate the window alone are not detectable, while higher energy betas like those from ^{60}Co (314 keV) can be readily detected. The beta detection efficiency at a field site is primarily a function of the beta energy, window thickness, and the surface condition. The detection sensitivity can be improved by using headphones or the audible response during scans. By integrating the count rate over a longer period or by counting the removable radioactive material collected on a swipe, the ability to detect surface contamination can be improved. The nominal 2 in. diameter detector can measure an increase of around 100 cpm above background, which equates to 4,200 Bq/m^2 (2,500 dpm/100 cm^2) of ^{60}Co on a surface under the detector or 20 Bq (500 pCi) on a swipe. Larger 100 cm^2 detectors improve sensitivity and eliminate the need to swipe. A swipe's collection efficiency may be below 100%, and depends on the wiping technique, the actual surface area covered, the texture and porosity of the surface, the affinity of the contamination for the swipe material, and the dryness of the swipe. This will proportionately change the values above. The sensitivity to gamma radiation is around 10% or less of the beta sensitivity, while the alpha detection efficiency is difficult to evaluate.

Cost of Equipment: $400 to $1,500.

Cost per Measurement: $5 to $10 per location.

B.4.3 Gamma ray detectors

System: ELECTRET ION CHAMBER
Lab/Field: Field
Radiation Detected:
Primary: Low energy beta (*e.g.*, tritium, ^{99}Tc, ^{14}C, ^{90}Sr, ^{63}Ni), alpha, gamma, or radon
Secondary: None

Applicability to Site Surveys: This system measures alpha- or beta-emitting contaminants on surfaces and in soils, gamma radiation dose, or radon air concentration, depending on how it is configured.

Operation: The system consists of a charged teflon disk (electret), open-faced ionization chamber, and electret voltage reader/data logger. When the electret is screwed into the chamber, a static electric field is established and a passive ionization chamber is formed. For alpha or beta radiation, the chamber is opened and deployed directly on the surface or soil to be measured so the particles can enter the chamber. For gammas, however, the chamber is left closed and the gamma rays incidenting on the chamber penetrate the 2 mm-thick plastic detector wall. These particles or rays ionize the air molecules, the ions are attracted to the charged electret, and the electret's charge is reduced. The electret charge is measured before and after deployment with the voltmeter, and the rate of change of the charge is proportional to the alpha or beta surface or soil activity, with appropriate compensation for background gamma levels. A thin mylar window may be used to protect the electret from dust. In low-level gamma measurements, the electret is sealed inside a mylar bag during deployment to minimize radon interference. For alpha and beta measurements, corrections must be made for background gamma radiation and radon response. This correction is accomplished by deploying additional gamma or radon-sensitive detectors in parallel with the alpha or beta detector. Electrets are simple and can usually be reused several times before recharging by a vendor. Due to their small size (3.8 cm tall by 7.6 cm diameter or l.5 in. tall by 3 in. diameter), they may be deployed in hard-to-access locations.

Specificity/Sensitivity: This method gives a gross alpha, gross beta, gross gamma, or gross radon measurement. The lower limit of detection depends on the exposure time and the volume of the chamber used. High surface alpha or beta contamination levels or high gamma radiation levels may be measured with deployment times of a few minutes. Much lower levels can be measured by extending the deployment time to 24 hours or longer. For gamma radiation, the response of the detector is nearly independent of energy from 15 to 1200 keV, and fading corrections are not required. To quantify ambient gamma radiation fields of 10 μR/hr, a 1000 ml chamber may be deployed for two days or a 50 ml chamber deployed for 30 days. The smallest chamber is particularly useful for long term monitoring and reporting of monthly or quarterly measurements. For alpha and beta particles, the measurement may be converted to isotopic concentration if the isotopes are known or measured separately. The lower limit of detection for alpha radiation is 83 Bq/m² (50 dpm/100 cm²) @ 1 hour, 25 Bq/m² (15 dpm/100 cm²) @ 8 hours, and 13 Bq/m² (8 dpm/100 cm²) @ 24 hours. For beta radiation from tritium it is 10,000 Bq/m² (6,000 dpm/cm²) @ 1 hour and 500 Bq/m² (300 dpm/cm²) @ 24 hours. For beta radiation from ^{99}Tc it is 830 Bq/m² (500 dpm/cm²) @ 1 hour and 33 Bq/m² (20 dpm/cm²) @ 24 hours.

Cost of Equipment: $4,000 to $25,000, for system if purchased.

Cost per Measurement: $8-$25, for use under service contract.

System: GM SURVEY METER WITH GAMMA PROBE
Lab/Field: Field
Radiation Detected:
Primary: Gamma
Secondary: Beta

Applicability to Site Surveys: This instrument is used to give a quick indication of gamma-radiation levels present at a site. Due to its high detection limit, the GM survey meter may be useful during characterization surveys but may not meet the needs of final status surveys.

Operation: This instrument consists of a cylindrical Geiger Mueller detector connected to a survey meter. It is calibrated to measure gamma exposure rate in mR/hr. The detector is surrounded on all sides by a protective rigid metal housing. Some units called end window or side window have a hinged door or rotating sleeve that opens to expose an entry window of mylar, mica, or a similar material, allowing beta radiation to enter the sensitive volume. The detector requires approximately 900 volts for operation. It is normally held at waist height, but is sometimes placed in contact with an item to be evaluated. It is moved slowly over the area to scan for elevated readings, observing the meter or, preferably, listening to the audible signal. Then it is held in place long enough to obtain a stable measurement. Radiation entering the detector ionizes the gas, causes a discharge throughout the entire tube, and results in a single count being sent to the meter. Conversion from count rate to exposure rate is accomplished at calibration by exposing the detector at discrete levels and adjusting the meter scale(s) to read accordingly. In the field, the exposure rate is read directly from the meter. If the detector housing has an entry window, an increase in ‘open-door’ over ‘closed-door’ reading indicates the presence of beta radiation in the radiation field, but the difference is not a direct measure of the beta radiation level.

Specificity/Sensitivity: GM meters measure gamma exposure rate, and those with an entry window can identify if the radiation field includes beta radiation. Since GM detectors are sensitive to any energy of alpha, beta, or gamma radiation that enters the detector, instruments that use these detectors cannot identify the type or energy of that radiation, or the specific radionuclide(s) present. The sensitivity can be improved by using headphones or the audible response during scans, or by integrating the exposure rate over time. The instrument has two primary limitations for environmental work. First, its minimum sensitivity is high, around 0.1 mR/hr in rate meter mode or 0.01 mR/hr in integrate mode. Some instruments use a large detector to improve low end sensitivity. However, in many instances the instrument is not sensitive enough for site survey work. Second, the detector energy response is non-linear. Energy compensated survey meters are commercially available, but the instrument sensitivity may be reduced.

Cost of Equipment: $400 to $1,500.

Cost per Measurement: $5 per measurement for survey and report.

System: HAND-HELD ION CHAMBER SURVEY METER
Lab/Field: Field
Radiation Detected:
Primary: Gamma
Secondary: None

Applicability to Site Surveys: The hand-held ion chamber survey meter measures true gamma radiation exposure rate, in contrast to most other survey meter/probe combinations which are calibrated to measure exposure rate at one energy and approximate the exposure rate at all other energies. Due to their high detection limit, these instruments are not applicable for many final status surveys.

Operation: This device uses an ion chamber operated at a bias voltage sufficient to collect all ion pairs created by the passage of ionizing radiation, but not sufficiently high to generate secondary ion pairs as a proportional counter does. The units of readout are mR/hr, or some multiple of mR/hr. If equipped with an integrating mode, the operator can measure the total exposure over a period of time. The instrument may operate on two 'D' cells or a 9 volt battery that will last for 100 to 200 hours of operation.

Specificity/Sensitivity: Ion chamber instruments respond only to gamma or X-radiation. They have no means to provide the identity of contaminants. Typical ion chamber instruments have a lower limit of detection of 0.5 mR/hr. These instruments can display readings below this, but the readings may be erratic and have large errors associated with them. In integrate mode, the instrument sensitivity can be as low as 0.05 mR/hr.

Cost of Equipment: $800 to $1,200.

Cost per Measurement: $5, or higher for making integrated exposure measurements.

System: HAND-HELD PRESSURIZED ION CHAMBER (PIC) SURVEY METER

Lab/Field: Field

Radiation Detected:

Primary: Gamma

Secondary: None

Applicability to Site Surveys: The hand-held pressurized ion chamber survey meter measures true gamma radiation exposure rate, in contrast to most other survey meter/probe combinations which are calibrated to measure exposure rate at one energy and approximate the exposure rate at all other energies. Due to their high detection limit, these instruments are not applicable for many final status surveys.

Operation: This device uses a pressurized air ion chamber operated at a bias voltage sufficient to collect all ion pairs created by the passage of ionizing radiation, but not sufficiently high to cause secondary ionization. The instrument is identical to the ion chamber meter on the previous page, except in this case the ion chamber is sealed and pressurized to 2 to 3 atmospheres to increase the sensitivity of the instrument by the same factors. The units of readout are µR/hr or mR/hr. A digital meter will allow an operator to integrate the total exposure over a period of time. The unit may use two 'D' cells or a 9-volt battery that will last for 100 to 200 hours of operation.

Specificity/Sensitivity: Since the ion chamber is sealed, pressurized ion chamber instruments respond only to gamma or X-radiation. They have no means to provide the identity of contaminants. Typical instruments have a lower limit of detection of 0.1 mR/hr, or as low as 0.01 mR in integrate mode. These instruments can display readings below this, but the readings may be erratic and have large errors associated with them.

Cost of Equipment: $1,000 to $1,500.

Cost per Measurement: $5, or higher for making integrated exposure measurements.

System: PORTABLE GERMANIUM MULTICHANNEL ANALYZER (MCA) SYSTEM

Lab/Field: Field

Radiation Detected:

Primary: Gamma

Secondary: None

Applicability to Site Surveys: This system produces semi-quantitative estimates of concentration of uranium and plutonium in soil, water, air filters, and quantitative estimates of many other gamma-emitting isotopes. With an appropriate dewar, the detector may be used in a vertical orientation to determine, in-situ, gamma isotopes concentrations in soil.

Operation: This system consists of a portable germanium detector connected to a dewar of liquid nitrogen, high voltage power supply, and multi-channel analyzer. It is used to identify and quantify gamma-emitting isotopes in soil or other surfaces.

Germanium is a semiconductor material. When a gamma ray interacts with a germanium crystal, it produces electron-hole pairs. An electric field is applied which causes the electrons to move in the conduction band and the holes to pass the charge from atom to neighbouring atoms. The charge is collected rapidly and is proportional to the deposited energy.

The typical system consists of a portable multi-channel analyzer (MCA) weighing about 7-10 lbs with batteries, a special portable low energy germanium detector with a built-in shield, and the acquisition control and spectrum analysis software. The detector is integrally mounted to a liquid nitrogen dewar. The liquid nitrogen is added 2-4 hours before use and replenished every 4-24 hours based on capacity.

The MCA includes all required front end electronics, such as a high voltage power supply, an amplifier, a digital stabilizer, and an analog-to-digital converter (ADC), which are fully controllable from a laptop computer and software.

One method uses the 94-104 keV peak region to analyze the plutonium isotopes from either 'fresh' or aged materials. It requires virtually no user input or calibration. The source-to-detector distance for this method does not need to be calibrated as long as there are enough counts in the spectrum to perform the analysis.

For in situ applications, a collimated detector is positioned at a fixed distance from a surface to provide multi-channel spectral data for a defined surface area. It is especially useful for qualitative and (based on careful field calibration or appropriate algorithms) quantitative analysis of freshly deposited contamination. Additionally, with prior knowledge of the depth distribution of the primary radio-nuclides of interest, which is usually not known, or using algorithms that match the site, the in-situ system can be used to estimate the content of radio-nuclides distributed below the surface (dependent, of course, on adequate detection capability.)

Calibration based on Monte Carlo modelling of the assumed source-to-detector geometry or computation of fluence rates with analytical expressions is an important component to the accurate use of field spectrometry, when it is not feasible or desirable to use real radioactive sources. Such modelling used in conjunction with field spectrometry is becoming much more common recently, especially using the MCNP Monte Carlo computer software system.

Specificity/Sensitivity: With proper calibration or algorithms, field spectrometers can identify and quantify concentrations of gamma emitting radio-nuclides in the middle to upper energy range (*i.e.*, 50 keV with a P-type detector or 10 keV with an N-type detector).

For lower energy photons, as are important for plutonium and americium, an N-type detector or a planar crystal is preferred with a very thin beryllium (Be) window. This configuration allows measurement of photons in the energy range 5 to 80 keV. The Be window is quite fragile and a target of corrosion, and should be protected accordingly.

The detector high voltage should only be applied when the cryostat has contained sufficient liquid nitrogen for several hours. These systems can accurately identify plutonium, uranium, and many gamma-emitting isotopes in environmental media, even if a mixture of radio-nuclides is present. Germanium has an advantage over sodium iodide because it can produce a quantitative estimate of concentrations of multiple radio-nuclides in samples like soil, water, and air filters.

A specially designed low energy germanium detector that exhibits very little deterioration in the resolution as a function of count rate may be used to analyze uranium and plutonium, or other gamma-emitting radio-nuclides. When equipped with a built-in shield, it is unnecessary to build complicated shielding arrangements while making field measurements. Tin filters can be used to reduce the count rate from the ^{241}Am 59 keV line which allows the electronics to process more of the signal coming from Pu or U.

A plutonium content of 10 mg can be detected in a 220 l waste drum in about 30 minutes, although with high uncertainty. A uranium analysis can be performed for an enrichment range from depleted to 93% enrichment. The measurement time can be in the order of minutes depending on the enrichment and the attenuating materials.

Cost of Equipment: $40,000

Cost per Measurement: $100 to $200

System: PRESSURIZED IONIZATION CHAMBER (PIC)
Lab/Field: Field
Radiation Detected:
Primary: Moderate (>80 keV) to high energy photons
Secondary: None

Applicability to Site Surveys: The pressurised ionization chamber is a highly accurate ionization chamber for measuring gamma exposure rate in air, and for correcting for the energy dependence of other instruments due to their energy sensitivities. It is excellent for characterizing and evaluating the effectiveness of remediation of contaminated sites based on exposure rate. However, most sites also require nuclide-specific identification of the contributing radio-nuclides. Under these circumstances, pressurised ionization chambers must be used in conjunction with other soil sampling or spectrometry techniques to evaluate the success of remediation efforts.

Operation: The pressurised ionization chamber detector is a large sphere of compressed argon-nitrogen gas at 10 to 40 atmospheres pressure surrounded by a protective box. The detector is normally mounted on a tripod and positioned to sit about three feet off the ground. It is connected to an electronics box in which a strip chart recorder or digital integrator measures instantaneous and integrated exposure rate. It operates at a bias voltage sufficient to collect all ion pairs created by the passage of ionizing radiation, but not sufficiently high to amplify or increase the number of ion pairs. The high pressure inside the detector and the integrate feature make the pressurised ionization chamber much more sensitive and precise than other ion chambers for measuring low exposures. The average exposure rate is calculated from the integrated exposure and the operating time. Arrays of pressurised ionization chamber systems can be linked by telecommunications so their data can be observed from a central and remote location.

Specificity/Sensitivity: The pressurised ionization chamber measures gamma or X-radiation and cosmic radiation. It is highly stable, relatively energy independent, and serves as an excellent tool to calibrate (in the field) other survey equipment to measure exposure rate. Since the pressurised ionization chamber is normally un-collimated, it measures cosmic, terrestrial, and foreign source contributions without discrimination. Its rugged and stable behaviour makes it an excellent choice for an unattended sensor where area monitors for gamma emitters are needed. Pressurised ionization chambers are highly sensitive, precise, and accurate to vast changes in exposure rate (1 μR/ hr up to 10 R/hr). Pressurised ionization chambers lack any ability to distinguish either energy spectral characteristics or source type. If sufficient background information is obtained, the data can be processed using algorithms that employ time and frequency domain analysis of the recorded systems to effectively separate terrestrial, cosmic, and 'foreign' source contributions. One major advantage of pressurised ionization chamber systems is that they can record exposure rate over ranges of 1 to 10,000,000 μR per hour (i.e., μR/hr to 10 R/hr) with good precision and accuracy.

Cost of Equipment: $15,000 to $50,000 depending on the associated electronics, data processing, and telecommunications equipment.

Cost per Measurement: $50 to $500 based on the operating time at each site and the number of measurements performed.

System: SODIUM IODIDE SURVEY METER
Lab/Field: Field
Radiation Detected:
Primary: Gamma
Secondary: None

Applicability to Site Surveys: Sodium iodide survey meters can be response checked against a pressurized ionization chamber (PIC) and then used in its place so readings can be taken more quickly. This check should be performed often, possibly several times each day. They are useful for determining ambient radiation levels and for estimating the concentration of radioactive materials at a site.

Operation: The sodium iodide survey meter measures gamma radiation levels in µR/hr (10-6 R/hr) or counts per minute (cpm). Its response is energy and count rate dependent, so comparison with a pressurized ionization chamber necessitates a conversion factor for adjusting the meter readings to true µR/hr values. The conversion factor obtained from this comparison is valid only in locations where the radionuclide mix is identical to that where the comparison is performed, and over a moderate range of readings. The detector is held at waist level or suspended near the surface and walked through an area listening to the audio and watching the display for changes. It is held in place and the response allowed to stabilize before each measurement is taken, with longer times required for lower responses. Generally, the centre of the needle swing or the integrated reading is recorded. The detector is a sodium iodide crystal inside an aluminium container with an optical glass window that is connected to a photomultiplier tube. A gamma ray that interacts with the crystal produces light that travels out of the crystal and into the photomultiplier tube. There, electrons are produced and multiplied to produce a readily measurable pulse whose magnitude is proportional to the energy of the gamma ray incidenting on the crystal. Electronic filters accept the pulse as a count if certain discrimination height restrictions are met. This translates into a meter response. Instruments with pulse height discrimination circuitry can be calibrated to view the primary gamma decay energy of a particular isotope. If laboratory analysis has shown a particular isotope to be present, the discrimination circuitry can be adjusted to partially tune out other isotopes, but this also limits its ability to measure exposure rate.

Specificity/Sensitivity: Sodium iodide survey meters measure gamma radiation in µR/hr or cpm with a minimum sensitivity of around 1-5 µR per hour, or 200-1,000 cpm, or lower in digital integrate mode. The reading error of 50% can occur at low count rates because of a large needle swing, but this decreases with increased count rate. The instrument is quite energy sensitive, with the greatest response around 100-120 keV and decreasing in either direction. Measuring the radiation level at a location with both a pressurized ionization chamber and the survey meter gives a factor for converting subsequent readings to actual exposure rates. This ratio can change with location. Some meters have circuitry that looks at a few selected ranges of gamma energies, or one at a time with the aid of a single channel analyzer. This feature is used to determine if a particular isotope is present. The detector should be protected against thermal or mechanical shock which can break the sodium iodide crystal or the photomultiplier tube. Covering at least the crystal end with padding is often sufficient. The detector is heavy, so adding a carrying strap to the meter and a means of easily attaching and detaching the detector from the meter case helps the user endure long surveys.

Cost of Equipment: $2,000

Cost per Measurement: $5

System: THERMOLUMINESCENCE DOSIMETER (TLD)
Lab/Field: Field and lab
Radiation Detected:
Primary: Gamma
Secondary: Neutron, beta, x-ray

Applicability to Site Surveys: TLDs can be used to measure such a low dose equivalent that they can identify gamma levels slightly above natural background. TLDs should be placed in areas outside the site but over similar media to determine the average natural background radiation level in the area. Other TLDs should be posted on site to determine the difference from background. Groups should be posted quarterly for days to quarters and compared to identify locations of increased onsite doses.

Operation: A TLD is a crystal that measures radiation dose. TLDs are semiconductor crystals that contain small amounts of added impurities. When radiation interacts with the crystal, electrons in the valence band are excited into the conduction band. Many lose their energy and return directly to the valence band, but some are trapped at an elevated energy state by the impurity atoms. This trapped energy can be stored for long periods, but the signal can fade with age, temperature, and light. Heating the TLD in a TLD reader releases the excess energy in the form of heat and light. The quantity or intensity of the light given off gives a measure of the radiation dose the TLD received. If the TLDs are processed at an off-site location, the transit dose (from the location to the site and return) must be determined and subtracted from the net dose. The ability to determine this transit dose affects the net sensitivity of the measurements. The TLD is left in the field for a period of a day to a quarter and then removed from the field and read in the laboratory on a calibrated TLD reader. The reading is the total dose received by the TLD during the posting period. TLDs come in various shapes (thin-rectangles, rods, and powder), sizes (0.08 cm to 0.6 cm (1/32 in. to 1/4 in.) on a side), and materials (CaF_2:Mn, $CaSO_4$:Dy, ^{6}LiF:Mn, ^{7}LiF:Mn, $LiBO_4$, LiF:Mg,Cu,P and Al_2O_3:C). The TLD crystals can be held loosely inside a holder, sandwiched between layers of teflon, affixed to a substrate, or attached to a heater strip and surrounded by a glass envelope. Most are surrounded by special thin shields to correct for an over response to low-energy radiation. Many have special radiation filters to allow the same type TLD to measure various types and energies of radiation.

Specificity/Sensitivity: TLDs are primarily sensitive to gamma radiation, but selected TLD/filter arrangements can be used to measure beta, X-ray, and neutron radiation. They are posted both on-site and off-site in comparable areas. These readings are compared to determine if the site can cause personnel to receive more radiation exposure than would be received from background radiation. The low-end sensitivity can be reduced by specially calibrating each TLD and selecting those with high accuracy and good precision. The new Al_2O_3 TLD may be capable of measuring doses as low as 0.1 μSv (0.01 mrem) while specially calibrated CaF_2 TLDs posted quarterly can measure dose differences as low as 0.05 mSv/y (5 mrem/y). This is in contrast to standard TLDs that are posted monthly and may not measure doses below 1 mSv/y (100 mrem/y). TLDs should be protected from damage as the manufacturer recommends. Some are sensitive to visible light, direct sunlight, fluorescent light, excessive heat, or high humidity.

Cost of Equipment: $5K-$ 100K (reader), $25-$40 (TLD). TLDs cost $5 to $40 per rental.

Cost per Measurement: $25 to $125.

B.4.4 Radon detectors and measurement techniques

System: ACTIVATED CHARCOAL ADSORPTION
Lab/Field: Field
Radiation Detected:
Primary: Radon gas
Secondary: None

Applicability to Site Surveys: Activated charcoal adsorption is a passive low cost screening method for measuring indoor air radon concentration. The charcoal adsorption method is not designed for outdoor measurements. For contaminated structures, charcoal is a good short-term indicator of radon contamination. Vendors provide measurement services which includes the detector and subsequent readout.

Operation: For this method, an airtight container with activated charcoal is opened in the area to be sampled and radon in the air adsorbs onto the charcoal. The detector, depending on its design, is deployed for 2 to 7 days. At the end of the sampling period, the container is sealed and sent to a laboratory for analysis. Proper deployment and analysis will yield accurate results.

Two analysis methods are commonly used in activated charcoal adsorption. The first method calculates the radon concentration based on the gamma decay from the radon progeny analyzed on a gamma scintillation or semiconductor detection system. The second method is liquid scintillation which employs a small vial containing activated charcoal for sampling. After exposure, scintillation fluid is added to the vial and the radon concentration is determined by the alpha and beta decay of the radon and progeny when counted in a liquid scintillation spectrometer.

Specificity/Sensitivity: Charcoal absorbers are designed to measure radon concentrations in indoor air. Some charcoal absorbers are sensitive to drafts, temperature and humidity. However, the use of a diffusion barrier over the charcoal reduces these effects. The minimum detectable concentration for this method ranges from 0.007-0.04 Bq/l (0.2-1.0 pCi/l).

Cost of Equipment: $10,000 for a liquid scintillation counter, $10,000 for a sodium iodide multi-channel analyzer system, or $30,000+ for a germanium multi-channel analyzer system. The cost of the activated charcoal itself is minimal.

Cost per Measurement: $5 to $30 including canister.

System: ALPHA TRACK DETECTOR
Lab/Field: Field
Radiation Detected:
Primary: Radon Gas (Alpha Particles)
Secondary: None

Applicability to Site Surveys: An alpha track detector is a passive, low cost, long term method used for measuring radon. Alpha track detectors can be used for site assessments both indoors and outdoors (with adequate protection from the elements).

Operation: Alpha track detectors employ a small piece of special plastic or film inside a small container. Air being tested diffuses through a filtering mechanism into the container. When alpha particles from the decay of radon and its progeny strike the detector, they cause damage tracks. At the end of exposure, the container is sealed and returned to the laboratory for analysis.

The plastic or film detector is chemically treated to amplify the damage tracks and then the number of tracks over a predetermined area are counted using a microscope, optical reader, or spark counter. The radon concentration is determined by the number of tracks per unit area. Detectors are usually exposed for 3 to 12 months, although shorter time frames may be used when measuring high radon concentrations.

Specificity/Sensitivity: Alpha track detectors are primarily used for indoor air measurements but specially designed detectors are available for outdoor measurements. Alpha track results are usually expressed as the radon concentration over the exposure period (Bq/l-days). The sensitivity is a function of detector design and exposure duration, and is on the order of 0.04 Bq/l-day (1 pCi/l-day).

Cost of Equipment: Not applicable when provided by a vendor.

Cost per Measurement: $5 to $25.

System: CONTINUOUS RADON MONITOR
Lab/Field: Field
Radiation Detected:
Primary: Radon gas
Secondary: None

Applicability to Site Surveys: Continuous radon monitors are devices that measure and record real-time measurements of radon gas or variations in radon concentration on an hourly basis. Since continuous monitors display real-time hourly radon measurements, they are useful for short-term site investigation.

Operation: Continuous radon monitors are precision devices that track and record real-time measurements and variations in radon gas concentration on an hourly basis. Air either diffuses or is pumped into a counting chamber. The counting chamber is typically a scintillation cell or ionization chamber. Using a calibration factor, the counts are processed electronically, and radon concentrations for predetermined intervals are stored in memory or directly transmitted to a printer.

Most continuous monitors are used for a relatively short measurement period, usually 1 to 7 days. These devices do require some operator skills and often have a ramp-up period to equilibrate with the surrounding atmosphere. This ramp-up time can range from 1 to 4 hours depending on the size of the counting chamber and rate of air movement into the chamber.

Specificity/Sensitivity: Most continuous monitors are designed for both indoor and outdoor radon measurements. The limiting factor for outdoor usage is the need for electrical power. In locations where external power is unavailable, the available operating time depends on the battery lifetime of the monitor. The minimum detectable concentration for these detectors ranges from 0.004-0.04 Bq/l (0.1-1.0 pCi/l).

Cost of Equipment: $1,000 to $5,000.

Cost per Measurement: $80 + based on duration of survey.

System: ELECTRET ION CHAMBER
Lab/Field: Field
Radiation Detected:
Primary: Radon gas (alpha, beta)
Secondary: Gamma

Applicability to Site Surveys: Electrets are used to measure radon concentration in indoor environments. For contaminated structures, the electret ion chamber is a good indicator of short-term and long-term radon concentrations.

Operation: For this method, an electro-statically charged disk (electret) is situated within a small container (ion chamber). During the measurement period, radon diffuses through a filter into the ion chamber, where the ionization produced by the decay of radon and its progeny reduces the charge on the electret. A calibration factor relates the voltage drop, due to the charge reduction, to the radon concentration. Variations in electret design enable the detector to make long term or short term measurements. Short term detectors are deployed for 2 to 7 days, whereas long term detectors may be deployed from 1 to 12 months. Electrets are relatively inexpensive, passive, and can be used several times before discarding or recharging, except in areas of extreme radon concentrations. These detectors need to be corrected for the background gamma radiation during exposure since this ionization also discharges the electret.

Specificity/Sensitivity: Electrets are designed to make radon measurements primarily in indoor environments. Care must be taken to measure the background gamma radiation at the site during the exposure period. Extreme temperatures and humidity encountered outdoors may affect electret voltage. The minimum detectable concentration ranges from 0.007-0.02 Bq/l (0.2 to 0.5 pCi/l).

Cost of Equipment: Included in rental price.

Cost per Measurement: $8 to $25 rental for an electret supplied by a vendor.

System: LARGE AREA ACTIVATED CHARCOAL COLLECTOR
Lab/Field: Field
Radiation Detected:
Primary: Radon gas
Secondary: None

Applicability to Site Surveys: This method is used to make radon flux measurements (the surface emanation rate of radon gas) and involves the adsorption of radon on activated carbon in a large area collector.

Operation: The collector consists of a 10 inch diameter PVC end cap, spacer pads, charcoal distribution grid, retainer pad with screen, and a steel retainer spring. Between 170 and 200 grams of activated charcoal is spread in the distribution grid and held in place by the retainer pad and spring.
The collector is deployed by firmly twisting the end cap into the surface of the material to be measured. After 24 hours of exposure, the activated charcoal is removed and transferred to plastic containers. The amount of radon adsorbed on the activated charcoal is determined by gamma spectroscopy. This data is used to calculate the radon flux in units of Bq m^{-2} s^{-1}.

Specificity/Sensitivity: These collectors give an accurate short-term assessment of the radon gas surface emanation rate from a material. The minimum detectable concentration of this method is 0.007 Bq m^{-2} s^{-1} (0.2 pCi m^{-2} s^{-1}).
Exposures greater than 24 hours are not recommended due to atmospheric and surface moisture and temperature extremes which may affect charcoal efficiency.

Cost of Equipment: Not applicable.

Cost per Measurement: $20 - $50 including canister.

B.4.5 X-Ray and low energy gamma detectors

System: FIDLER PROBE WITH SURVEY METER
Lab/Field: Field
Radiation Detected:
Primary: X-ray
Secondary: Low Energy Gamma

Applicability to Site Surveys: The FIDLER (Field Instrument for the Detection of Low Energy Radiation) probe is a specialized detector consisting of a thin layer of sodium or cesium iodide which is optimized to detect gamma and X-radiation below 100 keV. It is most widely used for determining the presence of Pu and ^{241}Am, and can be used for estimating radio-nuclide concentrations in the field.

Operation: The FIDLER consists of a thin beryllium or aluminium window, a thin crystal of sodium iodide, a quartz light pipe, and photomultiplier tube. The probe can have either a 3 in. or 5 in. crystal. The discussion below is applicable to 5 in. crystals. The survey meter requires electronics capable of setting a window about an X-ray or gamma ray energy. This window allows the probe and meter to detect specific energies and, in most cases, provide information about a single element or radionuclide. The window also lowers the background count. Two types of survey meters are generally used with FIDLER probes. One type resembles those used with GM and alpha scintillation probes. They have an analog meter and range switch. The second type is a digital survey meter, which can display the count rate or accumulate counts in a scaler mode for a preset length of time. Both types have adjustable high voltage and window settings. The advantage of the digital meter is that both background and sample counts can be acquired in scaler mode, yielding a net count above background. The activity of a radionuclide can then be estimated in the field.

Specificity/Sensitivity: The FIDLER probe is quite sensitive to X-ray and low energy gamma radiation. Since it has the ability to discriminate energies, an energy window can be set that makes it possible to determine the presence of specific radio-nuclides when the nature of the contamination is known. If the identity of a contaminant is known, the FIDLER can be used to quantitatively determine the concentration. However, interferences can cause erroneous results if other radio-nuclides are present. The FIDLER can also be used as a survey instrument to detect the presence of X-ray or low energy gamma contaminates, and to determine the extent of the contamination. FIDLER probes are most useful for determining the presence of Pu and ^{241}Am.

These isotopes have a complex of X-rays and gamma rays from 13-21 keV that have energies centred around 17 keV, and ^{241}Am has a gamma at 59 keV. There is an interference at 13 keV from both americium and uranium X-rays. The FIDLER cannot distinguish which isotope of Pu is present. ^{241}Am can be identified based on the 59 keV gamma. Typical sensitivities for ^{238}Pu and ^{239}Pu at one foot above the surface of a contaminated area are 500 to 700 and 250 to 350 counts per minute per µCi per square meter (cpm/µCi/m²), respectively. Assuming a soil density of 1.5, uniform contamination of the first 1 mm of soil, and a typical background of 400 counts per minute, the MDC for ^{238}Pu and ^{239}Pu would be 370 and 740 Bq/kg (10 and 20 pCi/g), or 1500 and 3000 Bq/m² (900 and 1,800 dpm/100 cm²). This MDC is for fresh deposition; and will be significantly less as the plutonium migrates into the soil. Because the window is fragile, most operations with a FIDLER probe require a low mass protective cover to prevent damaging the window. Styrofoam, cardboard, and other cushioning materials are common choices for a protective cover.

Cost of Equipment: $4,000 to $7,000.

Cost per Measurement: $10 to $20.

System: FIELD X-RAY FLUORESCENCE SPECTROMETER
Lab/Field: Field
Radiation Detected:
Primary: X-ray and low energy gamma radiation
Secondary: None

Applicability to Site Surveys: The system accurately measures relative concentrations of metal atoms in soil or water samples down to the ppm range.

Operation: This system is a rugged form of X-ray fluorescence system that measures the characteristic X-rays of metals as they are released from excited electron structures. The associated electronic and multi-channel analyzer systems are essentially identical to those used with germanium spectrometry systems. The spectra of characteristic X-rays give information for both quantitative and qualitative analysis; however, most frequently, the systems are only calibrated for relative atomic abundance or percent composition.

Specificity/Sensitivity: This is ideal for cases of contamination by metals that have strong X-ray emissions within 5-100 keV. Application for quantification of the transition metals (in the periodic table) is most common because of the X-ray emissions. Operation of this equipment is possible with only a moderate amount of training. The sensitivity ranges from a few percent to ppm depending on the particular atoms and their characteristic X-rays. When converted to activity concentration, the minimum detectable concentration for ^{238}U is around 1,850 Bq/kg (50 pCi/g) for typical soil matrices.

Cost of Equipment: $15,000 - $75,000 depending on size, speed of operation and auxiliary features employed for automatic analysis of the results.

Cost per Measurement: $200.

B.4.6 Other field survey equipment

System: CHEMICAL SPECIES LASER ABLATION MASS SPECTROMETER
Lab/Field: Field
Radiation Detected: None
Primary:
Secondary:

Applicability to Site Surveys: Chemical Species Laser Ablation Mass Spectrometry has been successfully applied to the analysis of organic and inorganic molecular species in condensed material with high sensitivity and specificity.

Operation: Solids can be converted into aerosol particles which contain much of the molecular species information present in the original material. (One way this is done is by laser excitation of one component of a solid mixture which, when volatilized, carries along the other molecular species without fragmentation.) Aerosol particles can be carried hundreds of feet without significant loss in a confined or directed air stream before analysis by mass spectrometry. Some analytes of interest already exist in the form of aerosol particles. Laser ablation is also preferred over traditional means for the conversion of the aerosol particles into molecular ions for mass spectral analysis. Instrument manufacturers are working with scientists at national laboratories and universities in the development of compact portable laser ablation mass spectrometry instrumentation for field based analyses.

Specificity/Sensitivity: This system can analyze soils and surfaces for organic and inorganic molecular species, with extremely good sensitivity. Environmental concentrations in the range of 10^{-9} - 10^{-14} g/g can be determined, depending on environmental conditions. It is highly effective when used by a skilled operator, but of limited use due to high costs. It may be possible to quantify an individual radio-nuclide if no other nuclides of that isotope are present in the sample matrix. Potential MDC's are $4x10^{-8}$ Bq/kg ($1x10^{-9}$ pCi/g) for ^{238}U, 0.04 Bq/kg (10^{-3} pCi/g) for ^{239}Pu, 4 Bq/kg (1 pCi/g) for ^{137}Cs, and 37 Bq/kg (10 pCi/g) for ^{60}Co.

Cost of Equipment: Very expensive (prototype).

Cost per Measurement: May be comparable to laser ablation inductively coupled plasma atomic emission spectrometry (LA-ICP-AES) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). When using the Atomic Emission Spectrometer, the reported cost is $4,000 per sample, or 80% of conventional sampling and analysis costs. This high cost for conventional samples is partly due to the 2-3 day time to analyze a sample for thorium by conventional methods. When using the mass spectrometer, the time required is about 30 minutes per sample.

System: LA-ICP-AES AND LA-ICP-MS

Lab/Field: Field

Radiation Detected: None

Primary:

Secondary:

Applicability to Site Surveys: LA-ICP-AES and LA-ICP-MS are acronyms for Laser Ablation-Inductively Coupled Plasma-Atomic Emission Spectrometry or Mass Spectrometry. LA-ICP-AES/MS techniques are used to screen/characterize very small samples of soils and concrete (non-destructively) in-situ to determine the level of contamination. It is particularly suited to measuring the surface concentration of uranium and thorium. The unit can assess the concentrations at various depths when lower levels are exposed by some means. It has the advantages of not consuming surface material, providing real time response, reducing sampling and analysis time, and keeping personnel clear of the materials being sampled. The information developed can assist in identifying locations for excavation. It is currently being tested.

Operation: Components of the system include a sampling system, fiber optics cables, spectrometer, potable water supply, cryogenic and high-pressure gas supply, a robotics arm, control computers, inductively coupled plasma torch, and video monitor.

Sampling probes have been developed and prototyped that will screen/characterize surface soils, concrete floors or pads, and subsurface soils. The sampling probes, both surface and subsurface, contain the laser (a 50-Hz Nd/YAG laser), associated optics, and control circuitry to raster the laser (ablation) energy across one square inch of sample surface. Either sampling probe is connected by an umbilical, currently 20 m long, to the Mobile Demonstration Laboratory for Environmental Screening Technologies (MDLEST), a completely self-contained mobile laboratory containing the instrumentation to immediately analyze the samples generated by the laser ablation.

A fiber optic cable delivers laser light to the surface of interest. This ablates a small quantity of material that is carried away in a stream of argon gas. The material enters the plasma torch where it is vaporized, atomized, ionized, and electrically excited at about 8,000 K. This produces an ionic emission spectrum that is analyzed on the atomic emission spectrometer.

The analysis instrumentation (ICP-AES/MS) in the MDLEST does not depend on radioactive decay for detection but looks directly at the atomic make up of the elements(s) of interest. A large number of metals including the longer half-life radioactive elements can be detected and quantified. The spectrometer is set up using either hardware, software, or both to simultaneously detect all elements of interest in each sample.

The MDLEST can be set up on-site to monitor soil treatment processes. This function enables the remediation manager to monitor, in real time, the treatment processes removing the contaminants and ensure that satisfactory agreement with both regulatory agency and quality control/quality assurance requirements is attained.

Specificity/Sensitivity: This system measures the surface or depth concentration of atomic species, and is particularly suited to uranium and thorium analysis. It is highly effective with skilled operators. Some advantages are no contact with the soil, real time results, and no samples to dispose of. The sample results are quickly available for field remediation decisions, with the LA-ICP-AES taking about 10 minutes and LA-ICP-MS taking about 30 minutes. The detection limits for the two spectrometers that have been used are as follows:

1) The AES (atomic emission spectrometer) can see ppm levels for some 70 elements and reportedly detects uranium and thorium concentrations at 1 ppm, or 10 Bq/kg (0.3 pCi/g) for ^{238}U and 0.4 Bq/kg (0.1 pCi/g) for ^{232}Th. However, the technique is only sensitive to elements; it cannot discriminate between the different isotopes of uranium and thorium. This prevents it from being used for assessing lower Z elements that have stable isotopes, or from determining relative abundances of isotopes of any element.

This may significantly limit its use at some sites.

2) The MS (mass spectrometer) can see sub-ppb levels and is capable of quantifying the uranium and thorium isotopes. This system has been used to search for ^{230}Th and ^{226}Ra and is reportedly useful in reaching 0.8 ppm or 0.6 Bq/g (15 pCi/g) for ^{230}Th content for remediated soil. It appears to measure uranium and thorium concentration of soil more sensitively than the LA-ICP-AES system.

Cost of Equipment: Very expensive, >$1M.

Cost per Measurement: When using the Atomic Emission Spectrometer, the reported cost is $4,000 per sample. When using the mass spectrometer, a dollar price was not provided.

B.5 Laboratory instruments

B.5.1 Alpha particle analysis

System: ALPHA SPECTROSCOPY WITH MULTICHANNEL ANALYZER
Lab/Field: Lab
Radiation Detected:
Primary: Alpha
Secondary: None

Applicability to Site Surveys: This is a very powerful tool for accurately identifying and quantifying the activity of multiple alpha-emitting radio-nuclides in a sample of soil, water, air filters, etc. Methods exist for the analyses of most alpha emitting radio-nuclides including uranium, thorium, plutonium, polonium, and americium. Samples must first be prepared in a chemistry lab to isolate the radio-nuclides of interest from the environmental matrix.

Operation: This system consists of an alpha detector housed in a light-tight vacuum chamber, a bias supply, amplifier, analog-to-digital converter, multi-channel analyzer, and computer. The bias is typically 25 to 100 volts. The vacuum is typically less than 10 microns (0.1 millitorr). The detector is a silicon diode that is reverse biased. Alpha particles which strike the diode create electron-hole pairs; the number of pairs is directly related to the energy of each alpha. These pairs cause a breakdown of the diode and a current pulse to flow. The charge is collected by a preamplifier and converted to a voltage pulse which is proportional to the alpha energy. It is amplified and shaped by an amplifier. The MCA stores the resultant pulses and displays a histogram of the number of counts vs. alpha energy. Since most alphas will loose all of their energy to the diode, peaks are seen on the MCA display that can be identified by specific alpha energies. Two system calibrations are necessary. A source with at least two known alpha energies is counted to correlate the voltage pulses with alpha energy. A standard source of known activity is analyzed to determine the system efficiency for detecting alphas. Since the sample and detector are in a vacuum, most commonly encountered alpha energies will be detected with approximately the same efficiency provided there is no self-absorption in the sample. Samples are prepared in a chemistry lab. The sample is placed in solution and the element of interest (uranium, plutonium, etc.) separated. A tracer of known activity is added before separation to determine the overall recovery of the sample from the chemical procedures. The sample is converted to a particulate having very little mass and collected on a special filter, or it is collected from solution by electroplating onto a metal disk. It is then placed in the vacuum chamber at a fixed distance from the diode and analyzed. For environmental levels, samples are typically analyzed for 1000 minutes or more.

Specificity/Sensitivity: The system can accurately identify and quantify the various alpha emitting radioactive isotopes of each elemental species provided each has a different alpha energy that can be resolved by the system. For soils, a radionuclide can be measured below 0.004 Bq/g (0.1 pCi/g). The system is appropriate for all alphas except those from gaseous radio-nuclides.

Cost of Equipment: $10,000 - $100,000 based on the number of detectors and sophistication of the computer and data reduction software. This does not include the cost of equipment for the chemistry lab.

Cost per Measurement: $250-$400 for the first element, $100-200 for each additional element per sample. The additional element cost depends on the separation chemistry involved and may not always be less. $200-$300 additional for a rush analysis.

System: GAS-FLOW PROPORTIONAL COUNTER
Lab/Field: Lab
Radiation Detected:
Primary: Alpha, Beta
Secondary: Gamma

Applicability to Site Surveys: This system can determine the gross alpha or gross beta activity of water, soil, air filters, or swipes. Results can indicate if nuclide-specific analysis is needed.

Operation: The system consists of a gas-flow detector, supporting electronics, and an optional guard detector for reducing background count rate. A thin window can be placed between the gas-flow detector and sample to protect the detector from contamination, or the sample can be placed directly into the detector. Systems with guard detectors operate sample and guard detectors in anti-coincidence mode to reduce the background and MDC. The detector high voltage and discriminator are set to count alpha radiation, beta radiation, or both simultaneously. The alpha and beta operating voltages are determined for each system by placing an alpha source, like ^{230}Th or ^{241}Am, in the detector and increasing the high voltage incrementally until the count rate becomes constant, then repeating with a beta source, like ^{90}Sr. The alpha plateau, or region of constant count rate, should have a slope < 2%/100V and be > 800V long. The beta plateau should have a slope of < 2.5%/100V and be > 200V long. Operation on the beta plateau will also allow detection of some gamma radiation and bremsstrahlung (X-rays), but the efficiency is very low. Crosstalk between the α-to-β channels is typically around 10% while β-to-α channels should be < 1%. The activity in soil samples is chemically extracted, separated if necessary, deposited in a thin layer in a planchet to minimize self absorption, and heated to dryness. Liquids are deposited and dried, while air filters and swipes are placed directly in the planchet. After each sample is placed under the detector, P-10 counting gas constantly flows through the detector. Systems with automatic sample changers can analyze tens to hundreds of planchet samples in a single run.

Specificity/Sensitivity: Natural radio-nuclides present in soil samples can interfere with the detection of other contaminants. Unless the nature of the contaminant and any naturally-occurring radio-nuclides is well known, this system is better used for screening samples. Although it is possible to use a proportional counter to roughly determine the energies of alpha and beta radiation, the normal mode of operation is to detect all alpha events or all alpha and beta events. Some systems use a discriminator to separate alpha and beta events, allowing simultaneous determination of both the alpha and beta activity in a sample. These systems do not identify the alpha or beta energies detected and cannot be used to identify specific radio-nuclides. The alpha channel background is very low, < 0.2 cpm (< 0.04 cpm guarded), depending on detector size. Typical, 4-pi, efficiencies for very thin alpha sources are 35-45% (window) and 40-50% (windowless). Efficiency depends on window thickness, particle energy, source-detector geometry, backscatter from the sample and holder, and detector size. The beta channel background ranges from 2 to 15 cpm (< 0.5 cpm guarded). The 4-pi efficiency for a thin $^{90}Sr/^{90}Y$ source is > 50% (window) to > 60% (windowless), but can reduce to < 5% for a thick source. MDA's for guarded gas-flow proportional counters are somewhat lower for beta emitters than for internal proportional counters because of the lower backgrounds. Analyzing a high radioactivity sample or flushing the detector with P-10 gas at too high a flow rate can suspend fine particles and contaminate the detector.

Cost of Equipment: $4K-$5K (manual), $25K-$30K (automatic).

Cost per Measurement: $30 to $50 plus radiochemistry.

System: LIQUID SCINTILLATION SPECTROMETER (LSC)
Lab/Field: Lab (primarily), field (secondarily)
Radiation Detected:
Primary: Alpha, beta
Secondary: Gamma

Applicability to Site Surveys: Liquid Scintillation can be a very effective tool for measuring the concentration of radio-nuclides in soil, water, air filters, and swipes. Liquid scintillation has historically been applied more to beta emitters, particularly the low energy beta emitters ^{3}H and ^{14}C, but it can also apply to other radio-nuclides. More recently it has been used for measuring radon in air and water. Initial scoping surveys may be done (particularly for loose surface contamination) with surface swipes or air particulate filters. They may be counted directly in liquid scintillation cocktails with no paper dissolution or other sample preparation.

Operation: The liquid scintillation process involves detection of light pulses (usually in the near visible range) by photo-multiplier tubes (or conceptually similar devices). The detected light pulses originate from the re-structuring of previously excited molecular electron structures. The molecular species that first absorb and then re-admit the visible light are called 'liquid scintillators' and the solutions in which they reside are called 'liquid scintillation cocktails'. For gross counting, samples may be placed directly into a LSC vial of cocktail, and counted with no preparation. Inaccuracies result when the sample itself absorbs the radiation before it can reach the LSC cocktail, or when the sample absorbs the light produced by the cocktail. For accurate results, these interferences are minimized. Interferences in liquid scintillation counting due to the inability of the solution to deliver the full energy pulse to the photo-multiplier detector, for a variety of reasons, are called 'pulse quenching'. Raw samples that cloud or colour the LSC cocktail so that the resulting scintillations are absorbed will 'quench' the sample and result in underestimates of the activity. Such samples are first processed by ashing, radiochemical or solvent extraction, or pulverizing to place the sample in intimate contact with the LSC cocktail. Actions like bleaching the sample may also be necessary to make the cocktail solution transparent to the wavelength of light it emits. The analyst has several reliable computational or experimental procedures to account for 'quenching'. One is by exposing the sample and pure cocktail to an external radioactive standard and measuring the difference in response.

Specificity/Sensitivity: The method is extremely flexible and accurate when used with proper calibration and compensation for quenching effects. Energy spectra are 10 to 100 times broader than gamma spectrum photo-peaks so that quantitative determination of complex multi-energy beta spectra is impossible. Sample preparation can range from none to complex chemical reactions. In some cases, liquid scintillation offers many unique advantages; no sample preparation before counting in contrast to conventional sample preparation for gas proportional counting. Recent advances in electronic stability and energy pulse shape discrimination has greatly expanded uses. Liquid scintillation counters are ideal instruments for moderate to high energy beta as well as alpha emitters, where the use of pulse shape discrimination has allowed dramatic increases in sensitivity by electronic discrimination against beta and gamma emitters. Additionally, very high energy beta emitters (above 1.5 MeV) may be counted using liquid scintillation equipment without 'liquid scintillation cocktails' by use of the Cerenkov light pulse emitted as high energy charged particles move through water or similar substances.

Cost of Equipment: $20,000 to $70,000 based on the specific features and degree of automation.

Cost per Measurement: $50 -200 plus cost of chemical separation, if required.

System: LOW-RESOLUTION ALPHA SPECTROSCOPY
Lab/Field: Lab (Soil Samples)
Radiation Detected:
Primary: Alpha
Secondary:

Applicability to Site Surveys: Low-resolution alpha spectroscopy is a method for measuring alpha activity in soils with a minimum of sample preparation. Some isotopic information can be obtained.

Operation: The system consists of a 2 in. diameter silicon detector, small vacuum chamber, roughing pump, multi-channel analyzer, laptop or bench-top computer, and analysis software. Soil samples are dried, milled to improve homogeneity, distributed into 2 in. planchets, loaded into the vacuum chamber, and counted. The accumulated alpha spectrum is displayed in real time. When sufficient counts have been accumulated, the spectrum is transferred to a data file and the operator inputs the known or suspected contaminant isotopes. The analysis software then fits the alpha spectrum with a set of trapezoidal peaks, one for each isotope, and outputs an estimate of the specific activity of each isotope.

Specificity/Sensitivity: This method fills the gap between gross alpha analysis and radiochemical separation/high-resolution alpha spectroscopy. Unlike gross alpha analysis, it does provide some isotopic information. Because this is a low-resolution technique, isotopes with energies closer than -0.2 MeV cannot be separated. For example, ^{238}U (4.20 MeV) can be readily distinguished from ^{234}U (4.78 MeV), but ^{230}Th (4.69 MeV) cannot be distinguished from ^{234}U.
Because no chemical separation of isotopes is involved, only modest MDC's can be achieved. Detection limits are determined by the background alpha activity in the region of interest of the contaminant of concern, and also by the counting time. Typical MDC's are 1,500 Bq/kg (40 pCi/g) @ l5 min counting time, 260 Bq/kg (7 pCi/g) @ 8 hours, and 185 Bq/kg (5 pCi/g) @ 24 hours. The method does not generate any new waste streams and does not require a sophisticated laboratory or highly-trained personnel.

Cost of Equipment: $11,000.

Cost per Measurement: $25-$100.

B.5.2 Beta particle analysis

System: GAS-FLOW PROPORTIONAL COUNTER
Lab/Field: Lab
Radiation Detected:
Primary: Alpha, Beta
Secondary: Gamma

Applicability to Site Surveys: This system can determine the gross alpha or gross beta activity of water, soil, air filters, or swipes. Results can indicate if nuclide-specific analysis is needed.

Operation: The system consists of a gas-flow detector, supporting electronics, and an optional guard detector for reducing background count rate. A thin window can be placed between the gas-flow detector and sample to protect the detector from contamination, or the sample can be placed directly into the detector. Systems with guard detectors operate sample and guard detectors in anti-coincidence mode to reduce the background and MDC. The detector high voltage and discriminator are set to count alpha radiation, beta radiation, or both simultaneously. The alpha and beta operating voltages are determined for each system by placing an alpha source, like ^{230}Th or ^{241}Am, in the detector and increasing the high voltage incrementally until the count rate becomes constant, then repeating with a beta source, like ^{90}Sr. The alpha plateau, or region of constant count rate, should have a slope < 2%/100V and be > 800V long. The beta plateau should have a slope of < 2.5%/100V and be > 200V long. Operation on the beta plateau will also allow detection of some gamma radiation and bremsstrahlung (X-rays), but the efficiency is very low. Crosstalk between the α-to-β channels is typically around 10% while β-to-α channels should be < 1%. The activity in soil samples is chemically extracted, separated if necessary, deposited in a thin layer in a planchet to minimize self absorption, and heated to dryness. Liquids are deposited and dried, while air filters and swipes are placed directly in the planchet. After each sample is placed under the detector, P-10 counting gas constantly flows through the detector. Systems with automatic sample changers can analyze tens to hundreds of planchet samples in a single run.

Specificity/Sensitivity: Natural radio-nuclides present in soil samples can interfere with the detection of other contaminants. Unless the nature of the contaminant and any naturally-occurring radio-nuclides is well known, this system is better used for screening samples. Although it is possible to use a proportional counter to roughly determine the energies of alpha and beta radiation, the normal mode of operation is to detect all alpha events or all alpha and beta events. Some systems use a discriminator to separate alpha and beta events, allowing simultaneous determination of both the alpha and beta activity in a sample. These systems do not identify the alpha or beta energies detected and cannot be used to identify specific radio-nuclides. The alpha channel background is very low, < 0.2 cpm (< 0.04 cpm guarded), depending on detector size. Typical, 4-pi, efficiencies for very thin alpha sources are 35-45% (window) and 40-50% (windowless). Efficiency depends on window thickness, particle energy, source-detector geometry, backscatter from the sample and holder, and detector size. The beta channel background ranges from 2 to 15 cpm (< 0.5 cpm guarded). The 4-pi efficiency for a thin ^{90}Sr/^{90}Y source is >50% (window) to >60% (windowless), but can reduce to <5% for a thick source. MDA's for guarded gas-flow proportional counters are somewhat lower for beta emitters than for internal proportional counters because of the lower backgrounds. Analyzing a high radioactivity sample or flushing the detector with P-10 gas at too high a flow rate can suspend fine particles and contaminate the detector.

Cost of Equipment: $4K-$5K (manual), $25K-$30K (automatic).

Cost per Measurement: $30 to $50 plus radiochemistry.

System: LIQUID SCINTILLATION SPECTROMETER (LSC)
Lab/Field: Lab (primarily), field (secondarily)
Radiation Detected:
Primary: Alpha, beta
Secondary: Gamma

Applicability to Site Surveys: Liquid Scintillation can be a very effective tool for measuring the concentration of radio-nuclides in soil, water, air filters, and swipes. Liquid scintillation has historically been applied more to beta emitters, particularly the low energy beta emitters ^{3}H and ^{14}C, but it can also apply to other radio-nuclides. More recently it has been used for measuring radon in air and water. Initial scoping surveys may be done (particularly for loose surface contamination) with surface swipes or air particulate filters. They may be counted directly in liquid scintillation cocktails with no paper dissolution or other sample preparation.

Operation: The liquid scintillation process involves detection of light pulses (usually in the near visible range) by photo-multiplier tubes (or conceptually similar devices). The detected light pulses originate from the re-structuring of previously excited molecular electron structures. The molecular species that first absorb and then re-admit the visible light are called ‘liquid scintillators’ and the solutions in which they reside are called ‘liquid scintillation cocktails’. For gross counting, samples may be placed directly into a LSC vial of cocktail, and counted with no preparation. Inaccuracies result when the sample itself absorbs the radiation before it can reach the LSC cocktail, or when the sample absorbs the light produced by the cocktail. For accurate results, these interferences are minimized. Interferences in liquid scintillation counting due to the inability of the solution to deliver the full energy pulse to the photo-multiplier detector, for a variety of reasons, are called ‘pulse quenching’. Raw samples that cloud or colour the LSC cocktail so that the resulting scintillations are absorbed will ‘quench’ the sample and result in underestimates of the activity. Such samples are first processed by ashing, radiochemical or solvent extraction, or pulverizing to place the sample in intimate contact with the LSC cocktail. Actions like bleaching the sample may also be necessary to make the cocktail solution transparent to the wavelength of light it emits. The analyst has several reliable computational or experimental procedures to account for ‘quenching’. One is by exposing the sample and pure cocktail to an external radioactive standard and measuring the difference in response.

Specificity/Sensitivity: The method is extremely flexible and accurate when used with proper calibration and compensation for quenching effects. Energy spectra are 10 to 100 times broader than gamma spectrum photo-peaks so that quantitative determination of complex multi-energy beta spectra is impossible. Sample preparation can range from none to complex chemical reactions. In some cases, liquid scintillation offers many unique advantages such as no sample preparation before counting in contrast to conventional sample preparation for gas proportional counting. Recent advances in electronic stability and energy pulse shape discrimination has greatly expanded uses. Liquid scintillation counters are ideal instruments for moderate to high energy beta as well as alpha emitters, where the use of pulse shape discrimination has allowed dramatic increases in sensitivity by electronic discrimination against beta and gamma emitters. Additionally, very high energy beta emitters (above 1.5 MeV) may be counted using liquid scintillation equipment without ‘liquid scintillation cocktails’ by use of the Cerenkov light pulse emitted as high energy charged particles move through water or similar substances.

Cost of Equipment: \$20,000 to \$70,000 based on the specific features and degree of automation.

Cost per Measurement: \$50 -200 plus cost of chemical separation, if required.

B.5.3 Gamma ray analysis

System: GERMANIUM DETECTOR WITH MULTICHANNEL ANALYZER (MCA)
Lab/Field: Lab
Radiation Detected:
Primary: Gamma
Secondary: None

Applicability to Site Surveys: This system accurately measures the activity of gamma-emitting radio-nuclides in a variety of materials like soil, water, air filters, etc. with little preparation. Germanium is especially powerful in dealing with multiple radio-nuclides and complicated spectra.

Operation: This system consists of a germanium detector connected to a dewar of liquid nitrogen, high voltage power supply, spectroscopy grade amplifier, analog to digital converter, and a multi-channel analyzer. P-type germanium detectors typically operate from +2000 to +5000 volts. N-type germanium detectors operate from -2000 to -5000 volts. Germanium is a semiconductor material. When a gamma ray interacts with a germanium crystal, it produces electron-hole pairs. An electric field is applied which causes the electrons to move in the conduction band and the holes to pass the charge from atom to neighbouring atom. The charge is collected rapidly and is proportional to the deposited energy. The count rate/energy spectrum is displayed on the MCA screen with the full energy photo-peaks providing more useful information than the general smear of Compton scattering events shown in between. The system is energy calibrated using isotopes that emit at least two known gamma ray energies, so the MCA data channels are given an energy equivalence. The MCA's display then becomes a display of intensity versus energy. Efficiency calibration is performed using known concentrations of mixed isotopes. A curve of gamma ray energy versus counting efficiency is generated, and it shows that P-type germanium is most sensitive at 120 keV and trails off to either side. Since the counting efficiency depends on the distance from the sample to the detector, each geometry must be given a separate efficiency calibration curve. From that point the centre of each gaussian shaped peak tells the gamma ray energy that produced it, the combination of peaks identifies each isotope, and the area under selected peaks is a measure of the amount of that isotope in the sample. Samples are placed in containers and tare weighed. Plastic petri dishes sit atop the detector and are useful for small volumes or low energies, while Marinelli beakers fit around the detector and provide exceptional counting efficiency for volume samples. Counting times of 1000 seconds to 1000 minutes are typical. Each peak is identified manually or by gamma spectrometry analysis software. The counts in each peak or energy band, the sample weight, the efficiency calibration curve, and the isotope decay scheme are factored together to give the sample concentration.

Specificity/Sensitivity: The system accurately identifies and quantifies the concentrations of multiple gamma-emitting radio-nuclides in samples like soil, water, and air filters with minimum preparation. A P-type detector is good for energies over 50 keV. An N-type or P-type planar (thin crystal) detector with beryllium-end window is good for 5-80 keV energies using a thinner sample placed over the window.

Cost of Equipment: $35,000 to $150,000 based on detector efficiency and sophistication of MCA/computer/software system.

Cost per Measurement: $ 100 to $200 (rush requests can double or triple costs).

System: SODIUM IODIDE DETECTOR WITH MULTICHANNEL ANALYZER
Lab/Field: Lab
Radiation Detected:
Primary: Gamma
Secondary: None

Applicability to Site Surveys: This system accurately measures the activity of gamma-emitting radio-nuclides in a variety of materials like soil, water, air filters, etc. with little preparation. Sodium iodide is inherently more efficient for detecting gamma rays but has lower resolution than germanium, particularly if multiple radio-nuclides and complicated spectra are involved.

Operation: This system consists of a sodium iodide detector, a high voltage power supply, an amplifier, an analog to digital converter, and a multi-channel analyzer. The detector is a sodium iodide crystal connected to a photomultiplier tube (PMT). Crystal shapes can vary extensively and typical detector high voltages are 900-1,000 V. Sodium iodide is a scintillation material. A gamma ray interacting with a sodium iodide crystal produces light which is passed to the PMT. This light ejects electrons which the PMT multiplies into a pulse that is proportional to the energy the gamma ray imparted to the crystal. The MCA assesses the pulse size and places a count in the corresponding channel. The count rate and energy spectrum is displayed on the MCA screen with the full energy photo-peaks providing more useful information than the general smear of Compton scattering events shown in between. The system is energy calibrated using isotopes that emit at least two gamma ray energies, so the MCA data channels are given an energy equivalence. The MCA's CRT then becomes a display of intensity versus energy. A non-linear energy response and lower resolution make isotopic identification less precise than with a germanium detector. Efficiency calibration is performed using known concentrations of single or mixed isotopes. The single isotope method develops a count rate to activity factor. The mixed isotope method produces a gamma ray energy versus counting efficiency curve that shows that sodium iodide is most sensitive around 100-120 keV and trails off to either side. Counting efficiency is a function of sample to detector distance, so each geometry must have a separate efficiency calibration curve. The centre of each peak tells the gamma ray energy that produced it and the combination of peaks identifies each isotope. Although the area under a peak relates to that isotope's activity in the sample, integrating a band of channels often provides better sensitivity. Samples are placed in containers and tare weighed. Plastic petri dishes sit atop the detector and are useful for small volumes or low energies, while Marinelli beakers fit around the detector and provide exceptional counting efficiency for volume samples. Counting times of 60 seconds to 1,000 minutes are typical. The CRT display is scanned and each peak is identified by isotope. The counts in each peak or energy band, the sample weight, the efficiency calibration curve, and the isotope decay scheme are factored together to give the sample concentration.

Specificity/Sensitivity: This system analyzes gamma-emitting isotopes with minimum preparation, better efficiency, but lower resolution compared to most germanium detectors. Germanium detectors do reach efficiencies of 150% compared with a 3 in. by 3 in. sodium iodide detector, but the cost is around $100,000 each compared with $3,000. Sodium iodide measures energies over 80 keV. The instrument response is energy dependent, the resolution is not superb, and the energy calibration is not totally linear, so care should be taken when identifying or quantifying multiple isotopes. Computer software can help interpret complicated spectra. Sodium iodide is fragile and should be protected from shock and sudden temperature changes.

Cost of Equipment: $6K-$20K.

Cost per Measurement: $100-$200 per sample.

B.6 Equipment summary tables

Table B.1 Radiation detectors with applications to alpha surveys

System	Description	Application	Remarks	Equipment cost	Measurement cost
Alpha spectroscopy	A system using silicon diode surface barrier detectors for alpha energy identification and quantification.	Accurately identifies and measures the activity of multiple alpha radio-nuclides in a thin extracted sample of soil, water, or air filters.	Sample requires radiochemical separation or other preparation before counting.	\$10K-\$100K	\$250-\$400
Alpha scintillation survey meter	< 1 mg/cm² window, probe face area 50 to 100 cm².	Field measurement of presence or absence of alpha contamination on non-porous surfaces, swipes, and air filters, or on irregular surfaces if the degree of surface shielding is known.	Minimum sensitivity is 10 cpm, or 1 cpm with headphones.	\$1000	\$5
Alpha track detector	Polycarbonate plastic sheet is placed in contact with a contaminated surface and kept in place.	Measures gross alpha surface contamination, soil activity level, or the depth profile of contamination.	Alpha radiation produces holes that are enlarged chemically. Density of holes gives a measure of the radioactivity level.		\$5-\$25
Electret ion chamber	A charged teflon disk in an open-faced ion chamber.	Measures alpha or beta contamination on surfaces and in soils, plus gamma radiation dose or radon concentration.	The type of radiation is determined by how the electret is employed, e.g., the unit is kept closed and bagged in plastic to measure gammas.	\$4,000-\$5,000	\$8-\$25
Long range alpha detector (LRAD)	1m x 1m detector measures ionization inside the box. Attached to tractor for movement. Has location finder and plots graph of contamination.	Measures surface contamination or soil concentration at grid points and plots curves of constant contamination. Intended for large areas.	Alpha detection limit is 20-50 dpm/100 cm² or 0.4 Bq/g (10 pCi/g).	\$25,000	\$80
Gas-flow proportional counter (field)	A detector through which P10 gas flows and which measures alpha and beta radiation. < 1-10 mg/cm² window, probe face area 50 to 100 cm² for hand held detectors; up to 600 cm² if cart mounted.	Surface scanning, surface activity measurement, or field evaluation of swipes. Serves as a screen to determine if more nuclide-specific analyses are needed.	Natural radio-nuclides in samples can interfere with the detection of other contaminants. Requires P10 gas.	\$2K-\$4K	\$2-\$10/m²
Gas-flow proportion-counter (lab)	Windowless (internal proportional) or window < 0.1 mg/cm^2, probe face area 10 to 20 cm^2. May have a second or guard detector to reduce background and MDA.	Laboratory measurement of water, air, and swipe samples.	Requires P10 gas. Windowless detectors can be contaminated.	\$4K-\$30K	\$50
Liquid scintillation counter (LSC)	Samples are mixed with LSC cocktail and the radiation emitted causes light pulses with proportional intensity.	Laboratory analysis of alpha or beta emitters, including spectrometry capabilities.	Highly selective for alpha or beta radiation by pulse shape discrimination. Requires LSC cocktail.	\$20K-\$70K	\$50-\$200

Table B.2 Radiation detectors with applications to beta surveys

System	Description	Application	Remarks	Equipment cost	Measurement cost
GM survey meter with beta pancake probe	Thin 1.4 mg/cm² window detector, probe area 10 to 100 cm².	Surface scanning of personnel, working areas, equipment, and swipes for beta contamination. Laboratory measurement of swipes when connected to a scaler.	Relatively high detection limit making it of limited value in final status surveys.	\$400-\$1,500	\$5-\$10
Gas-flow proportional counter (field)	A detector through which P10 gas flows and which measures alpha and beta radiation. < 1-10 mg/cm² window, probe face area 50 to 100 cm².	Surface scanning, surface activity measurement, or field evaluation of swipes. Serves as a screen to determine if more nuclide-specific analyses are needed.	Natural radio-nuclides in samples can interfere with the detection of other contaminants. Requires P10 gas, but can be disconnected for hours.	\$2K-\$4K	\$2-\$10/m²
Gas-flow proportional counter (lab)	Windowless (internal proportional) or window < 0.1 mg/cm², probe face area 10 to 20 cm². May have a second or guard detector to reduce background and MDA.	Laboratory measurement of water, air, and swipe samples.	Requires P10 gas. Windowless detectors can be contaminated.	\$4K-\$30K	\$50
Liquid scintillation counter (LSC)	Samples are mixed with LSC cocktail and the radiation emitted causes light pulses with proportional intensity.	Laboratory analysis of alpha and beta emitters, including spectrometry capabilities.	Highly selective for α and β radiation by pulse shape discrimination. Requires LSC cocktail.	\$20K-\$70K	\$100-\$200

Table B.3 Radiation detectors with applications to X-ray and gamma surveys

System	Description	Application	Remarks	Equipment cost	Measurement cost
GM survey meter with gamma probe	Thick-walled 30 mg/cm² detector.	Measure radiation levels above 0.1 mR/hr.	Its non-linear energy response can be corrected by using an energy compensated probe.	\$400-\$1,000	\$5
Pressurized ionization chamber (PIC)	A highly accurate ionization chamber that is rugged and stable.	Excellent for measuring gamma exposure rate during site remediation.	Is used in conjunction with radio-nuclide identification equipment.	\$15K -\$50K	\$50 -\$500
Electret ion chamber	Electrostatically charged disk inside an ion chamber.	Gamma exposure rate.	N/A, rented.	Included in rental price	\$8 -\$25
Hand-held ion chamber survey meter	Ion chamber for measuring higher radiation levels than typical background.	Measures true gamma exposure rate.	Not very useful for site surveys because of high detection limit above background levels.	\$800-\$1,200	\$5
Hand-held pressurized ion chamber survey meter	Ion chamber for measuring higher radiation levels than typical background.	Measures true gamma exposure rate with more sensitivity than the un-pressurized ion chamber.	Not very useful for site surveys because of high detection limit above background levels.	\$1,000-\$1,500	\$5
Sodium iodide survey meter	Detectors sizes up to 8"x8". Used in micro R-meter in smaller sizes.	Measures low levels of environmental radiation.	Its energy response is not linear, so it should be calibrated for the energy field it will measure or have calibration factors developed by comparison with a PIC for a specific site.	\$2K	\$5
FIDLER (Field Instrument for Detection of Low Energy Radiation)	Thin crystals of NaI or CsI.	Scanning of gamma/X-radiation from plutonium and americium.		\$6K-\$7K	\$10-\$20
Sodium iodide detector with multi-channel analyzer (MCA)	Sodium iodide crystal with a large range of sizes and shapes, connected to a photomultiplier tube and MCA.	Laboratory gamma spectroscopy to determine the identity and concentration of gamma emitting radio-nuclides in a sample.	Sensitive for surface soil or groundwater contamination. Analysis programs have difficulty if sample contains more than a few isotopes.	\$6K-\$20K	\$100 to \$200
Germanium detector with multi-channel analyzer (MCA)	Intrinsic germanium semiconductor in p-or n-type configuration and without a beryllium window.	Laboratory gamma spectroscopy to determine the identity and concentration of gamma emitting radio-nuclides in a sample.	Very sensitive for surface soil or groundwater contamination. Is especially powerful when more than one radionuclide is present in a sample.	\$35K-\$150K	\$100 to \$200
Portable germanium multi-channel analyzer (MCA)	A portable version of a laboratory based germanium detector and multi-channel analyzer.	Excellent during characterization through final status survey to identify and quantify the concentration of gamma ray emitting radio-nuclides and in-situ concentrations of soil and other media.	Requires a supply of liquid nitrogen or a mechanical cooling system, as well as highly trained operators.	\$40K	\$100
Field X-ray fluorescence spectrometer	Uses silicon or germanium semiconductor.	Determining fractional abundance of low percentage metal atoms.		\$15K-\$75K	\$200
Thermo-luminescence dosimeters (TLDs)	Crystals sensitive to gamma radiation.	Measure cumulative radiation dose over a period of days to months.	Requires special calibration to achieve high accuracy and reproducibility of results.	\$5K-\$50K for reader + \$25-\$40 per TLD	\$25-\$125

Table B.4 Radiation detectors with applications to radon surveys

System	Description	Application	Remarks	Equipment cost	Measurement cost
Large area activated charcoal collector	A canister containing activated charcoal is twisted into the surface and left for 24 hours.	Short term radon flux measurements.	The LLD is 0.007 Bq m^{-2} s^{-1} (0.2 pCi $m^{-2}s^{-1}$).	N/A, rented.	\$20-\$50 including canister.
Continuous radon monitor	Air pump and scintillation cell or ionization chamber.	Track the real time concentration of radon.	Takes 1 to 4 hours for system to equilibrate before starting. LLD is 0.004-0.04 Bq/l (0.1-1.0 pCi/l).	\$1K-\$5K	\$80
Activated charcoal adsorption	Activated charcoal is opened to the ambient air; then gamma counted on a gamma scintillator or in a liquid scintillation counter.	Measure radon concentration in indoor air.	Detector is deployed for 2 to 7 days. LLD is 0.007-0.04 Bq/l (0.2 to 1.0 pCi/l).	\$10K-\$30K	\$5-\$30 including canister if outsourced.
Electret ion chamber	This is a charged plastic vessel that can be opened for air to pass into.	Measure short-term or long-term radon concentration in indoor air.	Must correct reading for gamma background concentration. Electret is sensitive to extremes of temperature and humidity. LLD is 0.007-0.02 Bq/l (0.2-0.5 pCi/l).	N/A, rented.	\$8-\$25 for rental.
Alpha track detection	A small piece of special plastic or film inside a small container. Damage tracks from alpha particles are chemically etched and tracks counted.	Measure indoor or outdoor radon concentration in air.	LLD is 0.04 Bq $l^{-1}d^{-1}$ (1 pCi $l^{-1}d^{-1}$).		\$5-\$25

Table B.5 Systems that measure atomic mass or emissions

System	Description	Application	Remarks	Equipment cost	Measurement cost
LA-ICP-AES (Laser Ablation Inductively Coupled Plasma Atomic Emissions Spectrometer)	Vaporizes and ionizes the surface material, and measures emissions from the resulting atoms.	Live time analysis of radioactive U and Th contamination in the field.	Requires expensive equipment and skilled operators. LLD is 0.004 Bq/g (0.1 pCi/g) for ^{232}Th and 0.01 Bq/g (0.3 pCi/g) for ^{238}U.	> $1,000,000	$4,000
LA-ICP-MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometer)	Vaporizes and ionizes the surface material, then measures the mass of the resulting atoms.	Live time analysis of radioactive U and Th contamination in the field.	Requires expensive equipment and skilled operators. More sensitive than LA-ICP-AES. LLD is 0.6 Bq/g (15 pCi/g) for ^{230}Th.	> $1,000,000	> $4,000
Chemical speciation laser ablation/mass spectrometer	A laser changes the sample into an aerosol that it analyzed with a mass spectrometer.	Analyze organic and inorganic species with high sensitivity and specificity.	Volatilized samples can be carried hundreds of feet to the analysis area.	> $1,000,000	> $4,000

Appendix C: Derivation of the alpha scanning detection limit calculations

For alpha survey instrumentation with a background around one to three counts per minute, a single count will give a surveyor sufficient cause to stop and investigate further. Assuming this to be true, the probability of detecting given levels of alpha emitting radio-nuclides can be calculated by use of Poisson summation statistics.

Discussion

Experiments yielding numerical values for a random variable X, where X represents the number of events occurring during a given time interval or a specified region in space, are often called Poisson experiments [137]. The probability distribution of the Poisson random variable X, representing the number of events occurring in a given time interval t, is given by:

$$P(x; \lambda t) = \frac{e^{-\lambda t} (\lambda t)^x}{x!}, x = 0, 1, 2, ... \quad \text{(C-1)}$$

where:

P(x; λt) = probability of x events in time interval t

λ = Average number of events per unit time

λt = Average value expected

To define this distribution for an alpha scanning system, substitutions may be made giving:

$$P(n; m) = \frac{e^{-m} (m)^n}{n!} \quad \text{(C-2)}$$

where:

P(n; m) = probability of getting n counts when the average number expected is m

m = λt, average number of counts expected

n = x, number of counts actually detected

For a given detector size, source activity, and scanning rate, the probability of getting n counts while passing over the source activity with the detector can be written as:

$$P(n; m) = \frac{e^{-(GEd/60v)} (GEd/60v)^n}{n!} = \frac{e^{-(GEt/60)} (GEt/60)^n}{n!} \quad \text{(C-3)}$$

where:

G = source activity (dpm)

E = detector efficiency (4π)

d = width of the detector in the direction of scan (cm)

v = scan speed (cm/s)

t = d/v, dwell time over source (s)

If it is assumed that the detector background is equal to zero, then the probability of observing greater than or equal to 1 count, $P(n \geq 1)$, within a time interval t is:

$$P(n \geq 1) = 1 - P(n = 0) \quad \text{(C-4)}$$

If it is also assumed that a single count is sufficient to cause a surveyor to stop and investigate further, then:

$$P(n \geq 1) = 1 - P(n = 0) = 1 - e^{-(GEd/60v)} \qquad \text{(C-5)}$$

Figure C.1, Figure C.2 and Figure C.3 show this function plotted for three different detector sizes and four different source activity levels. Note that the source activity levels are given in terms of areal activity values (dpm per 100 cm^2), the probe sizes are the dimensions of the probes in line with the direction of scanning, and the detection efficiency has been assumed to be 15%. The assumption is made that the areal activity is contained within a 100 cm^2 area and that the detector completely passes over the area either in one or multiple passes.

Once a count has been recorded and the surveyor stops, the surveyor should wait a sufficient period of time such that, if the guideline level of contamination is present, the probability of getting another count is at least 90%. This minimum time interval can be calculated for given contamination guideline values by substituting the following parameters into Equation C-5 and solving:

$P(\geq 1)$ = 0.9

d/v = t

G = CA/100

where:

C = contamination guideline (dpm/100 cm^2)

A = detector area (cm^2)

Giving:

$$T = 13800/CAE \qquad \text{(C-6)}$$

Equation C-3 can be solved to give the probability of getting any number of counts while passing over the source area, although the solutions can become long and complex. Many portable proportional counters have background count rates on the order of 5 to 10 counts per minute and a single count will not give a surveyor cause to stop and investigate further. If a surveyor did stop for every count, and subsequently waited a sufficiently long period of time to make sure that the previous count either was or was not caused by an elevated contamination level, little or no progress would be made. For these types of instruments, the surveyor usually will need to get at least 2 counts while passing over the source area before stopping for further investigation. Assuming this to be a valid assumption, Equation C-3 can be solved for $n \geq 2$ as follows:

$$\begin{aligned} P(n \geq 2) &= 1 - P(n = 0) - P(n = 1) \\ &= 1 - e^{-(GE + B)t/60} - ((GE + B)t/60)e^{-(GE + B)t/60} \qquad \text{(C-7)} \\ &= 1 - e^{-(GE + B)t/60} (1 + (GE + B)t/60) \end{aligned}$$

where:

$P(n \geq 2)$ = probability of getting 2 or more counts during the time interval t

$P(n = 0)$ = probability of not getting any counts during the time interval t

$P(n = 1)$ = probability of getting 1 count during the time interval t

B = background count rate (cpm)

All other variables are the same as in Equation C-3.

Figure C.4, Figure C.5 and Figure C.6 show this function plotted for three different probe sizes and three different source activity levels. The same assumptions were made when calculating these curves as were made for Figure C.1, Figure C.2 and Figure C.3 except that the background was assumed to be 7 counts per minute.

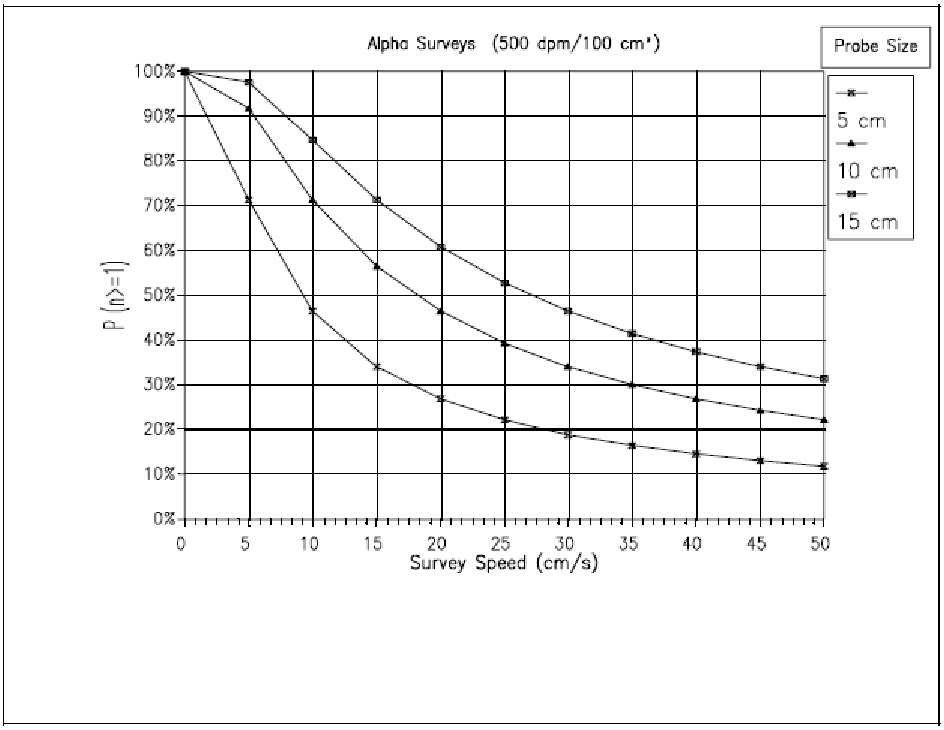


Figure C.1 Probability (P) of getting one or more counts when passing over a 100 cm^2 area contaminated at 500 dpm/100 cm^2 alpha. The chart shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimensions of the probes which are in line with the direction of scanning. A detection efficiency of 15% (4π) is assumed

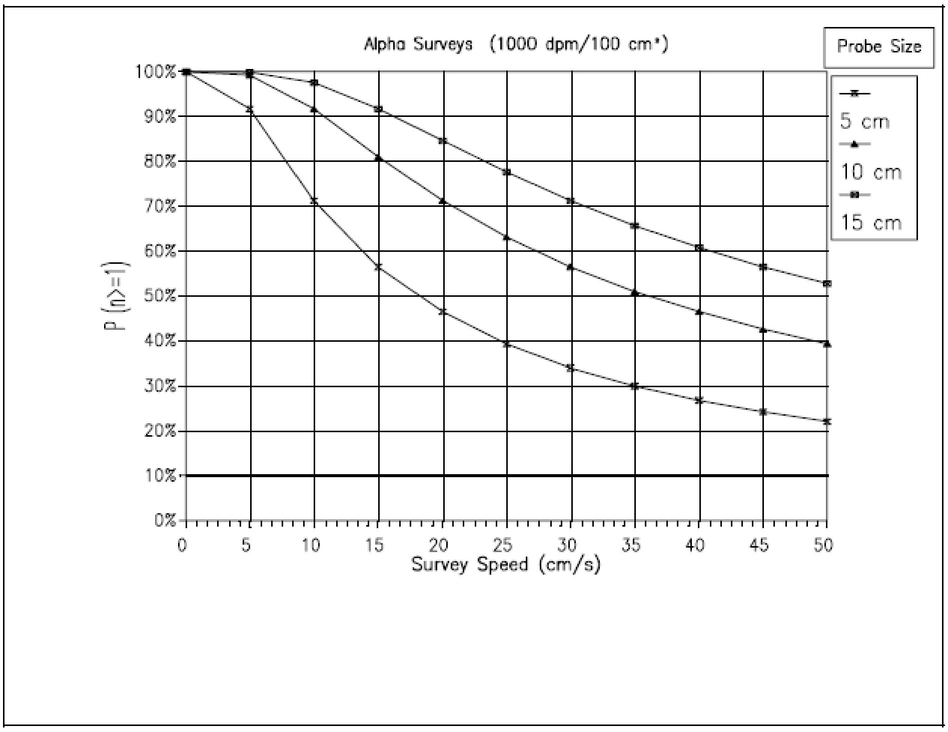


Figure C.2 Probability (P) of getting one or more counts when passing over a 100 cm^2 area contaminated at 1,000 dpm/100 cm^2 alpha. The chart shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimensions of the probes which are in line with the direction of scanning. A detection efficiency of 15% (4π) is assumed

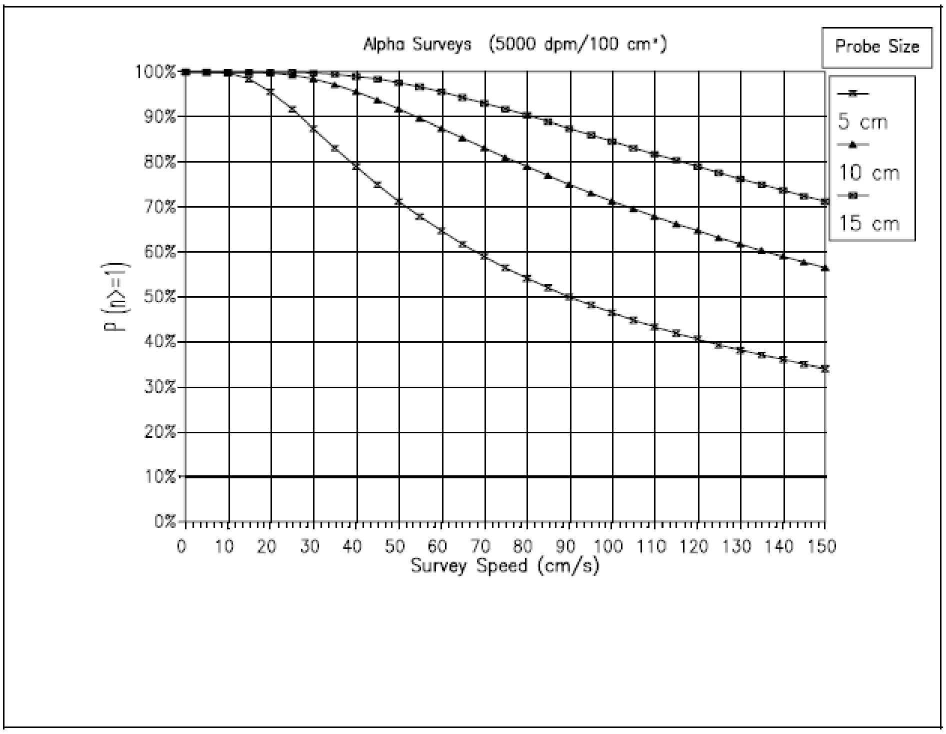


Figure C.3 Probability (P) of getting one or more counts when passing over a 100 cm^2 area contaminated at 5,000 dpm/100 cm^2 alpha. The chart shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimensions of the probes which are in line with the direction of scanning. A detection efficiency of 15% (4π) is assumed

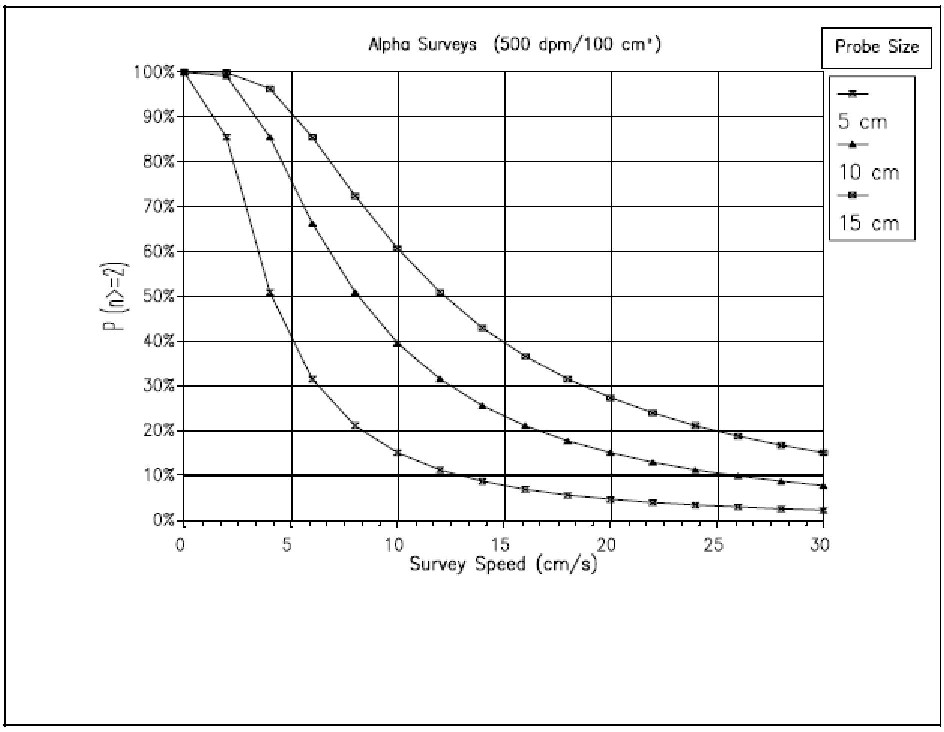


Figure C.4 Probability (P) of getting two or more counts when passing over a 100 cm^2 area contaminated at 500 dpm/100 cm^2 alpha. The chart shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimensions of the probes which are in line with the direction of scanning. A detection efficiency of 15% (4π) is assumed

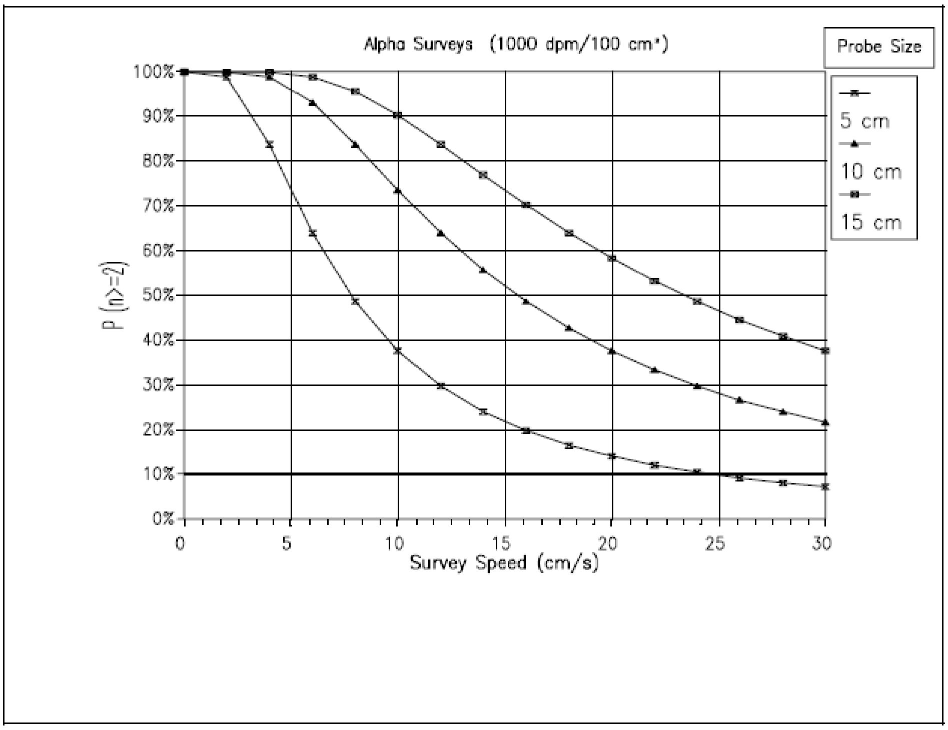


Figure C.5 Probability (P) of getting one or more counts when passing over a 100 cm^2 area contaminated at 1,000 dpm/100 cm^2 alpha. The chart shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimensions of the probes which are in line with the direction of scanning. A detection efficiency of 15% (4π) is assumed

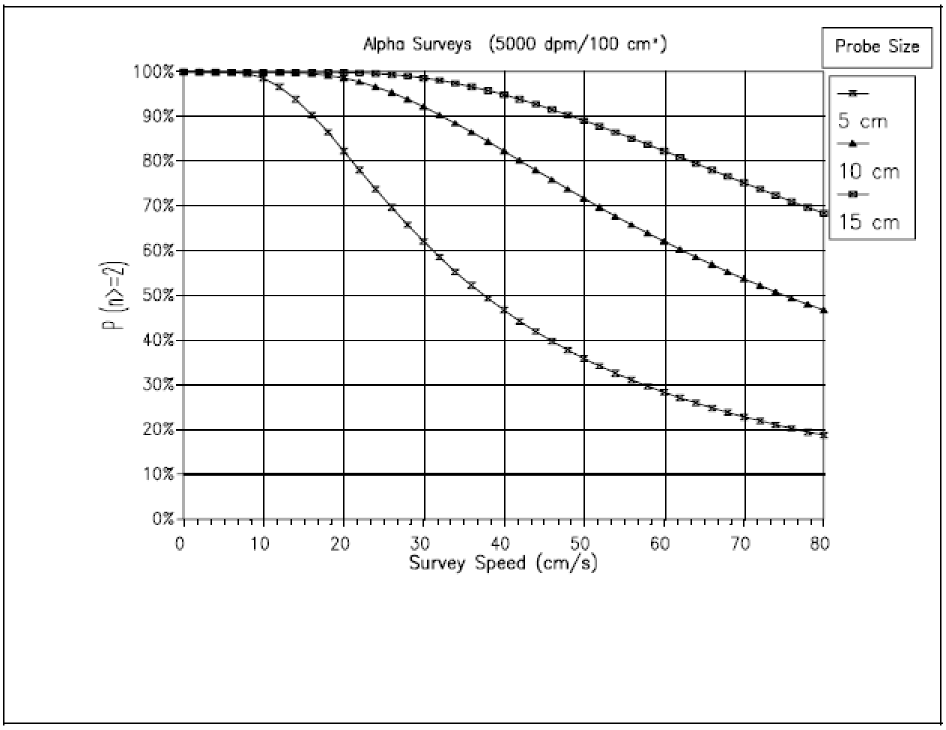


Figure C.6 Probability (P) of getting one or more counts when passing over a 100 cm^2 area contaminated at 5,000 dpm/100 cm^2 alpha. The chart shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimensions of the probes which are in line with the direction of scanning. A detection efficiency of 15% (4π) is assumed

Appendix D: Supporting information for interpreting survey results and tables of statistical data

D.1 Sign Test

D.1.1 Sample sizes for Sign test

Table D.1 Sample sizes for Sign test

(Number of measurements to be performed in each survey unit)

	(α,β) or (β,α)														
	0.01	**0.01**	**0.01**	**0.01**	**0.01**	**0.025**	**0.025**	**0.025**	**0.025**	**0.05**	**0.05**	**0.05**	**0.1**	**0.1**	**0.25**
Δ/σ	**0.01**	**0.025**	**0.05**	**0.1**	**0.25**	**0.025**	**0.05**	**0.1**	**0.25**	**0.05**	**0.1**	**0.25**	**0.1**	**0.25**	**0.25**
0.1	4095	3476	2984	2463	1704	2907	2459	1989	1313	2048	1620	1018	1244	725	345
0.2	1035	879	754	623	431	735	622	503	333	518	410	258	315	184	88
0.3	468	398	341	282	195	333	281	227	150	234	185	117	143	83	40
0.4	270	230	197	162	113	192	162	131	87	136	107	68	82	48	23
0.5	178	152	130	107	75	126	107	87	58	89	71	45	54	33	16
0.6	129	110	94	77	54	92	77	63	42	65	52	33	40	23	11
0.7	99	83	72	59	41	70	59	48	33	50	40	26	30	18	9
0.8	80	68	58	48	34	57	48	39	26	40	32	21	24	15	8
0.9	66	57	48	40	28	47	40	33	22	34	27	17	21	12	6
1.0	57	48	41	34	24	40	34	28	18	29	23	15	18	11	5
1.1	50	42	36	30	21	35	30	24	17	26	21	14	16	10	5
1.2	45	38	33	27	20	32	27	22	15	23	18	12	15	9	5
1.3	41	35	30	26	17	29	24	21	14	21	17	11	14	8	4
1.4	38	33	28	23	16	27	23	18	12	20	16	10	12	8	4
1.5	35	30	27	22	15	26	22	17	12	18	15	10	11	8	4
1.6	34	29	24	21	15	24	21	17	11	17	14	9	11	6	4
1.7	33	28	24	20	14	23	20	16	11	17	14	9	10	6	4
1.8	32	27	23	20	14	22	20	16	11	16	12	9	10	6	4
1.9	30	26	22	18	14	22	18	15	10	16	12	9	10	6	4
2.0	29	26	22	18	12	21	18	15	10	15	12	8	10	6	3
2.5	28	23	21	17	12	20	17	14	10	15	11	8	9	5	3
3.0	27	23	20	17	12	20	17	14	9	14	11	8	9	5	3

D.1.2 Critical values for the Sign Test

Table D.2 Critical values for the Sign test statistic S+

	Alpha								
N	***0.005***	***0.01***	***0.025***	***0.05***	***0.1***	***0.2***	***0.3***	***0.4***	***0.5***
4	4	4	4	4	3	3	3	2	2
5	5	5	5	4	4	3	3	3	2
6	6	6	5	5	5	4	4	3	3
7	7	6	6	6	5	5	4	4	3
8	7	7	7	6	6	5	5	4	4
9	8	8	7	7	6	6	5	5	4
10	9	9	8	8	7	6	6	5	5
11	10	9	9	8	8	7	6	6	5
12	10	10	9	9	8	7	7	6	6
13	11	11	10	9	9	8	7	7	6
14	12	11	11	10	9	9	8	7	7
15	12	12	11	11	10	9	9	8	7
16	13	13	12	11	11	10	9	9	8
17	14	13	12	12	11	10	10	9	8
18	14	14	13	12	12	11	10	10	9
19	15	14	14	13	12	11	11	10	9
20	16	15	14	14	13	12	11	11	10
21	16	16	15	14	13	12	12	11	10
22	17	16	16	15	14	13	12	12	11
23	18	17	16	15	15	14	13	12	11
24	18	18	17	16	15	14	13	13	12
25	19	18	17	17	16	15	14	13	12
26	19	19	18	17	16	15	14	14	13
27	20	19	19	18	17	16	15	14	13
28	21	20	19	18	17	16	15	15	14
29	21	21	20	19	18	17	16	15	14
30	22	21	20	19	19	17	16	16	15
31	23	22	21	20	19	18	17	16	15
32	23	23	22	21	20	18	17	17	16
33	24	23	22	21	20	19	18	17	16
34	24	24	23	22	21	19	19	18	17
35	25	24	23	22	21	20	19	18	17
36	26	25	24	23	22	21	20	19	18
37	26	26	24	23	22	21	20	19	18
38	27	26	25	24	23	22	21	20	19
39	27	27	26	25	23	22	21	20	19
40	28	27	26	25	24	23	22	21	20
41	29	28	27	26	25	23	22	21	20
42	29	28	27	26	25	24	23	22	21
43	30	29	28	27	26	24	23	22	21
44	30	30	28	27	26	25	24	23	22
45	31	30	29	28	27	25	24	23	22
46	32	31	30	29	27	26	25	24	23
47	32	31	30	29	28	26	25	24	23
48	33	32	31	30	28	27	26	25	24
49	33	33	31	30	29	27	26	25	24
50	34	33	32	31	30	28	27	26	25

For N greater than 50, the table (critical) value can be calculated from $N/2 + z/2*\sqrt{(N)}$, where z is the $(1-\alpha)$ percentile of a standard normal distribution, which can be found in Table D.3 or in Table 3.34.

D.1.3 Power of the Sign Test

The power of the Sign test for detecting residual radioactivity at the concentration level LBGR = DGCL - Δ, may be found using equation D-1.

$$1 - \beta = 1 - \sum_{i=0}^{k} \binom{N}{i} [q^*]^i . [1 - q^*]^{N-i} = 1 - \Phi((k - Nq^*)/\sqrt{(Nq^*(1-q^*))}) \qquad \text{(D-1)}$$

with

$$q^* = \Phi(\Delta/\sigma) \qquad \text{(D-2)}$$

The function Φ(z) is the standard normal cumulative distribution function tabulated in Table D.1. Note that if Δ/σ is large, q* approaches one, and the power also approaches one. This calculation can be performed for other values, Δ*, in order to construct a power curve for the test. These calculations can also be performed using the standard deviation of the actual measurement data, s, in order to construct a retrospective power curve for the test. This is an important step when the null hypothesis is not rejected, since it demonstrates whether the DQOs have been met.

The retrospective power curve for the Sign test can be constructed using Equations D-1 and D-2, together with the actual number of concentration measurements obtained, N. The power as a function of Δ/σ is calculated. The values of Δ/σ are converted to concentration using:

Concentration = $DCGL_W$ - (Δ/σ)(observed standard deviation).

The results for the Class 3 exterior survey unit example of Section 3.10.3.5 are plotted in Figure D.1. This figure shows the probability that the survey unit would have passed the release criterion using the Sign test versus concentration of residual radioactivity. This curve shows that the data quality objectives were met, despite the fact that the actual standard deviation was larger than that used in designing the survey. This is primarily due to the additional 20% that was added to the sample size, and also that sample sizes were always rounded up. The curve shows that a survey unit with less than 135 Bq/kg would almost always pass, and that a survey unit with more than 145 Bq/kg would almost always fail.

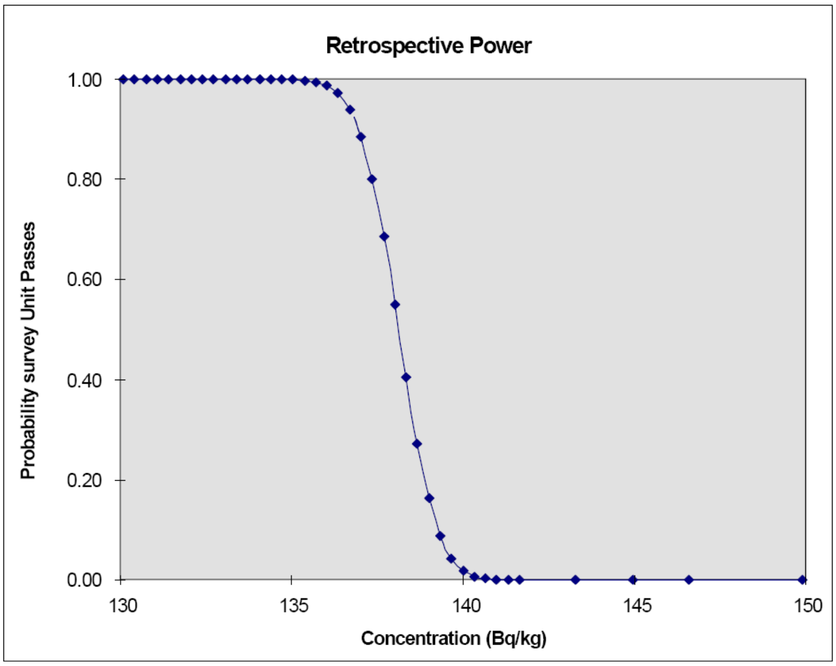


Figure D.1 Retrospective power curve for Class 3 exterior survey unit

D.2 Wilcoxon Rank Sum Test

D.2.1 Sample sizes for Wilcoxon Rank Sum Test

Table D.3 Sample sizes for Wilcoxon Rank Sum test

(Number of measurements to be performed in the reference area and in each survey unit)

	(α,β) or (β,α)														
	0.01	**0.01**	**0.01**	**0.01**	**0.01**	**0.025**	**0.025**	**0.025**	**0.025**	**0.05**	**0.05**	**0.05**	**0.1**	**0.1**	**0.25**
Δ/σ	**0.01**	**0.025**	**0.05**	**0.1**	**0.25**	**0.025**	**0.05**	**0.1**	**0.25**	**0.05**	**0.1**	**0.25**	**0.1**	**0.25**	**0.25**
0.1	5452	4627	3972	3278	2268	3870	3273	2646	1748	2726	2157	1355	1655	964	459
0.2	1370	1163	998	824	570	973	823	665	440	685	542	341	416	243	116
0.3	614	521	448	370	256	436	369	298	197	307	243	153	187	109	52
0.4	350	297	255	211	146	248	210	170	112	175	139	87	106	62	30
0.5	227	193	166	137	95	162	137	111	73	114	90	57	69	41	20
0.6	161	137	117	97	67	114	97	78	52	81	64	40	49	29	14
0.7	121	103	88	73	51	86	73	59	39	61	48	30	37	22	11
0.8	95	81	69	57	40	68	57	46	31	48	38	24	29	17	8
0.9	77	66	56	47	32	55	46	38	25	39	31	20	24	14	7
1.0	64	55	47	39	27	46	39	32	21	32	26	16	20	12	6
1.1	55	47	40	33	23	39	33	27	18	28	22	14	17	10	5
1.2	48	41	35	29	20	34	29	24	16	24	19	12	15	9	4
1.3	43	36	31	26	18	30	26	21	14	22	17	11	13	8	4
1.4	38	32	28	23	16	27	23	19	13	19	15	10	12	7	4
1.5	35	30	25	21	15	25	21	17	11	18	14	9	11	7	3
1.6	32	27	23	19	14	23	19	16	11	16	13	8	10	6	3
1.7	30	25	22	18	13	21	18	15	10	15	12	8	9	6	3
1.8	28	24	20	17	12	20	17	14	9	14	11	7	9	5	3
1.9	26	22	19	16	11	19	16	13	9	13	11	7	8	5	3
2.0	25	21	18	15	11	18	15	12	8	13	10	7	8	5	3
2.25	22	19	16	14	10	16	14	11	8	11	9	6	7	4	2
2.5	21	18	15	13	9	15	13	10	7	11	9	6	7	4	2
2.75	20	17	15	12	9	14	12	10	7	10	8	5	6	4	2
3.0	19	16	14	12	8	14	12	10	6	10	8	5	6	4	2
3.5	18	16	13	11	8	13	11	9	6	9	8	5	6	4	2
4.0	18	15	13	11	8	13	11	9	6	9	7	5	6	4	2

D.2.2 Critical values for the Wilcoxon Rank Sum Test test

Table D.4 Critical values for the Wilcoxon Rank Sum test (WRS) test

m is the number of reference area samples and n is the number of survey unit samples.

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 2	α=0.001	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43
	α=0.005	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	40	42
	α=0.01	7	9	11	13	15	17	19	21	23	25	27	28	30	32	34	36	38	39	41
	α=0.025	7	9	11	13	15	17	18	20	22	23	25	27	29	31	33	34	36	38	40
	α=0.05	7	9	11	12	14	16	17	19	21	23	24	26	27	29	31	33	34	36	38
	α=0.1	7	8	10	11	13	15	16	18	19	21	22	24	26	27	29	30	32	33	35
	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 3	α=0.001	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	56	59	62	65
	α=0.005	12	15	18	21	24	27	30	32	35	38	40	43	46	48	51	54	57	59	62
	α=0.01	12	15	18	21	24	26	29	31	34	37	39	42	45	47	50	52	55	58	60
	α=0.025	12	15	18	20	22	25	27	30	32	35	37	40	42	45	47	50	52	55	57
	α=0.05	12	14	17	19	21	24	26	28	31	33	36	38	40	43	45	47	50	52	54
	α=0.1	11	13	16	18	20	22	24	27	29	31	33	35	37	40	42	44	46	48	50
	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 4	α=0.001	18	22	26	30	34	38	42	46	49	53	57	60	64	68	71	75	78	82	86
	α=0.005	18	22	26	30	33	37	40	44	47	51	54	58	61	64	68	71	75	78	81
	α=0.01	18	22	26	29	32	36	39	42	46	49	52	56	59	62	66	69	72	76	79
	α=0.025	18	22	25	28	31	34	37	41	44	47	50	53	56	59	62	66	69	72	75
	α=0.05	18	21	24	27	30	33	36	39	42	45	48	51	54	57	59	62	65	68	71
	α=0.1	17	20	22	25	28	31	34	36	39	42	45	48	50	53	56	59	61	64	67
	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 5	α=0.001	25	30	35	40	45	50	54	58	63	67	72	76	81	85	89	94	98	102	107
	α=0.005	25	30	35	39	43	48	52	56	60	64	68	72	77	81	85	89	93	97	101
	α=0.01	25	30	34	38	42	46	50	54	58	62	66	70	74	78	82	86	90	94	98
	α=0.025	25	29	33	37	41	44	48	52	56	60	63	67	71	75	79	82	86	90	94
	α=0.05	24	28	32	35	39	43	46	50	53	57	61	64	68	71	75	79	82	86	89
	α=0.1	23	27	30	34	37	41	44	47	51	54	57	61	64	67	71	74	77	81	84
	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 6	α=0.001	33	39	45	51	57	63	67	72	77	82	88	93	98	103	108	113	118	123	128
	α=0.005	33	39	44	49	54	59	64	69	74	79	83	88	93	98	103	107	112	117	122
	α=0.01	33	39	43	48	53	58	62	67	72	77	81	86	91	95	100	104	109	114	118
	α=0.025	33	37	42	47	51	56	60	64	69	73	78	82	87	91	95	100	104	109	113
	α=0.05	32	36	41	45	49	54	58	62	66	70	75	79	83	87	91	96	100	104	108
	α=0.1	31	35	39	43	47	51	55	59	63	67	71	75	79	83	87	91	94	98	102
	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 7	α=0.001	42	49	56	63	69	75	81	87	92	98	104	110	116	122	128	133	139	145	151
	α=0.005	42	49	55	61	66	72	77	83	88	94	99	105	110	116	121	127	132	138	143
	α=0.01	42	48	54	59	65	70	76	81	86	92	97	102	108	113	118	123	129	134	139
	α=0.025	42	47	52	57	63	68	73	78	83	88	93	98	103	108	113	118	123	128	133
	α=0.05	41	46	51	56	61	65	70	75	80	85	90	94	99	104	109	113	118	123	128
	α=0.1	40	44	49	54	58	63	67	72	76	81	85	90	94	99	103	108	112	117	121

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 8	α=0.001	52	60	68	75	82	89	95	102	109	115	122	128	135	141	148	154	161	167	174
	α=0.005	52	60	66	73	79	85	92	98	104	110	116	122	129	135	141	147	153	159	165
	α=0.01	52	59	65	71	77	84	90	96	102	108	114	120	125	131	137	143	149	155	161
	α=0.025	51	57	63	69	75	81	86	92	98	104	109	115	121	126	132	137	143	149	154
	α=0.05	50	56	62	67	73	78	84	89	95	100	105	111	116	122	127	132	138	143	148
	α=0.1	49	54	60	65	70	75	80	85	91	96	101	106	111	116	121	126	131	136	141

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 9	α=0.001	63	72	81	88	96	104	111	118	126	133	140	147	155	162	169	176	183	190	198
	α=0.005	63	71	79	86	93	100	107	114	121	127	134	141	148	155	161	168	175	182	188
	α=0.01	63	70	77	84	91	98	105	111	118	125	131	138	144	151	157	164	170	177	184
	α=0.025	62	69	76	82	88	95	101	108	114	120	126	133	139	145	151	158	164	170	176
	α=0.05	61	67	74	80	86	92	98	104	110	116	122	128	134	140	146	152	158	164	170
	α=0.1	60	66	71	77	83	89	94	100	106	112	117	123	129	134	140	145	151	157	162

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 10	α=0.001	75	85	94	103	111	119	128	136	144	152	160	167	175	183	191	199	207	215	222
	α=0.005	75	84	92	100	108	115	123	131	138	146	153	160	168	175	183	190	197	205	212
	α=0.01	75	83	91	98	106	113	121	128	135	142	150	157	164	171	178	186	193	200	207
	α=0.025	74	81	89	96	103	110	117	124	131	138	145	151	158	165	172	179	186	192	199
	α=0.05	73	80	87	93	100	107	114	120	127	133	140	147	153	160	166	173	179	186	192
	α=0.1	71	78	84	91	97	103	110	116	122	128	135	141	147	153	160	166	172	178	184

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 11	α=0.001	88	99	109	118	127	136	145	154	163	171	180	188	197	206	214	223	231	240	248
	α=0.005	88	98	107	115	124	132	140	148	157	165	173	181	189	197	205	213	221	229	237
	α=0.01	88	97	105	113	122	130	138	146	153	161	169	177	185	193	200	208	216	224	232
	α=0.025	87	95	103	111	118	126	134	141	149	156	164	171	179	186	194	201	208	216	223
	α=0.05	86	93	101	108	115	123	130	137	144	152	159	166	173	180	187	195	202	209	216
	α=0.1	84	91	98	105	112	119	126	133	139	146	153	160	167	173	180	187	194	201	207

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 12	α=0.001	102	114	125	135	145	154	164	173	183	192	202	210	220	230	238	247	256	266	275
	α=0.005	102	112	122	131	140	149	158	167	176	185	194	202	211	220	228	237	246	254	263
	α=0.01	102	111	120	129	138	147	156	164	173	181	190	198	207	215	223	232	240	249	257
	α=0.025	100	109	118	126	135	143	151	159	168	176	184	192	200	208	216	224	232	240	248
	α=0.05	99	108	116	124	132	140	147	155	165	171	179	186	194	202	209	217	225	233	240
	α=0.1	97	105	113	120	128	135	143	150	158	165	172	180	187	194	202	209	216	224	231

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 13	α=0.001	117	130	141	152	163	173	183	193	203	213	223	233	243	253	263	273	282	292	302
	α=0.005	117	128	139	148	158	168	177	187	196	206	215	225	234	243	253	262	271	280	290
	α=0.01	116	127	137	146	156	165	174	184	193	202	211	220	229	238	247	256	265	274	283
	α=0.025	115	125	134	143	152	161	170	179	187	196	205	214	222	231	239	248	257	265	274
	α=0.05	114	123	132	140	149	157	166	174	183	191	199	208	216	224	233	241	249	257	266
	α=0.1	112	120	129	137	145	153	161	169	177	185	193	201	209	217	224	232	240	248	256

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 14	α=0.001	133	147	159	171	182	193	204	215	225	236	247	257	268	278	289	299	310	320	330
	α=0.005	133	145	156	167	177	187	198	208	218	228	238	248	258	268	278	288	298	307	317
	α=0.01	132	144	154	164	175	185	194	204	214	224	234	243	253	263	272	282	291	301	311
	α=0.025	131	141	151	161	171	180	190	199	208	218	227	236	245	255	264	273	282	292	301
	α=0.05	129	139	149	158	167	176	185	194	203	212	221	230	239	248	257	265	274	283	292
	α=0.1	128	136	145	154	163	171	180	189	197	206	214	223	231	240	248	257	265	273	282

	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 15	α=0.001	150	165	178	190	202	212	225	237	248	260	271	282	293	304	316	327	338	349	360
	α=0.005	150	162	174	186	197	208	219	230	240	251	262	272	283	293	304	314	325	335	346
	α=0.01	149	161	172	183	194	205	215	226	236	247	257	267	278	288	298	308	319	329	339
	α=0.025	148	159	169	180	190	200	210	220	230	240	250	260	270	280	289	299	309	319	329
	α=0.05	146	157	167	176	186	196	206	215	225	234	244	253	263	272	282	291	301	310	319
	α=0.1	144	154	163	172	182	191	200	209	218	227	236	246	255	264	273	282	291	300	309
	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 16	α=0.001	168	184	197	210	223	236	248	260	272	284	296	308	320	332	343	355	367	379	390
	α=0.005	168	181	194	206	218	229	241	252	264	275	286	298	309	320	331	342	353	365	376
	α=0.01	167	180	192	203	215	226	237	248	259	270	281	292	303	314	325	336	347	357	368
	α=0.025	166	177	188	200	210	221	232	242	253	264	274	284	295	305	316	326	337	347	357
	α=0.05	164	175	185	196	206	217	227	237	247	257	267	278	288	298	308	318	328	338	348
	α=0.1	162	172	182	192	202	211	221	231	241	250	260	269	279	289	298	308	317	327	336
	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 17	α=0.001	187	203	218	232	245	258	271	284	297	310	322	335	347	360	372	384	397	409	422
	α=0.005	187	201	214	227	239	252	264	276	288	300	312	324	336	347	359	371	383	394	406
	α=0.01	186	199	212	224	236	248	260	272	284	295	307	318	330	341	353	364	376	387	399
	α=0.025	184	197	209	220	232	243	254	266	277	288	299	310	321	332	343	354	365	376	387
	α=0.05	183	194	205	217	228	238	249	260	271	282	292	303	313	324	335	345	356	366	377
	α=0.1	180	191	202	212	223	233	243	253	264	274	284	294	305	315	325	335	345	355	365
	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 18	α=0.001	207	224	239	254	268	282	296	309	323	336	349	362	376	389	402	415	428	441	454
	α=0.005	207	222	236	249	262	275	288	301	313	326	339	351	364	376	388	401	413	425	438
	α=0.01	206	220	233	246	259	272	284	296	309	321	333	345	357	370	382	394	406	418	430
	α=0.025	204	217	230	242	254	266	278	290	302	313	325	337	348	360	372	383	395	406	418
	α=0.05	202	215	226	238	250	261	273	284	295	307	318	329	340	352	363	374	385	396	407
	α=0.1	200	211	222	233	244	255	266	277	288	299	309	320	331	342	352	363	374	384	395
	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 19	α=0.001	228	246	262	277	292	307	321	335	350	364	377	391	405	419	433	446	460	473	487
	α=0.005	227	243	258	272	286	300	313	327	340	353	366	379	392	405	419	431	444	457	470
	α=0.01	226	242	256	269	283	296	309	322	335	348	361	373	386	399	411	424	437	449	462
	α=0.025	225	239	252	265	278	290	303	315	327	340	352	364	377	389	401	413	425	437	450
	α=0.05	223	236	248	261	273	285	297	309	321	333	345	356	368	380	392	403	415	427	439
	α=0.1	220	232	244	256	267	279	290	302	313	325	336	347	358	370	381	392	403	415	426
	n =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
m = 20	α=0.001	250	269	286	302	317	333	348	363	377	392	407	421	435	450	464	479	493	507	521
	α=0.005	249	266	281	296	311	325	339	353	367	381	395	409	422	436	450	463	477	490	504
	α=0.01	248	264	279	293	307	321	335	349	362	376	389	402	416	429	442	456	469	482	495
	α=0.025	247	261	275	289	302	315	329	341	354	367	380	393	406	419	431	444	457	470	482
	α=0.05	245	258	271	284	297	310	322	335	347	360	372	385	397	409	422	434	446	459	471
	α=0.1	242	254	267	279	291	303	315	327	339	351	363	375	387	399	410	422	434	446	458

D.2.3 Rejecting null hypothesis based on Wilcoxon Rank Sum Test

Reject the null hypothesis if the test statistic (W_r) is greater than the table (critical) value. For n or m greater than 20, the table (critical) value can be calculated from:

$$m (n + m + 1)/2 + z \sqrt{(n m (n + m + 1)/12)} \quad \text{(D-3)}$$

if there are few or no ties, and from

$$m(n+m+1)/2 + z\sqrt{(nm/12^* [(n+m+1) - \sum_{j=1}^{g} \frac{t_j(t_j^2-1)}{(n+m)(n+m-1)}])} \quad \text{(D-4)}$$

if there are many ties, where g is the number of groups of tied measurements and t_j is the number of tied measurements in the j^{th} group. z is the (1- α) percentile of a standard normal distribution, which can be found in the following table:

α	z
0.001	3.09
0.005	2.575
0.01	2.326
0.025	1.960
0.05	1.645
0.1	1.282

Other values can be found in Table D.12.

D.2.4 Power of the Wilcoxon Rank Sum Test

The power of the WRS test is computed from

$$Power = 1 - \Phi\,[(W_c - 0.5 - 0.5\,m\,(m+1) - E(W_{MW}))/\sqrt{(V_{ar}(W_{MW})}] \quad \text{(D-5)}$$

where W_c is the critical value found in Table D.4 for the appropriate vales of α, n and m. Values of Φ(z), the standard normal cumulative distribution function, are given in Table D.12.

$W_{MW} = W_r - 0.5m(m+1)$ is the Mann-Whitney form of the WRS test statistic. Its mean is

$$E(W_{MW}) = m\,n\,P_r \quad \text{(D-6)}$$

and its variance is

$$Var(W_{MW}) = m\,n\,P_r(1 - P_r) + m\,n\,(n + m - 2)(p_2 - P_r^2) \quad \text{(D-7)}$$

Values of P_r and p_2 as a function of Δ/σ are given in Table D.5.

The power calculated in Equation D-5 is an approximation, but the results are generally accurate enough to be used to determine if the sample design achieves the DQOs.

The retrospective power curve for the WRS test can be constructed using Equations D-5, D-6, and D-7, together with the actual number of concentration measurements obtained, N. The power as a function of Δ/σ is calculated. The values of Δ/σ are converted to dpm/100 cm² using:

$$\text{dpm/100 cm}^2 = \text{DCGL} - (\Delta/\sigma)(\text{observed standard deviation}).$$

The results for this example are plotted in Figure D.2, showing the probability that the survey unit would have passed the release criterion using the WRS test versus dpm of residual radioactivity. This curve shows that the data quality objectives were easily achieved. The curve shows that a survey unit with less than 4,500 dpm/100 cm² above background would almost always pass, and that one with more than 5,100 dpm/100 cm² above background would almost always fail.

D.2.5 Spreadsheet Formulas for the Wilcoxon Rank Sum Test

The analysis for the WRS test is very well suited for calculation on a spreadsheet. This is how the analysis discussed above was done. This particular example was constructed using Excel 5.0™. The formula sheet corresponding to Table 3.56 is given in Table D.10. The function in Column D of Table D.10 calculates the ranks of the data. The RANK function in Excel™ does not return tied ranks in the way needed for the WRS. The COUNTIF function is used to correct for this. Column E simply picks out the reference area ranks from Column D.

Table D.5 Values of P_r and p_2 for computing the mean and variance of W_{MW}

Δ/σ	P_r	p_2	Δ/σ	P_r	p_2
-6.0	1.11E-05	1.16E-07	0.7	0.689691	0.544073
-5.0	0.000204	6.14E-06	0.8	0.714196	0.574469
-4.0	0.002339	0.000174	0.9	0.737741	0.604402
-3.5	0.006664	0.000738	1.0	0.760250	0.633702
-3.0	0.016947	0.002690	1.1	0.781662	0.662216
-2.5	0.038550	0.008465	1.2	0.801928	0.689800
-2.0	0.078650	0.023066	1.3	0.821015	0.716331
-1.9	0.089555	0.027714	1.4	0.838901	0.741698
-1.8	0.101546	0.033114	1.5	0.855578	0.765812
-1.7	0.114666	0.039348	1.6	0.871050	0.788602
-1.6	0.128950	0.046501	1.7	0.885334	0.810016
-1.5	0.144422	0.054656	1.8	0.898454	0.830022
-1.4	0.161099	0.063897	1.9	0.910445	0.848605
-1.3	0.178985	0.074301	2.0	0.921350	0.865767
-1.2	0.198072	0.085944	2.1	0.931218	0.881527
-1.1	0.218338	0.098892	2.2	0.940103	0.895917
-1.0	0.239750	0.113202	2.3	0.948062	0.908982
-0.9	0.262259	0.128920	2.4	0.955157	0.920777
-0.8	0.285804	0.146077	2.5	0.961450	0.931365
-0.7	0.310309	0.164691	2.6	0.967004	0.940817
-0.6	0.335687	0.184760	2.7	0.971881	0.949208
-0.5	0.361837	0.206266	2.8	0.976143	0.956616
-0.4	0.388649	0.229172	2.9	0.979848	0.963118
-0.3	0.416002	0.253419	3.0	0.983053	0.968795
-0.2	0.443769	0.278930	3.1	0.985811	0.973725
-0.1	0.471814	0.305606	3.2	0.988174	0.977981
0.0	0.500000	0.333333	3.3	0.990188	0.981636
0.1	0.528186	0.361978	3.4	0.991895	0.984758
0.2	0.556231	0.391392	3.5	0.993336	0.987410
0.3	0.583998	0.421415	4.0	0.997661	0.995497
0.4	0.611351	0.451875	5.0	0.999796	0.999599
0.5	0.638163	0.482593	6.0	0.999989	0.999978
0.6	0.664313	0.513387			

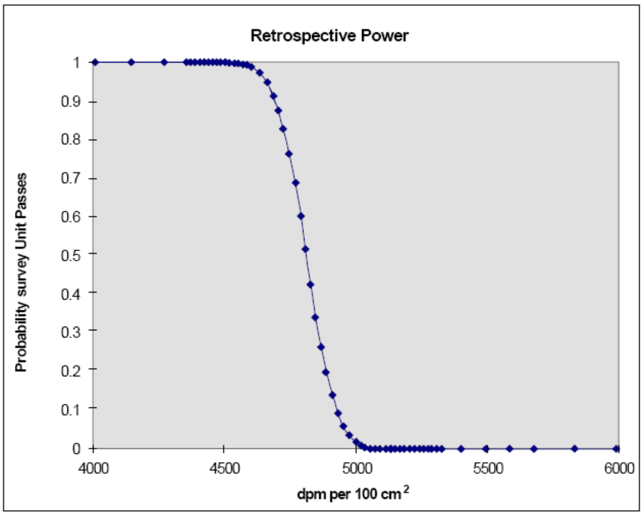


Figure D.2 Retrospective power curve for class 2 interior drywall survey unit

D.3 Interpreting survey results

D.3.1 Probability of detecting an area with an elevated contamination

Table D.6 Risk that an elevated area with length l/g and shape s will not be detected and the area (%) of the elevated area relative to a triangular sample grid area of 0.866 G^2

	Shape Parameter, S																			
	0.10		0.20		0.30		0.40		0.50		0.60		0.70		0.80		0.90		1.00	
L/G	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**
0.01	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%
0.02	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%
0.03	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%
0.04	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	0.99	1%	0.99	1%
0.05	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%
0.06	1.00	<1%	1.00	<1%	1.00	<1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%
0.07	1.00	<1%	1.00	<1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%
0.08	1.00	<1%	1.00	<1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.98	2%	0.98	2%
0.09	1.00	<1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.98	2%	0.97	3%	0.97	3%
0.10	1.00	<1%	0.99	1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.97	3%	0.97	3%	0.96	4%
0.11	0.99	1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.97	3%	0.96	4%	0.96	4%	0.96	4%
0.12	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.97	3%	0.96	4%	0.96	4%	0.95	5%	0.95	5%
0.13	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.96	4%	0.96	4%	0.95	5%	0.94	6%	0.94	6%
0.14	0.99	1%	0.99	1%	0.98	2%	0.97	3%	0.96	4%	0.96	4%	0.95	5%	0.94	6%	0.94	6%	0.93	7%
0.15	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.96	4%	0.95	5%	0.94	6%	0.93	7%	0.93	7%	0.92	8%
0.16	0.99	1%	0.98	2%	0.97	3%	0.96	4%	0.95	5%	0.94	6%	0.94	6%	0.93	7%	0.92	8%	0.91	9%
0.17	0.99	1%	0.98	2%	0.97	3%	0.96	4%	0.95	5%	0.94	6%	0.93	7%	0.92	8%	0.91	9%	0.90	10%
0.18	0.99	1%	0.98	2%	0.96	4%	0.95	5%	0.94	6%	0.93	7%	0.92	8%	0.91	9%	0.89	11%	0.88	12%
0.19	0.99	1%	0.97	3%	0.96	4%	0.95	5%	0.93	7%	0.92	8%	0.91	9%	0.90	10%	0.88	12%	0.87	13%
0.20	0.99	1%	0.97	3%	0.96	4%	0.94	6%	0.92	8%	0.91	9%	0.90	10%	0.88	12%	0.87	13%	0.85	15%
0.21	0.98	2%	0.97	3%	0.95	5%	0.94	6%	0.92	8%	0.90	10%	0.89	11%	0.87	13%	0.86	14%	0.84	16%
0.22	0.98	2%	0.96	4%	0.95	5%	0.93	7%	0.91	9%	0.89	11%	0.88	12%	0.86	14%	0.84	16%	0.82	18%
0.23	0.98	2%	0.96	4%	0.94	6%	0.92	8%	0.90	10%	0.88	12%	0.87	13%	0.85	15%	0.83	17%	0.81	19%
0.24	0.98	2%	0.96	4%	0.94	6%	0.92	8%	0.90	10%	0.87	13%	0.85	15%	0.83	17%	0.81	19%	0.79	21%
0.25	0.98	2%	0.95	5%	0.93	7%	0.91	9%	0.89	11%	0.86	14%	0.84	16%	0.82	18%	0.80	20%	0.77	23%
0.26	0.98	25	0.95	5%	0.93	7%	0.90	10%	0.88	12%	0.85	15%	0.83	17%	0.80	20%	0.78	22%	0.75	25%
0.27	0.97	3%	0.95	5%	0.92	8%	0.89	11%	0.87	13%	0.84	16%	0.81	19%	0.79	21%	0.76	24%	0.74	26%
0.28	0.97	35	0.94	6%	0.91	9%	0.89	11%	0.86	14%	0.83	17%	0.80	20%	0.77	23%	0.74	26%	0.72	28%
0.29	0.97	3%	0.94	6%	0.91	9%	0.88	12%	0.85	15%	0.82	18%	0.79	21%	0.76	24%	0.73	27%	0.69	31%
0.30	0.97	3%	0.93	7%	0.90	10%	0.87	13%	0.84	16%	0.80	20%	0.77	23%	0.74	26%	0.71	29%	0.67	33%
0.31	0.97	3%	0.93	7%	0.90	10%	0.86	14%	0.83	17%	0.79	21%	0.76	24%	0.72	28%	0.69	31%	0.65	35%
0.32	0.96	4%	0.93	7%	0.89	11%	0.85	15%	0.81	19%	0.78	22%	0.74	26%	0.70	30%	0.67	33%	0.63	37%
0.33	0.96	45	0.92	8%	0.88	12%	0.84	16%	0.80	20%	0.76	24%	0.72	28%	0.68	32%	0.64	36%	0.61	40%
0.34	0.96	45	0.92	8%	0.87	13%	0.83	17%	0.79	21%	0.75	25%	0.71	29%	0.66	34%	0.62	38%	0.58	42%
0.35	0.96	4%	0.91	9%	0.87	13%	0.82	18%	0.78	22%	0.73	27%	0.69	31%	0.64	36%	0.60	40%	0.56	44%
0.36	0.95	5%	0.91	9%	0.86	14%	0.81	19%	0.76	24%	0.72	28%	0.67	33%	0.62	38%	0.58	42%	0.53	47%
0.37	0.95	5%	0.90	10%	0.85	15%	0.80	20%	0.75	25%	0.70	30%	0.65	35%	0.60	40%	0.55	45%	0.50	50%
0.38	0.95	5%	0.90	10%	0.84	16%	0.79	21%	0.74	26%	0.69	31%	0.63	37%	0.58	42%	0.53	47%	0.48	52%
0.39	0.94	6%	0.89	11%	0.83	17%	0.78	22%	0.72	28%	0.67	33%	0.61	39%	0.56	44%	0.50	50%	0.45	55%
0.40	0.94	6%	0.88	12%	0.83	17%	0.77	23%	0.71	29%	0.65	35%	0.59	41%	0.54	46%	0.48	52%	0.42	58%
0.41	0.94	6%	0.88	12%	0.82	18%	0.76	24%	0.70	30%	0.63	37%	0.57	43%	0.51	49%	0.45	55%	0.39	61%
0.42	0.94	6%	0.87	13%	0.81	19%	0.74	26%	0.68	32%	0.62	38%	0.55	45%	0.49	51%	0.42	58%	0.36	64%

	Shape Parameter, S																			
	0.10		**0.20**		**0.30**		**0.40**		**0.50**		**0.60**		**0.70**		**0.80**		**0.90**		**1.00**	
L/G	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**
0.43	0.93	7%	0.87	13%	0.80	20%	0.73	27%	0.66	34%	0.60	40%	0.53	47%	0.46	54%	0.40	60%	0.33	67%
0.44	0.93	7%	0.86	14%	0.79	21%	0.72	28%	0.65	35%	0.58	42%	0.51	49%	0.44	56%	0.37	63%	0.30	70%
0.45	0.93	7%	0.85	15%	0.78	22%	0.71	29%	0.63	37%	0.56	44%	0.49	51%	0.41	59%	0.34	66%	0.27	73%
0.46	0.92	8%	0.85	15%	0.77	23%	0.69	31%	0.62	38%	0.54	46%	0.46	54%	0.39	61%	0.31	69%	0.23	77%
0.47	0.92	8%	0.84	16%	0.76	24%	0.68	32%	0.60	40%	0.52	48%	0.44	56%	0.36	64%	0.28	72%	0.20	80%
0.48	0.92	8%	0.83	17%	0.75	25%	0.67	33%	0.58	42%	0.50	50%	0.41	59%	0.33	67%	0.25	75%	0.16	84%
0.49	0.91	9%	0.83	17%	0.74	26%	0.65	35%	0.56	44%	0.48	52%	0.39	61%	0.30	70%	0.22	78%	0.13	87%
0.50	0.91	9%	0.82	18%	0.73	27%	0.64	36%	0.55	45%	0.46	54%	0.37	63%	0.27	73%	0.18	82%	0.09	91%
0.51	0.91	9%	0.81	19%	0.72	28%	0.62	38%	0.53	47%	0.43	57%	0.34	66%	0.25	75%	0.15	85%	0.07	94%
0.52	0.90	10%	0.80	20%	0.71	29%	0.61	39%	0.51	49%	0.41	59%	0.32	69%	0.22	78%	0.13	88%	0.05	98%
0.53	0.90	10%	0.80	20%	0.70	31%	0.59	41%	0.49	51%	0.39	61%	0.29	71%	0.19	82%	0.10	92%	0.03	102%
0.54	0.89	11%	0.79	21%	0.68	32%	0.58	42%	0.47	53%	0.37	63%	0.27	74%	0.17	85%	0.08	95%	0.02	106%
0.55	0.89	11%	0.78	22%	0.67	33%	0.56	44%	0.46	55%	0.35	66%	0.24	77%	0.14	88%	0.06	99%	0.01	110%
0.56	0.89	11%	0.77	23%	0.66	34%	0.55	46%	0.44	57%	0.33	68%	0.22	80%	0.12	91%	0.04	102%	0.00	114%
0.57	0.88	12%	0.77	23%	0.65	35%	0.54	47%	0.42	59%	0.31	71%	0.20	83%	0.10	94%	0.02	106%	0.00	118%
0.58	0.88	12%	0.76	24%	0.64	37%	0.52	49%	0.40	61%	0.29	73%	0.18	85%	0.08	98%	0.01	110%	0.00	122%
0.59	0.87	13%	0.75	25%	0.63	38%	0.51	51%	0.39	63%	0.27	76%	0.16	88%	0.06	101%	0.00	114%	0.00	126%
0.60	0.87	13%	0.74	26%	0.62	39%	0.49	52%	0.37	65%	0.25	78%	0.14	91%	0.04	104%	0.00	118%	0.00	131%
0.61	0.87	13%	0.73	27%	0.60	40%	0.48	54%	0.35	67%	0.23	81%	0.12	94%	0.03	108%	0.00	121%	0.00	135%
0.62	0.86	14%	0.73	28%	0.59	42%	0.46	56%	0.34	70%	0.21	84%	0.10	98%	0.02	112%	0.00	126%	0.00	139%
0.63	0.86	14%	0.72	29%	0.58	43%	0.45	58%	0.32	72%	0.20	86%	0.09	101%	0.01	115%	0.00	130%	0.00	144%
0.64	0.85	15%	0.71	30%	0.57	45%	0.43	59%	0.30	74%	0.18	89%	0.07	104%	0.00	119%	0.00	134%	0.00	149%
0.65	0.85	15%	0.70	31%	0.56	46%	0.42	61%	0.29	77%	0.16	92%	0.06	107%	0.00	123%	0.00	138%	0.00	153%
0.66	0.84	16%	0.69	32%	0.55	47%	0.40	63%	0.27	79%	0.15	95%	0.05	111%	0.00	126%	0.00	142%	0.00	158%
0.67	0.84	16%	0.68	33%	0.53	49%	0.39	65%	0.25	81%	0.13	98%	0.03	114%	0.00	130%	0.00	147%	0.00	163%
0.68	0.84	17%	0.68	34%	0.52	50%	0.38	67%	0.24	84%	0.12	101%	0.02	117%	0.00	134%	0.00	151%	0.00	168%
0.69	0.83	17%	0.67	35%	0.51	52%	0.36	69%	0.22	86%	0.10	104%	0.01	121%	0.00	138%	0.00	155%	0.00	173%
0.70	0.83	18%	0.66	36%	0.50	53%	0.35	71%	0.21	89%	0.09	107%	0.01	124%	0.00	142%	0.00	160%	0.00	178%
0.71	0.82	18%	0.65	37%	0.49	55%	0.33	73%	0.20	91%	0.08	110%	0.00	128%	0.00	146%	0.00	165%	0.00	183%
0.72	0.82	19%	0.64	38%	0.48	56%	0.32	75%	0.18	94%	0.07	113%	0.00	132%	0.00	150%	0.00	169%	0.00	188%
0.73	0.81	19%	0.63	39%	0.46	58%	0.31	77%	0.17	97%	0.05	116%	0.00	135%	0.00	155%	0.00	174%	0.00	193%
0.74	0.81	20%	0.62	40%	0.45	60%	0.29	79%	0.15	99%	0.04	119%	0.00	139%	0.00	159%	0.00	179%	0.00	199%
0.75	0.80	20%	0.61	41%	0.44	61%	0.28	82%	0.14	102%	0.04	122%	0.00	143%	0.00	163%	0.00	184%	0.00	204%
0.76	0.80	21%	0.61	42%	0.43	63%	0.27	84%	0.13	105%	0.03	126%	0.00	147%	0.00	168%	0.00	189%	0.00	210%
0.77	0.79	22%	0.60	43%	0.42	65%	0.25	86%	0.12	108%	0.02	129%	0.00	151%	0.00	172%	0.00	194%	0.00	215%
0.78	0.79	22%	0.59	44%	0.40	66%	0.24	88%	0.10	110%	0.01	132%	0.00	154%	0.00	177%	0.00	199%	0.00	221%
0.79	0.78	23%	0.58	45%	0.39	68%	0.23	91%	0.09	113%	0.01	136%	0.00	158%	0.00	181%	0.00	204%	0.00	226%
0.80	0.78	23%	0.57	46%	0.38	70%	0.22	93%	0.08	116%	0.00	139%	0.00	163%	0.00	186%	0.00	209%	0.00	232%
0.81	0.77	24%	0.56	48%	0.37	71%	0.20	95%	0.07	119%	0.00	143%	0.00	167%	0.00	190%	0.00	214%	0.00	238%
0.82	0.77	24%	0.55	49%	0.36	73%	0.19	98%	0.06	122%	0.00	146%	0.00	171%	0.00	195%	0.00	220%	0.00	244%
0.83	0.76	25%	0.54	50%	0.35	75%	0.18	100%	0.05	125%	0.00	150%	0.00	175%	0.00	200%	0.00	225%	0.00	250%
0.84	0.76	26%	0.53	51%	0.33	77%	0.17	102%	0.05	128%	0.00	154%	0.00	179%	0.00	205%	0.00	230%	0.00	256%
0.85	0.75	26%	0.52	52%	0.32	79%	0.16	105%	0.04	131%	0.00	157%	0.00	183%	0.00	210%	0.00	236%	0.00	262%
0.86	0.74	27%	0.51	54%	0.31	80%	0.14	107%	0.03	134%	0.00	161%	0.00	188%	0.00	215%	0.00	241%	0.00	268%
0.87	0.74	27%	0.50	55%	0.30	82%	0.13	110%	0.02	137%	0.00	165%	0.00	192%	0.00	220%	0.00	247%	0.00	275%
0.88	0.73	28%	0.50	56%	0.29	84%	0.12	112%	0.02	140%	0.00	169%	0.00	197%	0.00	225%	0.00	253%	0.00	281%
0.89	0.73	29%	0.49	57%	0.28	86%	0.11	115%	0.01	144%	0.00	172%	0.00	201%	0.00	230%	0.00	259%	0.00	287%
0.90	0.72	29%	0.48	59%	0.27	88%	0.10	118%	0.01	147%	0.00	176%	0.00	206%	0.00	235%	0.00	264%	0.00	294%

Shape Parameter, S																				
	0.10		**0.20**		**0.30**		**0.40**		**0.50**		**0.60**		**0.70**		**0.80**		**0.90**		**1.00**	
L/G	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**
0.91	0.72	30%	0.47	60%	0.26	90%	0.10	120%	0.01	150%	0.00	180%	0.00	210%	0.00	240%	0.00	270%	0.00	300%
0.92	0.71	31%	0.46	61%	0.25	92%	0.09	123%	0.00	154%	0.00	184%	0.00	215%	0.00	246%	0.00	276%	0.00	307%
0.93	0.71	31%	0.45	63%	0.24	94%	0.08	126%	0.00	157%	0.00	188%	0.00	220%	0.00	251%	0.00	282%	0.00	314%
0.94	0.70	32%	0.44	64%	0.23	96%	0.07	128%	0.00	160%	0.00	192%	0.00	224%	0.00	256%	0.00	288%	0.00	321%
0.95	0.69	33%	0.43	65%	0.22	98%	0.07	131%	0.00	164%	0.00	196%	0.00	229%	0.00	262%	0.00	295%	0.00	327%
0.96	0.69	33%	0.42	67%	0.21	100%	0.06	134%	0.00	167%	0.00	201%	0.00	234%	0.00	267%	0.00	301%	0.00	334%
0.97	0.68	34%	0.41	68%	0.20	102%	0.05	137%	0.00	171%	0.00	205%	0.00	239%	0.00	273%	0.00	307%	0.00	341%
0.98	0.68	35%	0.40	70%	0.19	105%	0.05	139%	0.00	174%	0.00	209%	0.00	244%	0.00	279%	0.00	314%	0.00	348%
0.99	0.67	36%	0.40	71%	0.18	107%	0.04	142%	0.00	178%	0.00	213%	0.00	249%	0.00	284%	0.00	320%	0.00	356%
1.00	0.67	36%	0.39	73%	0.17	109%	0.04	145%	0.00	181%	0.00	218%	0.00	254%	0.00	290%	0.00	326%	0.00	363%

D.3.2 Stem and leaf display

The construction of a *stem and leaf display* is a simple way to generate a crude histogram of the data quickly. The 'stems' of such a display are the most significant digits of the data. Consider the sample data of Section 3.10.8.3:

- 90.7, 83.5, 86.4, 88.5, 84.4, 74.2, 84.1, 87.6, 78.2, 77.6,
- 86.4, 76.3, 86.5, 77.4, 90.3, 90.1, 79.1, 92.4, 75.5, 80.5.

Here the data span three decades, so one might consider using the stems 70, 80 and 90. However, three is too few stems to be informative, just as three intervals would be too few for constructing a histogram. Therefore, for this example, each decade is divided into two parts. This results in the six stems 70, 75, 80, 85, 90, 95. The leaves are the least significant digits, so 90.7 has the stem 90 and the leaf 0.7. 77.4 has the stem 75 and the leaf 7.4. Note that even though the stem is 75, the leaf is *not* 2.4. The leaf is kept as 7.4 so that the data can be read directly from the display without any calculations.

Stem Leaves	
70	4.2
75	8.2, 7.6, 6.3, 7.4, 9.1, 5.5
80	3.5, 4.4, 4.1, 0.5
85	6.4, 8.5, 7.6, 6.4, 6.5
90	0.7, 0.3, 0.1, 2.4
95	
Stem Sorted Leaves	
70	4.2
75	5.5, 6.3, 7.4, 7.6, 8.2, 9.1
80	0.5, 3.5, 4.1, 4.4
85	6.4, 6.4, 6.5, 7.6, 8.5
90	0.1, 0.3, 0.7, 2.4
95	

Figure D.3 Example of a stem and leaf display

As shown in the top part of Figure D.3, simply arrange the leaves of the data into rows, one stem per row. The result is a quick histogram of the data. In order to ensure this, the same number of digits should be used for each leaf, so that each occupies the same amount of horizontal space.

If the stems are arranged in increasing order, as shown in the bottom half of Figure D.3, it is easy to pick out the minimum (74.2), the maximum (92.4), and the median (between 84.1 and 84.4).

A stem and leaf display (or histogram) with two peaks may indicate that residual radioactivity is distributed over only a portion of the survey unit. Further information on the construction and interpretation of data plots is given in [121].

D.3.3 Quantile plots

A quantile plot is constructed by first ranking the data from smallest to largest. Sorting the data is easy once the stem and leaf display has been constructed. Then, each data value is simply plotted against the percentage of the samples with that value or less. This percentage is computed from:

$$\textit{Percent} = 100\ (\textit{rank} - 0.5) / (\textit{number of data points}) \qquad \text{(D-8)}$$

The results for the example data of Appendix D.3.2 are shown in Table D.7. The quantile plot for this example is shown in Figure D.4.

The slope of the curve in the quantile plot is an indication of the amount of data in a given range of values. A small amount of data in a range will result in a large slope. A large amount of data in a range of values will result in a more horizontal slope. A sharp rise near the bottom or the top is an indication of asymmetry. Sudden changes in slope or notably flat or notably steep areas may indicate peculiarities in the survey unit data needing further investigation.

Table D.7 Data for quantile plot

Data:	74.2	75.5	76.3	77.4	77.6	78.2	79.1	80.5	83.5	84.1
Rank:	1	2	3	4	5	6	7	8	9	10
Percent:	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5
Data:	84.4	86.4	86.4	86.5	87.6	88.5	90.1	90.3	90.7	92.4
Rank:	11	12.5	12.5	14	15	16	17	18	19	20
Percent:	52.5	60.0	60.0	67.5	72.5	77.5	82.5	87.5	92.5	97.5

A useful aid to interpreting the Quantile plot is the addition of boxes containing the middle 50% and middle 75% of the data. These are shown as the dashed lines in Figure D.4. The 50% box has its upper right corner at the 75th percentile and its lower left corner at the 25th percentile. These points are also called the Quartiles. These are ~78 and ~88, respectively, as indicated by the dashed lines. They bracket the middle half of the data values. The 75% box has its upper right corner at the 87.5th percentile and its lower left corner at the 12.5th percentile. A sharp increase within the 50% box can indicate two or more modes in the data. Outside the 75% box, sharp increases can indicate outliers. The median (50th percentile) is indicated by the heavy solid line at the value ~84, and can be used as an aid to judging the symmetry of the data distribution.

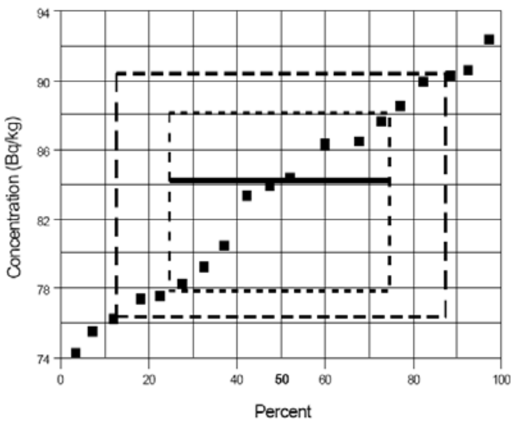


Figure D.4 Example of a quantile plot

There are no especially unusual features in the example quantile plot shown in Figure D.4, other than the possibility of slight asymmetry around the median.

Another quantile plot, for the example data of Section 3.10.3.4, is shown in Figure D.5.

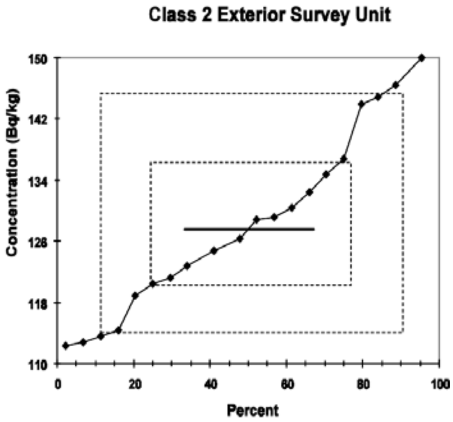


Figure D.5 Quantile plot for example Class 2 exterior survey unit

A quantile-quantile plot is extremely useful for comparing two sets of data. Suppose the following 17 concentration values were obtained in a reference area corresponding to the example survey unit data of Appendix D.3.2:

- 92.1, 83.2, 81.7, 81.8, 88.5, 82.4, 81.5, 69.7, 82.4, 89.7,
- 81.4, 79.4, 82.0, 79.9, 81.1, 59.4, 75.3.

A quantile-quantile plot can be constructed to compare the distribution of the survey unit data, Y_j, $j=1,...n$, with the distribution of the reference area data X_i , $i=1,... m$. (If the reference area data set were the larger, the roles of X and Y would be reversed.) The data from each set are ranked separately from smallest to largest. This has already been done for the survey unit data in Table D.7. For the reference area data, the results in Table D.8 are obtained.

Table D.8 Ranked reference area concentrations

Data:	59.4	69.7	75.3	79.4	79.9	81.1	81.4	81.5	81.7	81.8
Rank:	1	2	3	4	5	6	7	8	9	10
Data:	82.0	82.4	82.4	83.2	88.5	89.7	92.1			
Rank:	11	12.5	12.5	14	15	16	17			

The median for the reference area data is 81.7, the sample mean is 80.7, and the sample standard deviation is 7.5.

For the larger data set, the data must be interpolated to match the number of points in the smaller data set. This is done by computing

$$v_1 = 0.5\ (n/m) + 0.5 \text{ and } v_{i+1} = vi + (n/m) \text{ for } i = 1, \dots m\text{-}1 \qquad \text{(D-9)}$$

where m is the number of points in the smaller data set and n is the number of points in the larger data set. For each of the ranks, i, in the smaller data set, a corresponding value in the larger data set is found by first decomposing v_i into its integer part, j, and its fractional part, g.

Then the interpolated values are computed from the relationship:

$$Z_i = (1\text{-}g)\ Y_j + g\ Y_{j+1} \qquad \text{(D-10)}$$

The results of these calculations are shown in Table D.9.

Table D.9 Interpolated ranks for survey unit concentrations

Rank	1	2	3	4	5	6	7	8	9	10
v_i	1.09	2.26	3.44	4.62	5.79	6.97	8.15	9.33	10.50	11.68
Z_i	74.3	75.7	76.8	77.5	78.1	79.1	80.9	83.7	84.3	85.8
X_i	59.4	69.7	75.3	79.4	79.7	81.1	81.4	81.5	81.7	81.8
Rank	11	12.5	12.5	14	15	16	17			
v_i	12.85	14.03	15.21	16.38	17.56	18.74	19.91			
Z_i	86.4	86.5	87.8	89.1	90.2	90.6	92.3			
X_i	82.0	82.4	82.4	83.2	88.5	89.7	92.1			

Finally, Z_i is plotted against X_i to obtain the quantile-quantile plot. This example is shown in Figure D.6.

The quantile-quantile plot is valuable because it provides a direct visual comparison of the two data sets. If the two data distributions differ only in location (*e.g.*, mean) or scale (*e.g.*, standard deviation), the points will lie on a straight line. If the two data distributions being compared are identical, all of the plotted points will lie on the line Y=X. Any deviations from this would point to possible differences in these distributions. The middle data point plots the median of Y against the median of X. That this point lies above the line Y=X, in the example of Figure D.6, shows that the median of Y is larger than the median of X. Indeed, the cluster of points above the line Y = X in the region of the plot where the data points are dense, is an indication that the central portion of the survey unit distribution is shifted toward higher values than the reference area distribution. This could imply that there is residual radioactivity in the survey unit. This should be tested using the nonparametric statistical tests described in Section 3.10.

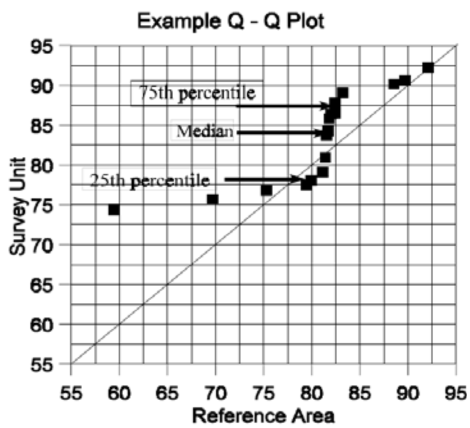


Figure D.6 Example quantile-quantile plot

Further information on the interpretation of Quantile and Quantile-Quantile plots are given in EPA QA/G-9 [121].

D.4 Multiple radio-nuclides

There are two cases to be considered when dealing with multiple radio-nuclides: 1) the radionuclide concentrations have a fairly constant ratio throughout the survey unit, or 2) the concentrations of the different radio-nuclides appear to be unrelated in the survey unit. In statistical terms, we are concerned about whether the concentrations of the different radio-nuclides are correlated or not. A simple way to judge this would be to make a scatter plot of the concentrations against each other, and see if the points appear to have an underlying linear pattern. The correlation coefficient can also be computed to see if it lies nearer to zero than to one. One could also perform a curve fit and test the significance of the result. Ultimately, however, sound judgement must be used in interpreting the results of such calculations. If there is no physical reason for the concentrations to be related, they probably are not. Conversely, if there is sound evidence that the radionuclide concentrations should be related because of how they were treated, processed or released, this information should be used.

Table D.10 Spreadsheet formulas used in Table 3.56

	A	B	C	D	E
1	**Data**	**Area**	**Adjusted Data**	**Ranks**	**Reference Area Ranks**
2	49	R	=IF(B2="R",A2+160,A2)	=RANK(C2,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C2) -1) / 2	=IF(B2="R",D2,0)
3	35	R	=IF(B3="R",A3+160,A3)	=RANK(C3,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C3) -1) / 2	=IF(B3="R",D3,0)
4	45	R	=IF(B4="R",A4+160,A4)	=RANK(C4,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C4) -1) / 2	=IF(B4="R",D4,0)
5	45	R	=IF(B5="R",A5+160,A5)	=RANK(C5,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C5) -1) / 2	=IF(B5="R",D5,0)
6	41	R	=IF(B6="R",A6+160,A6)	=RANK(C6,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C6) -1) / 2	=IF(B6="R",D6,0)
7	44	R	=IF(B7="R",A7+160,A7)	=RANK(C7,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C7) -1) / 2	=IF(B7="R",D7,0)
8	48	R	=IF(B8="R",A8+160,A8)	=RANK(C8,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C8) -1) / 2	=IF(B8="R",D8,0)
9	37	R	=IF(B9="R",A9+160,A9)	=RANK(C9,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C9) -1) / 2	=IF(B9="R",D9,0)
10	46	R	=IF(B10="R",A10+160,A10)	=RANK(C10,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C10) -1) / 2	=IF(B10="R",D10,0)
11	42	R	=IF(B11="R",A11+160,A11)	=RANK(C11,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C11) -1) / 2	=IF(B11="R",D11,0)
12	47	R	=IF(B12="R",A12+160,A12)	=RANK(C12,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C12) -1) / 2	=IF(B12="R",D12,0)
13	104	S	=IF(B13="R",A13+160,A13)	=RANK(C13,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C13) -1) / 2	=IF(B13="R",D13,0)
14	94	S	=IF(B14="R",A14+160,A14)	=RANK(C14,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C14) -1) / 2	=IF(B14="R",D14,0)
15	98	S	=IF(B15="R",A15+160,A15)	=RANK(C15,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C15) -1) / 2	=IF(B15="R",D15,0)
16	99	S	=IF(B16="R",A16+160,A16)	=RANK(C16,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C16) -1) / 2	=IF(B16="R",D16,0)
17	90	S	=IF(B17="R",A17+160,A17)	=RANK(C17,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C17) -1) / 2	=IF(B17="R",D17,0)
18	104	S	=IF(B18="R",A18+160,A18)	=RANK(C18,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C18) -1) / 2	=IF(B18="R",D18,0)
19	95	S	=IF(B19="R",A19+160,A19)	=RANK(C19,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C19) -1) / 2	=IF(B19="R",D19,0)
20	105	S	=IF(B20="R",A20+160,A20)	=RANK(C20,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C20) -1) / 2	=IF(B20="R",D20,0)
21	93	S	=IF(B21="R",A21+160,A21)	=RANK(C21,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C21) -1) / 2	=IF(B21="R",D21,0)
22	101	S	=IF(B22="R",A22+160,A22)	=RANK(C22,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C22) -1) / 2	=IF(B22="R",D22,0)
23	92	S	=IF(B23="R",A23+160,A23)	=RANK(C23,$C$2:$C$23,1)+(COUNTIF($C$2:$C$23,C23) -1) / 2	=IF(B23="R",D23,0)
24			Sum=	=SUM(D2:D23)	=SUM(E2:E23)

D.4.1 Using the unity rule

In either of the two above cases, the unity rule described in Section 3.3.6.3 is applied. The difference is in how it is applied. Suppose there are *n* radio-nuclides. If the concentration of radio-nuclide *i* is denoted by C_i, and its $DCGL_W$ is denoted by D_i, then the unity rule for the n radio-nuclides states that:

$$C_1 / D_1 + C_2 / D_2 + C_3 / D_3 + \quad + C_n / D_n = 1 \qquad \text{(D-11)}$$

This will ensure that the total dose or risk due to the sum of all the radio-nuclides does not exceed the release criterion. Note that if D_{min} is the smallest of the DCGLs, then

$$(C_1 + C_2 + C_3 + \quad + C_n)/D_{min} = C_1 / D_1 + C_2 / D_2 + C_3 / D_3 + \quad + C_n / D_n \qquad \text{(D-12)}$$

so that the smallest DCGL may be applied to the total activity concentration, rather than using the unity rule. While this option may be considered, in many cases it will be too conservative to be useful.

D.4.2 Radio-nuclide concentrations with fixed ratios

If there is an established ratio among the concentrations of the *n* radio-nuclides in a survey unit, then the concentration of every radio-nuclide can be expressed in terms of any one of them, *e.g.*, radio-nuclide #1. The measured radio-nuclide is often called a surrogate radio-nuclide for the others.

If

$$C_2 = R_2 C_1,\ C_3 = R_3 C_1, \ldots,\ C_i = R_i C_1,\ \ldots,\ C_n = R_n C_1$$

then

$$C_1 / D_1 + C_2 / D_2 + C_3 / D_3 + \quad + C_n / D_n$$
$$= C_1 / D_1 + R_2 C_1 / D_2 + R_3 C_1 / D_3 + \quad + R_n C_1 / D_n$$
$$= C_1 [1/D_1 + R_2/D_2 + R_3/D_3 + \quad + R_n/D_n]$$
$$= C_1/D_{total} \qquad \text{(D-13)}$$

where

$$D_{total} = 1/[1/D_1 + R_2/D_2 + R_3/D_3 + \quad + R_n/D_n] \qquad \text{(D-14)}$$

Thus, D_{total} is the $DCGL_W$ for the surrogate radio-nuclide when the concentration of that radio-nuclide represents all radio-nuclides that are present in the survey unit. Clearly, this scheme is applicable only when radio-nuclide specific measurements of the surrogate radio-nuclide are made. It is unlikely to apply in situations where the surrogate radionuclide appears in background, since background variations would tend to obscure the relationships between it and the other radio-nuclides.

Thus, in the case where there are constant ratios among radio-nuclide concentrations, the statistical tests are applied as if only the surrogate radio-nuclide were contributing to the residual radioactivity, with the $DCGL_W$ for that radionuclide replaced by D_{total}. For example, in planning the final status survey, only the expected standard deviation of the concentration measurements for the surrogate radionuclide is needed to calculate the sample size.

For the elevated measurement comparison, the $DCGL_{EMC}$ for the surrogate radio-nuclide is replaced by

$$E_{total} = 1/[1/E_1 + R_2/E_2 + R_3/E_3 + \quad + R_n/E_n] \qquad \text{(D-15)}$$

where E_i is the $DCGL_{EMC}$ for radio-nuclide i.

D.4.3 Unrelated radio-nuclide concentrations

If the concentrations of the different radio-nuclides appear to be unrelated in the survey unit, there is little alternative but to measure the concentration of each radio-nuclide and use the unity rule. The exception would be in applying the most restrictive $DCGL_W$ to all of the radio-nuclides, as mentioned later in this section.

Since the release criterion is

$$C_1 / D_1 + C_2 / D_2 + C_3 / D_3 + \quad + C_n / D_n \leq 1 \qquad \text{(D-16)}$$

the quantity to be measured is the *weighted sum*, $T = C_1/D_1 + C_2/D_2 + C_3/D_3 + \quad + C_n/D_n$. The $DCGL_W$ for T is one. In planning the final status survey, the measurement standard deviation of the weighted sum, T, is estimated by

$$\sigma^2(T) = [\sigma(C_1)/D_1]^2 + [\sigma(C_2)/D_2]^2 + [\sigma(C_3)/D_3]^2 + \quad + [\sigma(C_n)/D_n]^2 \qquad \text{(D-17)}$$

since the measured concentrations of the various radio-nuclides are assumed to be uncorrelated.

For the elevated measurement comparison, the inequality

$$C_1 / E_1 + C_2 / E_2 + C_3 / E_3 + \quad + C_n / E_n \leq 1 \qquad \text{(D-18)}$$

is used, where E_i is the $DCGL_{EMC}$ for radio-nuclide i. For scanning, the most restrictive $DCGL_{EMC}$ should generally be used.

When some of the radio-nuclides also appear in background, the quantity $T = C_1/D_1 + C_2/D_2 + C_3/D_3 + \quad + C_n/D_n$ must also be measured in an appropriate reference area. If radionuclide i does not appear in background, set $C_i = 0$ in the calculation of T for the reference area.

Note that if there is a fixed ratio between the concentrations of some radio-nuclides, but not others, a combination of the method of this section with that of the previous section may be used. The appropriate value of D_{total} with the concentration of the measured surrogate radio-nuclide should replace the corresponding terms in equation D-17.

D.4.4 Example application of WRS Test to multiple radio-nuclides

This section contains an example application of the non-parametric statistical methods in this report to sites that have residual radioactivity from more than one radio-nuclide. Consider a site with both ^{60}Co and ^{137}Cs contamination. ^{137}Cs appears in background from global atmospheric weapons tests at a typical concentration of about 1 pCi/g. Assume that the $DCGL_W$ for ^{60}Co is 2 pCi/g and for ^{137}Cs is 1.4 pCi/g. In disturbed areas, the background concentration of ^{137}Cs can vary considerably. An estimated spatial standard deviation of 0.5 pCi/g for ^{137}Cs will be assumed. During remediation, it was found that the concentrations of the two radio-nuclides were not well correlated in the survey unit. ^{60}Co concentrations were more variable than the ^{137}Cs concentrations, and 0.7 pCi/g is estimated for its standard deviation. Measurement errors for both ^{60}Co and ^{137}Cs using gamma spectrometry will be small compared to this. For the comparison to the release criteria, the weighted sum of the concentrations of these radio-nuclides is computed from:

$$\begin{aligned}\text{Weighted sum} &= (^{60}\text{Co Concentration})/(^{60}\text{Co DCGL}_W) + (^{137}\text{Cs Concentration})/(^{137}\text{Cs DCGL}_W) \\ &= (^{60}\text{Co Concentration})/(2) + (^{137}\text{Cs Concentration})/(1.4)\end{aligned}$$

The variance of the weighted sum, assuming that the ^{60}Co and ^{137}Cs concentrations are spatially unrelated is

$$\begin{aligned}\sigma^2 &= [(^{60}\text{Co Standard deviation})/(^{60}\text{Co DCGL}_W)]^2 + [(^{137}\text{Cs Standard Deviation})/(^{137}\text{Cs DCGL}_W)]^2 \\ &= [(0.7)/(2)]^2 + [(0.5)/(1.4)]^2 = 0.25.\end{aligned}$$

Thus $\sigma = 0.5$. The $DCGL_W$ for the weighted sum is one. The null hypothesis is that the survey unit exceeds the release criterion. During the DQO process, the LBGR was set at 0.5 for the weighted sum, so that $\Delta = DCGL_W - LBGR = 1.0 - 0.5 = 0.5$, and $\Delta/\sigma = 0.5/0.5 = 1.0$. The acceptable error rates chosen were $\alpha = \beta = 0.05$. To achieve this, 32 samples each are required in the survey unit and the reference area.

The weighted sums are computed for each measurement location in both the reference area and the survey unit. The WRS test is then performed on the weighted sum. The calculations for this example are shown in Table D.11. The $DCGL_W$ (i.e., 1.0) is added to the weighted sum for each location in the reference area. The ranks of the combined survey unit and adjusted reference area weighted sums are then computed. The sum of the ranks of the adjusted reference area weighted sums is then compared to the critical value for $n = m = 32$, $\alpha = 0.05$, which is 1162 (see formula following Table D.4). In Table D.11, the sum of the ranks of the adjusted reference area weighted sums is 1281. This exceeds the critical value, so the null hypothesis is rejected. The survey unit meets the release criterion. The difference between the mean of the weighted sums in the survey unit and the reference area is 1.86 - 1.16 = 0.7. Thus, the estimated dose or risk due to residual radioactivity in the survey unit is 70% of the release criterion.

Table D.11 Example WRS test for two radio-nuclides

		Reference Area		Survey Unit		Weighted Sum		Ranks	
	^{137}Cs	^{60}Co	137Cs	60Co	Ref	Survey	Adj Ref	Survey	Adj Ref
1	2.00	0	1.12	0.06	1.43	0.83	2.43	1	56
2	1.23	0	1.66	1.99	0.88	2.18	1.88	43	21
3	0.99	0	3.02	0.56	0.71	2.44	1.71	57	14
4	1.98	0	2.47	0.26	1.41	1.89	2.41	23	55
5	1.78	0	2.08	0.21	1.27	1.59	2.27	9	50
6	1.93	0	2.96	0.00	1.38	2.11	2.38	37	54
7	1.73	0	2.05	0.20	1.23	1.56	2.23	7	46
8	1.83	0	2.41	0.00	1.30	1.72	2.30	16	52
9	1.27	0	1.74	0.00	0.91	1.24	1.91	2	24
10	0.74	0	2.65	0.16	0.53	1.97	1.53	27	6
11	1.17	0	1.92	0.63	0.83	1.68	1.83	13	18
12	1.51	0	1.91	0.69	1.08	1.71	2.08	15	32
13	2.25	0	3.06	0.13	1.61	2.25	2.61	47	63
14	1.36	0	2.18	0.98	0.97	2.05	1.97	30	28
15	2.05	0	2.08	1.26	1.46	2.12	2.46	39	58
16	1.61	0	2.30	1.16	1.15	2.22	2.15	45	41
17	1.29	0	2.20	0.00	0.92	1.57	1.92	8	25
18	1.55	0	3.11	0.50	1.11	2.47	2.11	59	35
19	1.82	0	2.31	0.00	1.30	1.65	2.30	11	51
20	1.17	0	2.82	0.41	0.84	2.22	1.84	44	19
21	1.76	0	1.81	1.18	1.26	1.88	2.26	22	48
22	2.21	0	2.71	0.17	1.58	2.02	2.58	29	62
23	2.35	0	1.89	0.00	1.68	1.35	2.68	3	64
24	1.51	0	2.12	0.34	1.08	1.68	2.08	12	33
25	0.66	0	2.59	0.14	0.47	1.92	1.47	26	5
26	1.56	0	1.75	0.71	1.12	1.60	2.12	10	38
27	1.93	0	2.35	0.85	1.38	2.10	2.38	34	53
28	2.15	0	2.28	0.87	1.54	2.06	2.54	31	61
29	2.07	0	2.56	0.56	1.48	2.11	2.48	36	60
30	1.77	0	2.50	0.00	1.27	1.78	2.27	17	49
31	1.19	0	1.79	0.30	0.85	1.43	1.85	4	20
32	1.57	0	2.55	0.70	1.12	2.17	2.12	42	40
Avg	1.62	0	2.28	0.47	1.16	1.86	2.16	sum =	sum =
Std Dev	0.43	0	0.46	0.48	0.31	0.36	0.31	799	1281

D.5 Normal distribution

Table D.12 Cumulative normal distribution function Φ(z)

z	***0.00***	***0.01***	***0.02***	***0.03***	***0.04***	***0.05***	***0.06***	***0.07***	***0.08***	***0.09***
0.00	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.10	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5674	0.5714	0.5753
0.20	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.30	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.40	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.50	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.60	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.70	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.80	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.90	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.6315	0.8340	0.8365	0.8389
1.00	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.10	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.20	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.30	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.40	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.50	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.60	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.70	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.80	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.90	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.00	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.10	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.20	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.30	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.40	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.50	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.60	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.70	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.80	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.90	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.00	0.9987	0.9987	0.9987	0.9988	0.9988	0.9989	0.9989	0.9989	0.9990	0.9990
3.10	0.9990	0.9991	0.9991	0.9991	0.9992	0.9992	0.9992	0.9992	0.9993	0.9993
3.20	0.9993	0.9993	0.9994	0.9994	0.9994	0.9994	0.9994	0.9995	0.9995	0.9995
3.30	0.9995	0.9995	0.9995	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9997
3.40	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9998

Negative values of z can be obtained from the relationship $\Phi(-z) = 1 - \Phi(z)$.

D.6 Random numbers

Table D.13 1,000 Random numbers uniformly distributed between zero and one

0.163601	0.647423	0.555548	0.248859	0.259801	0.718368	0.305020	0.812482	0.601951	0.973160
0.934196	0.951102	0.979831	0.132364	0.157808	0.040605	0.997626	0.896462	0.360578	0.443218
0.054552	0.965257	0.999181	0.172627	0.583713	0.852958	0.116336	0.748483	0.058602	0.738495
0.972409	0.241889	0.799991	0.926726	0.585505	0.453993	0.877990	0.947022	0.910821	0.388081
0.556401	0.621126	0.293328	0.984335	0.366531	0.912588	0.733824	0.092405	0.717362	0.423421
0.625153	0.838711	0.196153	0.630553	0.867808	0.957094	0.830218	0.783518	0.141557	0.444997
0.527330	0.124034	0.351792	0.161947	0.688925	0.140346	0.553577	0.890058	0.470457	0.566196
0.826643	0.673286	0.550827	0.885295	0.690781	0.371540	0.108632	0.090765	0.618443	0.937184
0.296068	0.891272	0.392367	0.649633	0.261410	0.523221	0.769081	0.358794	0.924341	0.167665
0.848882	0.083603	0.274621	0.268003	0.272254	0.017727	0.309463	0.445986	0.244653	0.944564
0.779276	0.484461	0.101393	0.995100	0.085164	0.611426	0.030270	0.494982	0.426236	0.270225
0.095038	0.577943	0.186239	0.267852	0.786070	0.208937	0.184565	0.826397	0.256825	0.489034
0.011672	0.844846	0.443407	0.915087	0.275906	0.883009	0.243728	0.865552	0.796671	0.314429
0.215993	0.476035	0.354717	0.883172	0.840666	0.393867	0.374810	0.222167	0.114691	0.596046
0.982374	0.101973	0.683995	0.730612	0.548200	0.084302	0.145212	0.337680	0.566173	0.592776
0.860868	0.794380	0.819422	0.752871	0.158956	0.317468	0.062387	0.909843	0.779089	0.648967
0.718917	0.696798	0.463655	0.762408	0.823097	0.843209	0.368678	0.996266	0.542048	0.663842
0.800735	0.225556	0.398048	0.437067	0.642698	0.144068	0.104212	0.675095	0.318953	0.648478
0.915538	0.711742	0.232159	0.242961	0.327863	0.156608	0.260175	0.385141	0.681475	0.978186
0.975506	0.652654	0.928348	0.513444	0.744095	0.972031	0.527368	0.494287	0.602829	0.592834
0.435196	0.272807	0.452254	0.793464	0.817291	0.828245	0.407518	0.441518	0.358966	0.619741
0.692512	0.368151	0.821543	0.583707	0.802354	0.133831	0.569521	0.474516	0.437608	0.961559
0.678823	0.930602	0.657348	0.025057	0.294093	0.499623	0.006423	0.290613	0.325204	0.044439
0.642075	0.029842	0.289042	0.891009	0.813844	0.973093	0.952871	0.361623	0.709933	0.466955
0.174285	0.863244	0.133649	0.773819	0.891664	0.246417	0.272407	0.517658	0.132225	0.795514
0.951401	0.921291	0.210993	0.369411	0.196909	0.054389	0.364475	0.716718	0.096843	0.308418
0.186824	0.005407	0.310843	0.998118	0.725887	0.143171	0.293721	0.841304	0.661969	0.409622
0.105673	0.026338	0.878006	0.105936	0.612556	0.124601	0.922558	0.648985	0.896805	0.737256
0.801080	0.619461	0.933720	0.275881	0.637352	0.644996	0.713379	0.302687	0.904515	0.457172
0.101214	0.236405	0.945199	0.005975	0.893786	0.082317	0.648743	0.511871	0.298942	0.121573
0.177754	0.930066	0.390527	0.575622	0.390428	0.600575	0.460949	0.191600	0.910079	0.099444
0.846157	0.322467	0.156607	0.253388	0.739021	0.133498	0.293141	0.144834	0.626600	0.045169
0.812147	0.306383	0.201517	0.306651	0.827112	0.277716	0.660224	0.268538	0.518416	0.579216
0.691055	0.059046	0.104390	0.427038	0.148688	0.480788	0.026511	0.572705	0.745522	0.986078
0.483819	0.797573	0.174899	0.892670	0.118990	0.813221	0.857964	0.279164	0.883509	0.154562
0.165133	0.985134	0.214681	0.595309	0.741697	0.418602	0.301917	0.338913	0.680062	0.097350
0.281668	0.476899	0.839512	0.057760	0.474156	0.898409	0.482638	0.198725	0.888281	0.018872
0.554337	0.350955	0.942401	0.526759	0.509846	0.408165	0.800079	0.789263	0.564192	0.140684
0.873143	0.349662	0.238282	0.383195	0.568383	0.298471	0.490431	0.731405	0.339906	0.431645
0.401675	0.061151	0.771468	0.795760	0.365952	0.221234	0.947374	0.375686	0.828215	0.113060
0.574987	0.154831	0.808117	0.723544	0.134014	0.360957	0.166572	0.112314	0.242857	0.309290
0.745415	0.929459	0.425406	0.118845	0.386382	0.867386	0.808757	0.009573	0.229879	0.849242
0.613554	0.926550	0.857632	0.014438	0.004214	0.592513	0.280223	0.283447	0.943793	0.205750
0.880368	0.303741	0.247850	0.341580	0.867155	0.542130	0.473418	0.650251	0.326222	0.036285
0.567556	0.183534	0.696381	0.373333	0.716762	0.526636	0.306862	0.904790	0.151931	0.328792
0.280015	0.237361	0.336240	0.424191	0.192603	0.770194	0.284572	0.992475	0.308979	0.698329
0.502862	0.818555	0.238758	0.057148	0.461531	0.904929	0.521982	0.599127	0.239509	0.424858
0.738375	0.794328	0.305231	0.887161	0.021104	0.469779	0.913966	0.266514	0.647901	0.246223
0.366209	0.749763	0.634971	0.261038	0.869115	0.787951	0.678287	0.667142	0.216531	0.763214
0.739267	0.554299	0.979969	0.489597	0.545130	0.931869	0.096443	0.374089	0.140070	0.840563
0.375690	0.866922	0.256930	0.518074	0.217373	0.027043	0.801938	0.040364	0.624283	0.292810
0.894101	0.178824	0.443631	0.110614	0.556232	0.969563	0.291364	0.695764	0.306903	0.303885

0.668169	0.296926	0.324041	0.616290	0.799426	0.372555	0.070954	0.045748	0.505327	0.027722
0.470107	0.135634	0.271284	0.494071	0.485610	0.382772	0.418470	0.004082	0.298068	0.539847
0.047906	0.694949	0.309033	0.223989	0.008978	0.383695	0.479858	0.894958	0.597796	0.162072
0.917713	0.072793	0.107402	0.007328	0.176598	0.576809	0.052969	0.421803	0.737514	0.340966
0.839439	0.338565	0.254833	0.924413	0.871833	0.480599	0.172846	0.736102	0.471802	0.783451
0.488244	0.260352	0.129716	0.153558	0.305933	0.777100	0.111924	0.412930	0.601453	0.083217
0.488369	0.485094	0.322236	0.894264	0.781546	0.770237	0.707400	0.587451	0.571609	0.981580
0.311380	0.270400	0.807264	0.348433	0.172763	0.914856	0.011893	0.014317	0.820797	0.261767
0.028802	0.072165	0.944160	0.804761	0.770481	0.104256	0.112919	0.184068	0.940946	0.238087
0.466082	0.603884	0.959713	0.547834	0.487552	0.455150	0.240324	0.428921	0.648821	0.277620
0.720229	0.575779	0.939622	0.234554	0.767389	0.735335	0.941002	0.794021	0.291615	0.165732
0.861579	0.778039	0.331677	0.608231	0.646094	0.498720	0.140520	0.259197	0.782477	0.922273
0.849884	0.917789	0.816247	0.572502	0.753757	0.857324	0.988330	0.597085	0.186087	0.771997
0.989999	0.994007	0.349735	0.954437	0.741124	0.791852	0.986074	0.444554	0.177531	0.743725
0.337214	0.987184	0.344245	0.039033	0.549585	0.688526	0.225470	0.556251	0.157058	0.681447
0.706330	0.082994	0.299909	0.613361	0.031334	0.941102	0.772731	0.198070	0.460602	0.778659
0.417239	0.916556	0.707773	0.249767	0.169301	0.914420	0.732687	0.934912	0.985594	0.726957
0.653326	0.529996	0.305465	0.181747	0.153359	0.353168	0.673377	0.448970	0.546347	0.885438
0.099373	0.156385	0.067157	0.755573	0.689979	0.494021	0.996216	0.051811	0.049321	0.595525
0.860299	0.210143	0.026232	0.838499	0.108975	0.455260	0.320633	0.150619	0.445073	0.275619
0.067160	0.791992	0.363875	0.825052	0.047561	0.311194	0.447486	0.971659	0.876616	0.455018
0.944317	0.348844	0.210015	0.769274	0.253032	0.239894	0.208165	0.600014	0.945046	0.505316
0.917419	0.185575	0.743859	0.655124	0.185320	0.237660	0.271534	0.949825	0.441666	0.811135
0.365705	0.800723	0.116707	0.386073	0.837800	0.244896	0.337304	0.869528	0.845737	0.194553
0.911453	0.591254	0.920222	0.707522	0.782902	0.092884	0.426444	0.320336	0.226369	0.377845
0.027171	0.058193	0.726183	0.057705	0.935493	0.688071	0.752543	0.932781	0.048914	0.591035
0.768066	0.387888	0.655990	0.690208	0.746739	0.936409	0.685458	0.090931	0.242120	0.067899
0.052305	0.899285	0.092643	0.058916	0.826653	0.772790	0.785028	0.967761	0.588503	0.896590
0.623285	0.492051	0.644294	0.821341	0.600824	0.901289	0.774379	0.391874	0.810022	0.437879
0.624284	0.308522	0.208541	0.297156	0.576129	0.373705	0.370345	0.372748	0.965550	0.874416
0.853117	0.671602	0.018316	0.095780	0.871263	0.885420	0.919787	0.439594	0.460586	0.629443
0.967796	0.933631	0.397054	0.682343	0.505977	0.406611	0.539543	0.066152	0.885414	0.857606
0.759450	0.768853	0.115419	0.744466	0.607572	0.179839	0.413809	0.228607	0.362857	0.826932
0.514703	0.108915	0.864053	0.076280	0.352557	0.674917	0.572689	0.588574	0.596215	0.639101
0.826296	0.264540	0.255775	0.180449	0.405715	0.740170	0.423514	0.537793	0.877436	0.512284
0.354198	0.792775	0.051583	0.806962	0.385851	0.655314	0.046701	0.860466	0.848112	0.515684
0.744807	0.960789	0.123099	0.163569	0.621969	0.571558	0.482449	0.346358	0.795845	0.207558
0.642312	0.356643	0.797708	0.505570	0.418534	0.634642	0.033111	0.393330	0.105093	0.328848
0.824625	0.855876	0.770743	0.678619	0.927298	0.204828	0.831460	0.979875	0.566627	0.056160
0.755877	0.679791	0.442388	0.899944	0.563383	0.197074	0.679568	0.244433	0.786084	0.337991
0.625370	0.967123	0.321605	0.697578	0.122418	0.475395	0.068207	0.070374	0.353248	0.461960
0.124012	0.133851	0.761154	0.501578	0.204221	0.866481	0.925783	0.329001	0.327832	0.844681
0.825392	0.382001	0.847909	0.520741	0.404959	0.308849	0.418976	0.972838	0.452438	0.600528
0.999194	0.297058	0.617183	0.570478	0.875712	0.581618	0.284410	0.405575	0.362205	0.427077
0.536855	0.667083	0.636883	0.043774	0.113509	0.980045	0.237797	0.618925	0.670767	0.814902
0.361632	0.797162	0.136063	0.487575	0.682796	0.952708	0.759989	0.058556	0.292400	0.871674
0.923253	0.479871	0.022855	0.673915	0.733795	0.811955	0.417970	0.095675	0.831670	0.043950
0.845432	0.202336	0.348421	0.050704	0.171916	0.600557	0.284838	0.606715	0.758190	0.394811

Appendix E: Glossary of specific terms applied in site characterization, remediation and restoration processes

absorbed dose: A measure of the energy from ionising radiation deposited in a unit mass of any specified material. The unit of absorbed dose is the Gray.

absorption: Process where material in contact with the skin may pass through the pores on the skin's surface and enter the bloodstream. Identified as a possible route for contaminant entry into the body.

absorption of gamma rays: The process resulting from interaction of gamma quanta (photons) with matter, caused by photoeffect and pair production.

^{228}Ac: actinium-228.

accuracy: Level of agreement between true value and observed value.

accuracy of gamma ray spectrometry analyses: The reliability of analyses in the sense of the relationship of resulting data to the true value of the radioelement concentration.

action level: The numerical value that will cause the *decision maker* to choose one of the alternative actions. It may be a regulatory threshold standard (*e.g.*, Maximum Contaminant Level for drinking water), a dose- or risk-based concentration level (*e.g.*, *DCGL*), or a reference-based standard. See *investigation level*.

activation: Process where a neutron is captured by a nucleus to form a new isotope (often a radionuclide).

activation product: An isotope created by activation.

active flushing: An engineered (artificially enhanced) version of natural flushing, often used to increase the groundwater magnitude and flow velocity.

activity concentration: Terminology used to describe radioactivity levels relative to the mass or volume of the sample matrix (e.g., Bg/kg in soil, Bg/L in water).

activity: See *radioactivity*.

ADP: Automatic Data Processing.

adsorption: A process somewhat similar to ion exchange whereby molecular contaminants are immobilized onto a solid matrix (sorbed onto the solid surface).

airborne gamma ray spectrometer: A high sensitivity gamma ray spectrometer with the capacity to detect gamma rays, analyse and record energy gamma ray spectra in short (s) time intervals within a flight.

airborne gamma ray survey: A survey carried out using an airborne gamma ray spectrometer installed in an aeroplane.

ALARA (acronym for As Low As Reasonably Achievable): A basic concept of radiation protection which specifies that exposure to ionizing radiation and releases of radioactive materials should be managed to reduce collective doses as far below regulatory limits as is reasonably achievable considering economic, technological, and societal factors, among others. Reducing exposure at a site to *ALARA* strikes a balance between what is possible through additional planning and management, remediation, and the use of additional resources to achieve a lower collective dose level. A determination of *ALARA* is a site-specific analysis that is open to interpretation, because it depends on approaches or circumstances that may differ between regulatory agencies. An *ALARA* recommendation should not be interpreted as a set limit or level.

ALARP: As Low As Reasonably Practicable - a standard for assessing necessary control measures taking into account the practicalities of the task in hand. Note: "reasonably practicable" has a defined legal meaning in the UK. ALARP incorporates this legal meaning as opposed to any other meaning that may be implied from technical publications such as those by the International Commission on Radiological Protection (ICRP).

ALF: Action Levels and Standards Framework.

alluvium: A surface accumulation or near surface deposit of unconsolidated or poorly consolidated gravel, sand, clays or peats that are loosely arranged, unstratified or not cemented together.

alpha (α): The specified maximum probability of a *Type I error*. In other words, the maximum probability of rejecting the *null hypothesis* when it is true. *Alpha* is also referred to as the *size of the test*. *Alpha* reflects the amount of evidence the *decision maker* would like to see before abandoning the *null hypothesis*.

alpha decay: A form of radioactive decay resulting in the emission of a positively charged particle (a helium nucleus).

alpha particle: A positively charged particle emitted by some radioactive materials undergoing *radioactive decay*.

alpha radiation: The flux of alpha particles, formed by 2 protons and 2 neutrons.

alpha spectrometry: A sample analysis technique that detects alpha particles emitted from radioisotopes at energies between about 4 and 6 MeV.

alternative hypothesis (H_a): See *hypothesis*.

AM: action memorandum.

^{241}Am: americium-241.

AMD: Acid Mine Drainage.

A_{min}: The smallest *area of elevated activity* identified using the DQO Process that is important to identify.

analytical measurement error: The degree to which a laboratory is able to measure a constituent in a given sample within its actual value.

annual effective dose: A measure of the energy deposited by radiation in organs and tissue per year – measures the biological effects of radiation to humans.

anomaly: a variation in radiation level exceeding those fluctuations normally expected because of the statistical nature of radioactive decay.

anthropogenic radionuclides: Artificially produce radionuclides, by means of activation or nuclear fission.

Approved Dosimetry Service (ADS): A dosimetry service approved by HSE (or a body specified by HSE) for measuring, assessing and recording radiological doses to workers. The aim of approval is to ensure, as far as is possible, that doses are assessed on the basis of accepted national standards.

ARD: Acid Rock Drainage.

area: A general term referring to any portion of a *site*, up to and including the entire *site*.

area factor (A_m): A factor used to adjust $DCGL_W$ to estimate $DCGL_{EMC}$ and the *minimum detectable concentration* for scanning surveys in *Class 1* survey units - $DCGL_{EMC} = DCGL_W \bullet A_m$. A_m is the magnitude by which the *residual radioactivity* in a small *area of elevated activity* can exceed the $DCGL_W$ while maintaining compliance with the *release criterion*. Examples of *area factors* are provided in Section 5 of this manual.

area of elevated activity: An *area* over which *residual radioactivity* exceeds a specified value $DCGL_{EMC}$.

arithmetic mean: The average value obtained when the sum of individual values is divided by the number of values.

arithmetic standard deviation: A statistic used to quantify the variability of a set of data. It is calculated in the following manner: 1) subtracting the arithmetic mean from each data value individually, 2) squaring the differences, 3) summing the squares of the differences, 4) dividing the sum of the squared differences by the total number of data values less one, and 5) taking the square root of the quotient. The calculation process produces the Root Mean Square Deviation (RMSD).

ASL: Analytical Support Level.

assessment: The evaluation process used to measure the performance or effectiveness of a system and its elements. As used in MARSSIM, assessment is an all-inclusive term used to denote any of the following: audit, performance evaluation, management systems review, peer review, inspection, or surveillance.

atmospheric fallout: Widespread dispersion of radionuclides. Normally refers to the effects of nuclear weapons testing or events with global impact such as Chernobyl.

ATP: Adenosine Triphosphate.

attainment objectives: Objectives that specify the design and scope of the sampling study including the radio-nuclides to be tested, the cleanup standards to be attained, the measure or parameter to be compared to the cleanup standard, and the *Type I* and *Type II* error rates for the selected statistical tests.

ATV: All-Terrain Vehicle.

audit (quality): A systematic and independent examination to determine whether quality activities and related results comply with planned arrangements and whether these arrangements are implemented effectively and are suitable to achieve objectives.

available (or existing) technology: A technology that is fully proven in routine commercial use and for which sufficient performance and cost information are available.

averaging volume: The volume of waste over which the activity concentration is measured and averaged to give an average activity concentration for waste sentencing purposes.

background radiation: Radiation from cosmic sources, *naturally occurring radioactive material*, including radon (except as a decay product of *source* or *special nuclear material*), and global fallout as it exists in the environment from the testing of nuclear explosive devices or from nuclear accidents like Chernobyl which contribute to *background radiation* and are not under the control of the cognizant organization. *Background radiation* does not include radiation from *source*, *by-product*, or *special nuclear materials* regulated by the cognizant Federal or State agency. Different definitions may exist for this term. The definition provided in regulations or regulatory program being used for a site release should always be used if it differs from the definition provided here.

background reference area: See *reference area*.

Becquerel (Bq): The International System (SI) unit of activity equal to one nuclear transformation (disintegration) per second. 1 *Bq* = $2.7\text{x}10^{11}$ *Curies (Ci)* = 27.03 picocuries (pCi).

beta (β): The probability of a *Type II error*, *i.e.*, the probability of accepting the null hypothesis when it is false. The complement of *beta* (1-β) is referred to as the *power* of the test.

beta decay: A form of radioactive decay resulting in the emission of an electron or positron.

beta particle: An electron emitted from the nucleus during *radioactive decay*.

beta radiation: The flux of beta particles, formed by electrons.

bias: The systematic or persistent distortion of a measurement process which causes errors in one direction (*i.e.*, the expected sample measurement is different from the sample's true value).

biased sample or measurement: See *judgement measurement*.

bio-barrier: A low permeability barrier which employs the growth of bacteria to block the pores in a geological formation, thereby retarding fluid flow.

BOD: Biological Oxygen Demand.

BPEO: Best Practicable Environmental Option.

Bq: Becquerel – a unit of radioactivity (one nuclear transformation per second).

BWR: Boiling Water Reactor.

by-product material: Any radioactive material (except *special nuclear material*) yielded in or made radioactive by exposure to the radiation incident to the process of producing or utilizing *special nuclear material*.

CA: Chloroethane.

CAHs: Chlorinated Aliphatic Hydrocarbons.

calibration: The process by which the response of a radiometric instrument is related to sources of known activity or other defined radioactivity quantities. Calibration of radiometric instruments implies the estimation of instrument sensitivities and other constants.

calibration pads: Concrete cylindrical or rectangular pads, enriched individually by radioelements of interest – usually K, U and Th.

CANDU: Canada Deuterium Uranium (pressurized heavy water reactor).

car-borne gamma ray spectrometer: High sensitivity gamma ray spectrometer mounted in a motor vehicle for the detection of gamma-radiation over short (s) time intervals.

CBO: community based organisation.

CD: compact disc.

CDE (Committed Dose Equivalent): The *dose equivalent* calculated to be received by a tissue or organ over a 50-year period after the intake into the body. It dose not include contributions from radiation sources external to the body. CDE is expressed in units of Sv or rem.

CEDE (Committed Effective Dose Equivalent): The sum of the committed *dose equivalent* to various tissues in the body, each multiplied by the appropriate weighting factor (W_t). CEDE is expressed in units of Sv or rem. See *TEDE*.

CF: Concentration Factor for a radionuclide between different environmental compartments, for example soil solution and plants (ratio of Bq/g plant to Bq/mL water or soil solution).

CG: Coordination Group.

chain of custody: An unbroken trail of accountability that ensures the physical security of samples, data, and records.

characterization survey: A type of *survey* that includes facility or *site* sampling, monitoring, and analysis activities to determine the extent and nature of contamination. *Characterization surveys* provide the basis for acquiring necessary technical information to develop, analyze, and select appropriate *cleanup* techniques.

CLARC: Cleanup Levels And Risk Calculation.

class 1 area: An *area* that is projected to require a *Class 1 final status survey*.

class 1 survey: A type of *final status survey* that applies to *areas* with the highest potential for contamination, and meet the following criteria: (1) *impacted*; (2) potential for delivering a dose above the *release criterion*; (3) potential for small *areas of elevated activity*; and (4) insufficient evidence to support reclassification as *Class 2* or *Class 3*.

class 2 area: An *area* that is projected to require a *Class 2 final status survey*.

class 2 survey: A type of *final status survey* that applies to *areas* that meet the following criteria: (1) *impacted*; (2) low potential for delivering a dose above the *release criterion*; and (3) little or no potential for small *areas of elevated activity*.

class 3 area: An *area* that is projected to require a *Class 3 final status survey*.

class 3 survey: A type of *final status survey* that applies to *areas* that meet the following criteria: (1) *impacted*; (2) little or no potential for delivering a dose above the *release criterion*; and (3) little or no potential for small *areas of elevated activity*.

class I survey area: A type of final status survey that applies to areas with the highest potential for contamination and that meet the following criteria: (1) impacted, (2) potential for delivering a dose above the release criterion, (3) potential for small areas of elevated activity, and (4) insufficient evidence to support classification as Class 2 or Class 3. Available on-line at http://www.epa.gov/radiation/terms/.

class II survey area: A type of final status survey that applies to areas that meet the following criteria: (1) impacted, (2) low potential for delivering a dose above the release criterion, and (3) little or no potential for small areas of elevated activity. Available on-line at http://www.epa.gov/radiation/terms/.

class III survey area: A type of final status survey that applies to areas meeting the following criteria: (1) impacted, (2) little or no potential of delivering a dose above the release criterion, and (3) little or no potential for small areas of elevated activity. Available on-line at http://www.epa.gov/radiation/terms/.

classification: The act or result of separating *areas* or *survey units* into one of three designated classes: *Class 1 area*, *Class 2 area*, or *Class 3 area*.

classified worker: A category of worker defined under the Ionising Radiations Regulations 1999. Any person who, during the course of their work, is likely to receive an annual effective dose in excess of 6 mSv or three-tenths of the appropriate dose limit should be a classified worker.

clastic dyke: Geologic formation which can facilitate vertical transport of contaminants (preferential pathway).

clean-up: Actions taken to deal with a release or threatened release of hazardous substances that could affect public health or the environment. The term is often used broadly to describe various Superfund response actions or phases of remedial responses, such as remedial investigation/ feasibility study. Cleanup is sometimes used interchangeably with the terms *remedial action*, response action, or *corrective action*.

clean-up standard: A numerical limit set by a regulatory agency as a requirement for releasing a *site* after *cleanup*. See *release criterion*.

clean-up (survey) unit: A geographical *area* of specified size and shape defined for the purpose of survey design and compliance testing.

cm: centimetre.

cm^2: square centimetre.

^{60}Co: cobalt-60.

COC: contaminant of concern.

coefficient of variation: A unitless measure that allows the comparison of dispersion across several sets of data. It is often used in environmental applications because variability (expressed as a standard deviation) is often proportional to the mean. See *relative standard deviation*.

collimating shield: A window-like device made of a material that is impenetrable to gamma rays, such as lead, that can be attached to a scintillator to decrease the size of the detection field.

comparability: The degree to which one set of measurement data agrees with another for similar samples and sampling conditions; it is an overall indicator of data quality that combines accuracy, precision, and representativeness.

completeness: A measure of the amount of valid data obtained from a measurement system compared to the amount that was expected to be obtained under correct, normal conditions.

composite sample: A sample formed by collecting several samples and combining them (or selected portions of them) into a new sample which is then thoroughly mixed.

Compton continuum: That part of the gamma energy spectrum formed by photons that have lost part of their original energies through Compton scattering.

Compton scattering: The interaction of a photon with an orbit electron of an atom, in which the photon loses part of its energy and changes its direction.

conceptual model: A textual or schematic hypothesis of the sources and nature of contamination on a site, the pathways and migration mechanisms by which it may be transported, and the receptors that may be affected.

conceptual site model: A compilation of pertinent information about a site, historical land use, waste disposal records, analytical data sets, etc., that helps investigators to identify existing data gaps. The conceptual site model supports the development of data collection strategies that target those data gaps.

cone penetrometer technologies: Widely used in both federal and private sector cleanups, CPTs are a type of direct-push technology. Instead of producing a borehole as with traditional drilling equipment, a hydraulic ram mounted onto a 20- to 40-ton truck is used to drive a narrow steel cone (e.g., 1.75 in) with attached geotechnical sensors and analytical detectors directly into the ground, saving time and eliminating the potential need for hazardous waste disposal.

confidence interval: A range of values for which there is a specified probability (*e.g.*, 80%, 90%, 95%) that this set contains the true value of an estimated parameter.

confirmatory survey: A type of *survey* that includes limited independent (third-party) measurements, sampling, and analyses to verify the findings of a *final status survey*.

consensus standard: A standard established by a group representing a cross section of a particular industry or trade, or a part thereof.

constituent: A chemical species present in a system; often called a component, although the term component has a more restricted meaning in physical chemistry.

contaminant: An undesirable concentration or quantity of a substance, or activity concentration of a radionuclide, present in water, atmosphere or soil.

contaminated land: Any land on or under which radioactive or non-radioactive contaminants are suspected to be present at concentration levels above the natural and artificial background concentration levels that are typical of the location of the site. This is not the same as the statutory definition in Part IIA of the Environmental Protection Act, 1990 which defines the presence of contamination by the possibility of significant harm or the pollution of controlled waters.

contamination: The presence of *residual radioactivity* in excess of levels which are acceptable for release of a *site* or facility for *unrestricted use*.

control chart: A graphic representation of a process, showing plotted values of some statistic gathered from that characteristic, and one or two control limits. It has two basic uses: 1) as a judgement to determine if a process was in control, and 2) as an aid in achieving and maintaining statistical control.

controlled area: Any area where the annual effective dose to persons working there is likely to exceed 6 mSv or three-tenths of the appropriate dose limit.

controlled waste: Defined for the purposes of the Environmental Protection Act 1990 as comprising household, commercial and industrial waste. Excludes certain categories of waste, such as radioactive waste.

controlled waters: Defined in Part III (Section 104) of the Water Resources Act 1991, this embraces territorial and coastal waters, inland fresh waters, and groundwaters.

core sample: A soil sample taken by core drilling.

corrective action: An action taken to eliminate the causes of an existing non-conformance, deficiency, or other undesirable situation in order to prevent recurrence.

cosmic radiation: The component of natural radiation formed by high energy particles and photons coming from outer space. Intensity of cosmic radiation increases with altitude.

cosmogenic radionuclides: Radionuclides produced by the interaction of cosmic rays with terrestrial matter (e.g., in the atmosphere).

count rate: The response of a radiometric instrument to detected radiation, given in counts per unit time.

counting time: Preselected time for a radiometric instrument to accumulate counts as a measure of radiation.

counts: Recorded response of a radiometric instrument to radiation sources. The response is due to either a detected particle or photon of energy.

cpm: counts per minute.

CPTs: Cone Penetrometer Technologies.

CPU: Central Processing Unit.

criterion: See *release criterion*.

critical group: The group of individuals reasonably expected to receive the greatest exposure to *residual radioactivity* for any applicable set of circumstances.

critical level (L_C): A fixed value of the *test statistic* corresponding to a given probability level, as determined from the sampling distribution of the *test statistic*. L_C is the level at which there is a statistical probability (with a predetermined confidence) of correctly identifying a background value as "greater than background."

critical value: The value of a statistic (t) corresponding to a given significance level as determined from its sampling distribution; e.g., if $Pr(t > t_0) = 0.05$, t_0 is the critical value of t at the 5 percent level.

cross-contamination: A process whereby, during a series of intrusive investigations or within a single investigation, contaminated material from one area comes into contact with material from another area, thereby potentially affecting the results of any analyses being carried out.

^{137}Cs: cesium-137.

CSM: Conceptual Site Model.

CT: Carbon tetrachloride.

curie (Ci): The customary unit of radioactivity. One *curie* (Ci) is equal to 37 billion disintegrations per second (3.7×10^{10} dps = 3.7×10^{10} *Bq*), which is approximately equal to the decay rate of one gram of ^{226}Ra. Fractions of a *curie*, *e.g.* picocurie (pCi) or 10^{-12} Ci and microcurie (µCi) or 10^{-6} Ci, are levels typically encountered in *decommissioning*.

cut-off wall: A vertical barrier installed to prevent the horizontal migration of groundwater.

cyclotron: A device used to impart high energy to charged particles, of atomic weight one or greater, which can be used to initiate nuclear transformations upon collision with a suitable target.

D: The true, but unknown, value of the difference between the mean concentration of *residual radioactivity* in the *survey unit* and the *reference area*.

D&D: Decommissioning and Decontamination.

Data Life Cycle (DLF): The process of planning the survey, implementing the survey plan, and assessing the survey results prior to making a decision is called the Data Life Cycle.

Data Quality Assessment (DQA): The scientific and statistical evaluation of data to determine if the data are of the right type, quality, and quantity to support their intended use.

Data Quality Indicators (DQI): Measurable attributes of the attainment of the necessary quality for a particular decision. *Data quality indicators* include *precision, bias, completeness, representativeness, reproducibility, comparability*, and statistical confidence.

Data Quality Objectives (DQOs): Qualitative and quantitative statements derived from the DQO process that clarify study technical and quality objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions.

Data Quality Objectives Process: A systematic strategic planning tool based on the scientific method that identifies and defines the type, quality, and quantity of data needed to satisfy a specified use. The key elements of the process include:

- Concisely defining the problem;
- Identifying the decision to be made;
- Identifying the inputs to that decision;
- Defining the boundaries of the study;
- Developing the decision rule;
- Specifying tolerate limits on potential decision errors;
- Selecting the most resource efficient data collection design.

DQOs are the qualitative and quantitative outputs from the DQO process. The DQO process was developed originally by the U.S. Environmental Protection Agency, but has been adapted for use by other organizations to meet their specific planning requirement. See also *graded approach*.

data usability: The process of ensuring or determining whether the quality of the data produced meets the intended use of the data.

daughter nuclide: See *decay product*.

daughter products: Radioelements formed in a disintegration series from a mother element.

DCA: Dichloroethane.

DCE: Dichloroethene.

DCF: Dose Conversion Factor.

DCGL: See *Derived Concentration Guideline Level*

$DCGL_{EMC}$: derived concentration guideline level: elevated measurement criterion.

$DCGL_{W}$: derived concentration guideline level: Wilcoxon Rank Sum Test.

dead time: The time required for a detector or a radiometric instrument to generate and process a signal (electrical signal) as a response to detected nuclear particle. During this time the instrument is insensitive to other incident particles or photons.

decay: The decrease in the amount of a radionuclide due to the spontaneous emission of atomic particles from the nucleus.

decay chain: A series of radionuclides, each of which decays into the next radionuclide in the series until a stable nuclide is reached.

decay constant, λ: For a particular radionuclide, $\lambda = dP/dt$, where dP is the probability of a given nucleus undergoing a spontaneous nuclear transition in the time interval dt.

decay product: The nuclide produced following a radioactive decay. Also called a daughter nuclide.

decision maker: The person, team, board, or committee responsible for the final decision regarding disposition of the *survey unit*.

decision rule: A statement that describes a logical basis for choosing among alternative actions.

decommission: To remove a facility or *site* safely from service and reduce *residual radioactivity* to a level that permits release of the property and termination of the *license* and other authorization for site operation.

decommissioning: The process of removing a facility or *site* from operation, followed by *decontamination*, and license termination (or termination of authorization for operation) if appropriate. The objective of *decommissioning* is to reduce the *residual radioactivity* in structures, materials, soils, groundwater, and other media at the *site* so that the concentration of each radionuclide contaminant that contributes to *residual radioactivity* is indistinguishable from the *background radiation* concentration for that radionuclide.

decontamination: The removal of radiological contaminants from, or their neutralization on, a person, object or area to within levels established by governing regulatory agencies. *Decontamination* is sometimes used interchangeably with *remediation*, remedial action, and *cleanup*.

deconvolution of a spectrum: The process of decomposition of an energy spectrum to spectral components corresponding to that from individual contributing sources.

Defence site: In this guidance, non-nuclear sites that have been or are being used for defence activities and for which a change of use and/or ownership is planned. Nuclear sites that are operated for MoD by contractors and that are licensed and regulated by HSE under the Nuclear Installations Act are *nuclear-licensed sites.*

delicensing: The process of releasing a *nuclear-licensed site* from regulation under the Nuclear Installations Act and of releasing the operator from his period of responsibility for any nuclear liability.

delta (δ): The amount that the distribution of measurements for a *survey unit* is shifted to the right of the distribution of measurements of the *reference area*.

delta (Δ): The width of the *gray region*. Δ divided by σ, the *arithmetic standard deviation* of the measurements, is the *relative shift* expressed in multiples of standard deviations. See *relative shift, gray region*.

dense non-aqueous phase liquids: Chemicals that are denser than and immiscible with water upon environmental release.

Derived Concentration Guideline Level (DCGL): A derived, radionuclide-specific activity concentration within a *survey unit* corresponding to the *release criterion*. The *DCGL* is based on the spatial distribution of the contaminant and hence is derived differently for the *nonparametric* statistical test ($DCGL_W$) and the *Elevated Measurement Comparison* ($DCGL_{EMC}$). *DCGLs* are derived from activity/dose relationships through various *exposure pathway* scenarios.
The *DCGL* can also be used for non-radiological parameters e.g. temperature, relative humidity, concentration of volatile-organic-compounds, concentration of chemical compounds etc.

design specification process: The process of determining the sampling and analysis procedures that are needed to demonstrate that the attainment objectives are achieved.

detection efficiency: Probability that an incident particle or photon will interact with the detector - the ratio of registered counts to the number of incident particles.

detection limit: The net response level that can be expected to be seen with a detector with a fixed level of certainty.

detection sensitivity: The minimum level of ability to identify the presence of radiation or *radioactivity*.

detector: A sensitive sensor having the capacity to register ionizing radiation directly or to transform the energy of incident nuclear particles to electrical quantities.

dH: Deutsche Harte = one degree dH = one gram CaO/100 Liter H_2O.

differential gamma ray spectrometer: Radiometric instrument that registers gamma rays of energies within defined lower and upper limits (in energy channels).

direct measurement: Radioactivity measurement obtained by placing the detector near the surface or media being surveyed. An indication of the resulting radioactivity level is read out directly.

discharge: Any emission of a contaminant into the environment.

displacement barrier: A barrier constructed by forcing the barrier material into the ground without any associated excavation.

distribution coefficient (K_d): The ratio of elemental (*i.e.*, radionuclide) concentration in soil to that in water in a soil-water system at equilibrium. K_d is generally measured in terms of gram weights of soil and volumes of water (g/cm^3 or g/ml).

DLF: See *Data Life Cycle*.

DNAPL: Dense Non-Aqueous Phase Liquid.

dose: A measure of the energy deposits by radiation in a target.

dose commitment: The dose that an organ or tissue would receive during a specified period of time (*e.g.*, 50 or 70 years) as a result of intake (as by ingestion or inhalation) of one or more radio-nuclides from a given release.

dose constraint: A target maximum individual dose set by an employer or Radiation Protection Adviser for any project involving the use of ionising radiations. The target is set on the basis of what can be achieved by best practice and helps to keep doses ALARP.

dose equivalent (dose): A quantity that expresses all radiations on a common scale for calculating the effective absorbed dose. This quantity is the product of absorbed dose (rads) multiplied by a quality factor and any other modifying factors. Dose is measured in *Sv* or *rem*.

dose rate: The ratio of the dose deposited by radiation in a target to the exposure time.

double-blind measurement: Measurements that cannot be distinguished from routine measurements by the individual performing the measurement. See *non-blind measurement* and *single-blind measurement*.

dpm: Disintegrations per minute.

DQA: See *Data Quality Assessment.*

DQI: Data Quality Indicator.

DQOs: See *Data Quality Objectives.*

DVS: Dynamic Verification Study.

EA: Environment Agency.

EDE: Effective Dose Equivalent.

EE/CA: Engineering Evaluation/Cost Analysis.

effective dose: The quantity E, defined as a summation of the tissue equivalent doses (HT), each multiplied by the appropriate tissue weighting factor (w_T). $E = \Sigma w_T H_T$.

effective probe area: The *physical probe area* corrected for the amount of the probe area covered by a protective screen.

EIA: Environmental Impact Assessment.

electro-kinetics: The use of an electrical field to remove contaminants from the groundwater or from soil.

electron-hole pairs: In a semiconductor crystal, a gamma ray can excite an electron up from ist valence band to a higher energy level. The electron leaves behind a .hole. that acts like a positively charged particle. The electron-hole pairs are held together with their opposite charges and can carry electric current throughout the crystal.

electrowinning: Concentration of metals from a pregnant solution using electrolysis techniques.

elevated area: See *area of elevated activity*.

elevated measurement: A measurement that exceeds a specified value $DCGL_{EMC}$.

Elevated Measurement Comparison (EMC): This comparison is used in conjunction with the Wilcoxon test to determine if there are any measurements that exceed a specified value $DCGL_{EMC}$.

emerging technology: Those technologies that require additional laboratory or pilot-scale testing to document the technical viability of the process.

EMC: elevated measurement criterion.

EML: Environmental Measurements Laboratory.

EMS: Excavation Monitoring System.

energy calibration: The process of establishing the relationship between energy of recorded gamma rays, and the channel number of a multichannel gamma ray spectrometer.

energy gamma ray spectrum: A graphical presentation of the energies of gamma rays against their frequency (counts per channel). Peaks in the spectrum indicate radionuclide emission lines.

energy resolution: Parameter describing the ability of detector to distinguish gamma ray energies.

energy threshold: An energy below which all particles/photons are ignored.

energy window: A defined energy interval of the gamma ray spectrum. Energy window implies several energy channels.

environment: The environment includes, but is not limited to, people's property (e.g. houses and land), existing and potential resources (e.g. groundwater, water quality, air quality) and natural ecosystems. In this guidance, *people* are regarded separately from the environment. The distinction is made for consistency with health and safety, and radiological protection, terminology.

envisageable options: All the options that would be effective for managing the *contaminated land*.

equivalent dose: The sum of the corrected doses (see quality factor) for each type of radiation. Takes into account the different amounts of damage done by different radioactive decay types. The unit of equivalent dose is the Sievert.

equivalent uranium, equivalent thorium: The concentration of uranium/thorium estimated by gamma ray spectrometry under the assumption that the U and Th decay series are in secular equilibrium.

excavated barrier: A barrier constructed by removing soil material and replacing it with the a desired barrier material.

exempt waste: Radioactive waste that is exempt from some or all of the requirements of the Radioactive Substances Act 1993. Such wastes are defined in Exemption Orders made under the Act. See also *SoLA*.

exemption orders: Subsidiary legislation, operating under the Radioactive Substances Act 1993, that "exempts" certain materials and forms up to prescribed activity concentrations from some or all of the requirements of the Act.

exposure pathway: The route by which radioactivity travels through the environment to eventually cause radiation exposure to a person or group.

exposure rate: The amount of ionization produced per unit time in air by X-rays or gamma rays. The unit of exposure rate is Roentgens/hour (R/h); for decommissioning activities the typical units are microRoentgens per hour (μR/h), *i.e.*, 10^{-6} R/h.

ex-situ technology: A process applied external to the contaminated region, above ground.

external radiation: Radiation from a source outside the body.

extraction: Removal (extraction) of groundwater via pumping.

fallout: Fallout, nuclear fallout, man-made radioactive isotopes deposited on the earth surface.

false negative decision error: The error that occurs when the null hypothesis (H_0) is not rejected when it is false. For example, the false negative decision error occurs when the decision maker concludes that the waste is hazardous when it truly is not hazardous. A statistician usually refers to a false negative error as a *Type II decision error*. The measure of the size of this error is called *beta*, and is also known as the complement of the power of a hypothesis test.

false positive decision error: A false positive decision error occurs when the null hypothesis (H_0) is rejected when it is true. Consider an example where the decision maker presumes that a certain waste is hazardous (*i.e.*, the null hypothesis or baseline condition is "the waste is hazardous"). If the decision maker concludes that there is insufficient evidence to classify the waste as hazardous when it truly is hazardous, the decision maker would make a false positive decision error. A statistician usually refers to the false positive error as a *Type I decision error*. The measure of the size of this error is called *alpha*, the level of significance, or the size of the critical region.

FID: Flame Ionization Detector.

FIDLER: Field Instrument for Detecting Low Energy Radiation.

field sampling plan: As defined for Superfund in the Code of Federal Regulations 40 CFR 300.430, a document which describes the number, type, and location of samples and the type of analyses to be performed. It is part of the *Sampling and Analysis Plan*.

final remediation levels: Media-specific cleanup goals that are indicative of a site that requires no further remediation.

final status survey: Measurements and sampling to describe the radiological conditions of a site, following completion of decontamination activities (if any) in preparation for release.

fingerprint (radiological): A mixture of radioactive isotopes that distinguish a particular emission.

fission product: A nuclide produced as a result of nuclear fission.

fluence: A measure of the strength of a radiation field.

fluence rate: A fundamental parameter for assessing the level of radiation at a measurement site. In the case of *in situ* spectrometric measurements, a calibrated detector provides a measure of the *fluence rate* of primary photons at specific energies that are characteristic of a particular radionuclide.

FRL: Final Remediation Levels.

ft: foot.

funnel and gate: A variation of a reactive barrier wherein low permeability barriers are employed to channel contaminated groundwater through a reactive barrier of treatment zone.

FUSRAP: Formerly Utilized Sites Remedial Action Program.

future: The period over which the potential effects of the *contaminated land* need to be considered when evaluating the options that may be applied to it. Many contaminants have long half-lives in the environment, and so it may be necessary to consider hundreds of years or more.

future use: The range of uses to which the *contaminated land* will be able to be put after the selected *option* has been implemented successfully. The range of future uses may be restricted to reduce the potential hazards associated with residual contamination. Alternatively, the site may be made available for any future use, in which case lower levels of residual concentrations of contaminants are likely to be required.

g: gram.

gamma (γ) radiation: Penetrating high-energy, short-wavelength electromagnetic radiation (similar to X-rays) emitted during *radioactive decay*. Gamma rays are very penetrating and require dense materials (such as lead or steel) for shielding.

gamma ray: Hyphenated when used as an adjective (eg. gamma ray spectrometer).

gamma rays: Photons of energy that posses neither charge nor mass. Electromagnetic radiation with a frequency of about 3×10^{19}Hz.

gamma ray spectrometry: Radiometric method based on the proportionality between energy of gamma quanta deposited in the detector and pulse amplitudes at the output of the detector, that enables the qualitative and quantitative analyses of gamma ray emitting sources.

gamma spectrometry: See *gamma ray spectrometry*.

gamma total count measurements: Measurement of gamma radiation with instruments responding to gamma rays of all energies.

ganglion: A globule of a substance.

gas-filled detector: Radiation detector consisting of a tube filled with ionisable gas. When the gas is ionised by radiation, the ions are detected by electrodes.

GCR: Gas Cooled Reactor.

geometric correction: A correction applied to instrument sensitivities estimated from calibrations using calibration pads of limited horizontal and vertical dimensions.

geophysics: The science of detecting geological structure and buried objects using a variety of (normally non-intrusive) investigative techniques.

geotechnical testing: Determination of the physical properties of soil/rock.

GIS: Geographic Information System.

global positioning systems: Using satellites in orbit over the earth, a GPS unit can identify a person's location using built-in internal triangulation calculations. With three satellites in view, latitude and longitude can be calculated; with four satellites in view, latitude, longitude, and elevation can be calculated. Differentially corrected GPS units have an error of approximately 2 m horizontally and tens of meters vertically, while civil-survey grade systems can provide sub-centimeter accuracy in all three dimensions.

GPERS-II: Global Positioning Environmental Radiological Surveyor System.

GPS: Global Positioning System.

graded approach: The process of basing the level of application of managerial controls applied to an item or work according to the intended use of the results and the degree of confidence needed in the quality of the results. See *data quality objectives process*.

gradient, hydrological: The rate of change in total hydraulic head per unit distance of flow in a given direction.

gradient manipulation: See *active flushing*.

Gray (Gy): SI unit of kerma and absorbed dose, equal to 1 J/kg.

gray region: A quantitative statistical value that expresses the degree of the variability associated or expected with measurements of the radioactivity at a site and captures the range of values over which radiological measurements are expected to vary. The upper bound of the gray region is defined as the DCGLw. The lower bound of the gray region (LBGR) is set so that the gray region spans a range equal to between one and three times the known or estimated value of the standard deviation (σ) of the measurements.

grid: A network of parallel horizontal and vertical lines forming squares on a map that may be overlaid on a property parcel for the purpose of identification of exact locations. See *reference coordinate system*.

grid block: A square defined by two adjacent vertical and two adjacent horizontal reference grid lines.

gridding: The interpolation of irregularly spaced data onto a mesh at regularly spaced intervals.

gross activity: The total activity measured from a dry sample.

groundwater: All water that is below the surface of the ground in the saturation zone and is in direct contact with the ground or subsoil.

half-life ($t_{1/2}$): The time required for one-half of the atoms of a particular radionuclide present to disintegrate.

harm: Adverse effect on the health of living organisms, or other interference with ecological systems of which they form a part, and, in the case of humans, including property.

hazard: The potential for harm posed by a contaminant or circumstance, taking no account of the likelihood of exposure.

hazardous: Waste and material that because of their quantity, concentration and/or physical, chemical or infectious characteristics may pose a substantial potential threat to human health or the environment when improperly handled, treated, stored or disposed of, or otherwise mismanaged.

HEAST: Health Effects Assessment Summary Tables.

hectare: A unit of area, equivalent to 10 000 m^2.

height correction: The correction of airborne gamma ray spectrometric data for variations in the height of the survey aircraft above the ground.

HEPA filtration: High Efficiency Particulate Air filtration.

heterogeneous: Material with areas of different composition within its volume.

Historical Site Assessment (HSA): A detailed investigation to collect existing information, primarily historical, on a *site* and its surroundings.

HLW: High Level Waste.

HM: Heavy Metal.

HMX: High Melting (point) eXplosive (also known as octogen and cyclotetramethylene-tetranitramine).

hold point: Exposure limit specified for a particular project, which cannot be exceeded without re-assessment of working practices, including any PPE and RPE requirements.

homogeneous: Material of uniform composition throughout its volume.

homogenized sample: A sample that has been thoroughly mixed so that the concentration of constituents in subsequent subsamples would be equivalently distributed.

hot measurement: See *elevated measurement*.

hot spot: See *area of elevated activity*.

HPGe: High Purity Germanium.

HPGe detectors: A real-time instrumentation technology used to detect gamma rays at low activity levels or when many nuclides are present in a sample. This detector produces electron hole pairs upon the photo-ionization of the germanium crystal by high-energy gamma rays.

hr: hour.

HSA: Historical Site Assessment.

HSE: Health and Safety Executive.

HSP: Health and Safety Plan.

HSRAM: Hanford Site Risk Assessment Methodology.

HWGC: Heavy Water Gas Cooled reactor.

hydraulic containment: Containment achieved through the manipulation by hydraulic means of the groundwater flow around a particular region of contamination in order to prevent further migration or movement of the contaminants.

hypothesis: An assumption about a property or characteristic of a set of data under study. The goal of statistical inference is to decide which of two complementary hypotheses is likely to be true. The *null* *hypothesis* (H_0) describes what is assumed to be the true state of nature and the *alternative hypothesis* (H_a) describes the opposite situation.

IAEA: International Atomic Energy Agency.

IC: Institutional Control.

ICRP: International Commission on Radiologic Protection.

ILCR: Incremental Lifetime Cancer Risk.

ILW: Intermediate Level Waste.

impacted area: Any *area* that is not *classified* as *non-impacted*. Areas with a reasonable possibility of containing *residual radioactivity* in excess of natural background or fallout levels.

in: inch.

in situ sample: Measurements of a constituent taken directly in the field.

independent assessment: An assessment performed by a qualified individual, group, or organization that is not part of the organization directly performing and accountable for the work being assessed.

indistinguishable from background: The term indistinguishable from background means that the detectable concentration distribution of a radio-nuclide is not statistically different from the background concentration distribution of that radionuclide in the vicinity of the site or, in the case of structures, in similar materials using adequate measurement technology, survey, and statistical techniques.

industrial process: Term used very broadly in the present report to denote any human activity involving the application of technology, for example, mining, processing and drinking water treatment.

inferential uncertainty: The relationship between the measured parameters and the contaminants of concern.

infiltration rate: The rate at which a quantity of a hazardous substance moves from one environmental medium to another - *e.g.*, the rate at which a quantity of a radio-nuclide moves from a source into and through a volume of soil or solution.

infinite radiation source: A source of gamma radiation represented by an infinite half-space with homogeneous concentration of a radionuclide or radionuclides.

ingestion: Contaminant entering the stomach and gastrointestinal tract through eating contaminated food or hand to mouth contact.

inhalation: Breathing contaminant (eg particulate material, vapour, gas) in through the mouth or nose.

injection: Contaminant entering the body tissue and blood stream directly through cuts and abrasions.

innovative technology: A treatment technology for which cost or performance information is incomplete, thus hindering routine use at hazardous waste sites. An innovative technology may require additional full-scale field testing before it is considered proven and ready for commercialization and routine use.

in-situ technology: A process applied in place (within the ground or contaminated region).

inspection: An activity such as measuring, examining, testing, or gauging one or more characteristics of an entity and comparing the results with specified requirements in order to establish whether conformance is achieved for each characteristic.

internal radiation: The term describing the radiation field and absorbed doses from internal sources in the human body.

internal radiation dose: Dose received internally to the body via inhalation, absorption, ingestion or injection routes.

intervention: Any action intended to reduce or avert exposure or the likelihood of exposure to sources which are not part of a controlled practice or which are out of control as a consequence of an accident.

inventory: Total residual quantity of formerly licensed radioactive material at a site.

investigation level: A derived media-specific, radio-nuclide-specific concentration or activity level of radioactivity that: 1) is based on the release criterion, and 2) triggers a response, such as further investigation or cleanup, if exceeded. See *action level*.

ion exchange: A usually reversible exchange of one ion with another, either on a solid surface , or within a lattice. A commonly used method for treatment of liquid waste.

ionising radiation: Any form of radiation that is capable of ionising matter. Typically this ionisation takes the form of displacing an electron from an atom.

ionization: The interaction of nuclear radiation with matter resulting in the generation of charged particles.

IRA: Interim Remedial Action

irradiation: The process of subjecting an entity to radiation.

ISO: International Organization for Standardization.

isopleth: A line drawn through points on a graph or plot at which a given quantity has the same numerical value or occurs with the same frequency.

ITRC: Interstate Technology & Regulatory Council.

judgment measurement: Measurements performed at locations selected using professional judgment based on unusual appearance, location relative to known contaminated areas, high potential for residual radioactivity, general supplemental information, *etc*. Judgment measurements are not included in the statistical evaluation of the survey unit data because they violate the assumption of randomly selected, independent measurements. Instead, judgment measurements are individually compared to the $DCGL_W$.

karst terrain: A kind of terrain with characteristics of relief and drainage arising from a high degree of rock solubility. The majority of karst conditions occur in limestone areas, but karst may also occur in areas of dolomite, gypsum, or salt deposits. Features associated with karst terrain may include irregular topography, abrupt ridges, sink holes, caverns, abundant springs, and disappearing streams. Well developed or well integrated drainage systems of streams and tributaries are generally not present.

keV: kiloelectronvolt.

key principle: A fundamental principle that should be adhered to during *land management*. Through consultation, SAFEGROUNDS has developed five key principles on the protection of *people* and the *environment, stakeholder* involvement, the identification of the preferred *land management option*, taking immediate action and record keeping.

kg: kilogram.

klystron: An electron tube used in television, *etc*., for converting a stream of electrons into ultra high-frequency waves that are transmitted as a pencil-like radio beam.

^{40}K: potassium-40.

LAN: Local Area Network.

LARADS: Laser-Assisted Ranging And Data System.

laser-induced fluorescence probe: A real-time technology sensor used to determine the presence of chemicals that fluoresce at standard excitation wavelengths.

LBGR: Lower Bound of the Gray Region.

LCA: Life Cycle Analysis. A systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle.

LCBL: Life Cycle Baseline.

LDR: Land Disposal Restrictions.

less-than data: Measurements that are less than the *minimum detectable concentration*.

LET: Linear Energy Transfer.

levelling the data: The normalization of radiometric data measured under different environmental conditions, with various instruments in adjacent areas.

license: A license issued under the regulations in parts 30 through 35, 39, 40, 60, 61, 70 or part 72 of 10 CFR Chapter I.

licensee: The organisation that is the holder of the nuclear site licence on a *nuclear-licensed site*. The licensee is responsible for nuclear safety on the site and for discharging all the obligations and liabilities associated with the nuclear site licence.

license termination: Discontinuation of a *license*, the eventual conclusion to *decommissioning*.

LIF: Laser-Induced Fluorescence.

linear attenuation coefficient, μ (m^{-1}): A constant describing the attenuation of a specific radiation in a particular medium - attenuation of the specified radiation per unit distance (m^{-1}).

live time: The counting time corrected for the total dead time of the radiometric measurement.

LLC: Local Liaison Committee.

LLD: Lower Limit of Detection.

LLW: Low Level (radioactive) Waste.

LMU: Liabilities Management Unit.

LNAPL: Light Non-Aqueous Phase Liquid.

lower bound of the gray region (LBGR): The minimum value of the gray region. The width of the *gray region* (*DCGL-LBGR*) is also referred to as the shift, Δ.

lower limit of detection (L_D): The smallest amount of radiation or radioactivity that statistically yields a net result above the method background. The critical detection level, L_C, is the lower bound of the 95% detection interval defined for L_D and is the level at which there is a 5% chance of calling a background value "greater than background." This value should be used when actually counting samples or making direct radiation measurements. Any response above this level should be considered as above background; *i.e.*, a net positive result. This will ensure 95% detection capability for L_D. A 95% confidence interval should be calculated for all responses greater than L_C.

LQA: Land Quality Assessment.

LQS: Land Quality Statement.

LSG: Local Stakeholder Group (now called SSG: Site Stakeholder Group).

LTS: Long-Term Stewardship.

m: meter.

m: The number of measurements from the reference area used to conduct a statistical test.

m^2: square meter.

made ground: Ground produced by infilling with material from outside the site or from another part of the site. Typically this could include rubble, gravel or sand or waste materials.

magnetron: A vacuum tube in which the flow of ions from the heated cathode to the anode is controlled by a magnetic field externally applied and perpendicular to the electric field by which they are propelled. Magnetrons are used to produce very short radio waves.

management of contaminated land: The taking of any actions to detect, charcterise, control, monitor or remove (wholly or partially) contamination in on or under land (including groundwater) and all the processes that lead up to decisions to take such actions.

man-made radiation: Radiation from sources other than natural sources.

Marl: Friable earthy deposit consisting of clay and calcium carbonate.

MARSSIM: The *Multi-Agency Radiation Survey and Site Investigation Manual* is a tool developed by EPA, NRC, DOE, and DOD to determine if constituents at a radiologically contaminated site have been cleaned up to concentrations that fall below regulatory limits.

mass attenuation coefficient, μ /q (m^2/kg): A constant describing the attenuation of specific radiation per unit surface density of absorbing medium. A ratio of linear attenuation coefficient μ to the density ρ of the absorbing medium.

mass number: The number of nucleons (protons and neutrons) in the nucleus of an atom.

MC: Methylene Chloride.

MCA: Multi-Channel pulse height Analyzer.

MCB: Multi-Channel Buffer.

MCL: Maximum Contaminant Level.

MDC: Minimal Detectable Concentrations.

measurement: For the purpose of EURSSEM, it is used interchangeably to mean: 1) the act of using a detector to determine the level or quantity of radioactivity on a surface or in a sample of material removed rom a media being evaluated, or 2) the quantity obtained by the act of measuring.

MeV: mega-electronvolt.

MFA: Material Flow Accounting or Analysis; a method whereby the streams of material, chemical elements, energy, etc. are assessed and possibly balanced. It is centred on the material and chemical compound, rather than on the product or service in the case of LCA. MFA covers approaches such as substance flow analysis (SFA), product flow accounts, material balancing and overall material flow accounts.

mg: milligram.

micrometeorology: The study of weather conditions in a local or very small area, such as immediately around a tree or building, that can affect meteorological conditions.

min: minute.

minimum detectable concentration (MDC): The minimum detectable concentration (MDC) is the *a priori* activity level that a specific instrument and technique can be expected to detect 95% of the time. When stating the detection capability of an instrument, this value should be used. The *MDC* is the detection limit, L_D, multiplied by an appropriate conversion factor to give units of activity.

minimum detectable count rate (MDCR): The minimum detectable count rate (MDCR) is the *a priori* count rate that a specific instrument and technique can be expected to detect.

missing or unusable data: Data (measurements) that are mis-labelled, lost, or do not meet quality control standards. *Less-than data* are not considered to be missing or unusable data. See *R*.

mixed wastes: Radioactive waste that contains non-radioactive toxic or hazardous materials that could cause undesirable effects in the environment. Such waste has to be handled, processed and disposed of in such a manner that takes into account the chemical as well as its radioactive components.

MOX: Mixed OXide reactor fuel.

mph: miles per hour.

multi-channel amplitude analyzer: That part of a gamma ray spectrometer that sorts input pulses into channels according to the amplitude (energy) of the input pulses.

multi-channel pulse height analyzer: A device that sorts the pulses of energy leaving a scintillation detector by amplitude. The amplitude of the energy that leaves the detector is proportional to the energy that entered it, allowing investigators to determine the relative concentration and type of radionuclide present in a sample.

munitions: Military supplies, especially weapons and ammunition.

n: Number of measurements from a survey unit used to conduct a statistical test.

N: $N = m + n$, is the total number of measurements required from the reference area and a *survey unit*. See *m* and *n*.

NAD: Nicotinamide Adenine Dinucleotide.

NaI: sodium iodide.

NaI scintillator: A device that uses crystals made of an alkali-halide salt to detect high levels of radionuclides. When an NaI crystal is hit by high-energy gamma rays, the crystal produces charged particles that react within the crystal itself to emit lower energy photons in the visible range. This detector is used when simple spectra resulting from few radionuclides are expected.

NAPL: Non-Aqueous Phase Liquid.

NARM: Naturally occurring or Accelerator-produced Radioactive Material, such as radium, and not classified as *source material*.

natural flushing: The application of the existing groundwater flow and geochemical attenuating conditions to flush (remove) the contaminant from the region of concern.

naturally occurring radio-nuclides: Radio-nuclides and their associated progeny produced during the formation of the earth or by interactions of terrestrial matter with cosmic rays.

natural radiation: Radiation originating from the decay of naturally occurring radionuclides, and cosmic radiation.

NCRP: National Council on Radiation Protection and Measurements.

NDA: Nuclear Decommissioning Authority.

neutron: Uncharged particle, constitutes approximately 50 per cent by mass of most atomic nucleii.

neutron flux: A measurement of the intensity of a neutron source (measured in $J/cm^2.s$ or $neutrons/cm^2.s$).

n_f: The number of samples that should be collected in an *area* to assure that the required number of measurements from that area for conducting statistical tests is obtained. $n_f = n/(1\text{-}R)$.

NGO: Non-Governmental Organisation.

NIM: Nuclear Instrument Model.

non-blind measurement: Non-blind measurements are measurements that have a concentration and origin that are known to the individual performing the measurement. See *single-blind measurement* and *double-blind measurement*.

non-conformance: A deficiency in characteristic, documentation, or procedure that renders the quality of an item or activity unacceptable or indeterminate; non-fulfilment of a specified requirements.

non-impacted area: Areas where there is no reasonable possibility (extremely low probability) of residual contamination. Non-impacted areas are typically located off-site and may be used as background *reference areas*.

non-parametric test: A test based on relatively few assumptions about the exact form of the underlying probability distributions of the measurements. As a consequence, nonparametric tests are generally valid for a fairly broad class of distributions. The *Wilcoxon Rank Sum test* and the *Sign test* are examples of nonparametric tests.

non-radioactively contaminated land: Any land in, on or under (including groundwater) which there are non-radioactive contaminants above natural and artificial background levels that are typical of the area of a country in which the site is located.

NORM: Naturally Occurring Radioactive Material.

normal (gaussian) distribution: A family of bell shaped distributions described by the mean and variance.

normalization of data: A conversion of older (uncalibrated) radiometric data to a new reference level.

NPP: Nuclear Power Plant.

NRC: United States Nuclear Regulatory Commission.

NRPB: National Radiological Protection Board.

nuclear fission: Process by which an atom splits into two or more pieces, each of which is an entirely separate nuclide.

nuclear-licensed site: Sites that are regulated by HSE under the provisions of the Nuclear Installations Act 1965 (as amended) with a nuclear site licence. The Act applies to fixed sites for the purposes of constructing and operating nuclear reactors and other prescribed nuclear installations. The guidance applies to operating sites and those being *decommissioned*, whether or not they are to be *delicensed*.

nuclear radiation: Radiation originating by disintegration of unstable atomic nuclei.

objective: An aim set for the management of contaminated land. Objectives are set by considering factors such as government policy, corporate/organisational policy and the views of *stakeholders*. It is recommended that environment, health and safety objectives are established separately from those of a commercial and administrative nature.

OPC: Ordinary Portland Cement.

optimisation: The form, scale and duration of the intervention (remedial action) maximises the net benefit. The principle of optimisation means that there is no predetermined end point for remediation that is applicable in all circumstances. In the extension to Part 2A, where a remediation scheme addresses significant pollutant linkages, some but not all, of which relate to lasting exposure, any intervention should be optimised having regard to their benefit in respect of any remedial treatment actions relating to non-radioactive significant pollutant linkages.

option: A method, approach or technology that can be used for *land management*. Options can include, but may go further than, some or all of the actions defined as ‘remediation’ in Part IIA of the Environmental Protection Act, 1990. In evaluating options, consideration should always be given to ‘doing nothing more’ to the contamination or to removing contamination to background levels. See also *strategy*.

organization: a company, corporation, firm, government unit, enterprise, facility, or institution, or part thereof, whether incorporated or not, public or private, that has its own functions and administration.

outlier: Measurements that are unusually large or small relative to the rest and therefore are suspected of misrepresenting the population from which they were collected.

p: The probability that a random measurement from the *survey unit* is less than Δ.

p’: The probability that the sum of two independent random measurements from the *survey unit* is less than 2Δ.

PA: Preliminary Assessment.

PAH: Polycyclic Aromatic Hydrocarbon.

pair production: The interaction of a gamma ray photon with the nucleus of an atom, in which the photon is absorbed and its energy, E > 1.02 MeV, is transformed into an electronpositron pair. Environment Act, 1995).

pathway: A mechanism or route by which a contaminant can reach, or be made to affect, a receptor.

PCB: Polychlorinated Biphenyl.

PCE: Tetrachloroethene.

peer review: A documented critical review of work generally beyond the state of the art or characterized by the existence of potential uncertainty. The peer review is conducted by qualified individuals (or organization) who are independent of those who performed the work, but are collectively equivalent in technical expertise (*i.e.*, peers) to those who performed the original work. The peer review is conducted to ensure that activities are technically adequate, competently performed, properly documented, and satisfy established technical and quality requirements. The peer review is an in-depth assessment of the assumptions, calculations, extrapolations, alternate interpretations, methodology, acceptance criteria, and conclusions pertaining to specific work and of the documentation that supports them. Peer reviews provide an evaluation of a subject where quantitative methods of analysis or measures of success are unavailable or undefined, such as in research and development.

people: Those individuals that could be affected by *contaminated land*. People are distinguished from *environment* following health and safety and radiological protection convention. Separate consideration may be given to 'workers' (who receive a direct financial benefit from the *owner/operator*) and the public (who do not). Consideration should also be given to people at present and in the *future*.

performance evaluation: A type of audit in which the quantitative data generated in a measurement system are obtained independently and compared with routinely obtained data to evaluate the proficiency of an analyst or laboratory.

permeability: The relative ease with which a porous medium can transmit a fluid under a hydraulic gradient.

pH: Negative ^{10}log of H^+-concentration; a unit of measure for acidity/alkalinity.

photo-effect: The interaction of an photon with an orbital electron of an atom, in which the photon is absorbed and its energy is used for the release of the orbital electron (kinetic energy).

photomultiplier tube: An evacuated glass tube consisting of an anode, cathode, and a series of dynodes that amplifies the detection of a photon. Radiation hits the photocathode; normally, due to the photoelectric effect (in which electrons are emitted from metal when hit with incident electromagnetic radiation) many electrons would be emitted and collected at an anode for the purposes of amplifying the original signal. In a PMT, electrons are deflected toward a series of dynodes that are maintained at a positive potential before finally hitting the terminal anode. Typically, the original photon is amplified by 5 to 7 orders of magnitude and is collected at the anode.

photo-peak: A local maximum in the gamma energy spectrum, representing the emission energy of photons of a source.

PHWR: Pressurised Heavy Water Reactor.

physical probe area: The physical surface area assessed by a detector. The physical probe area is used to make probe area corrections in the activity calculations.

phyto-remediation: The use of plants to remove contaminants from the subsurface into a harvestable biomass.

PID: Photoionization Detector.

Pitman efficiency: A measure of performance for statistical tests. It is equal to the reciprocal of the ratio of the sample sizes required by each of two tests to achieve the same power, as these sample sizes become large.

plume: The spatial distribution of a release of airborne or waterborne material as it disperses in the environment.

PMT: Photo-Multiplier Tube.

point radiation source: A radiation source of limited dimensions.

pollutant linkage: The relationship of a contaminant, a pathway and a receptor.

polypropylene core liner: A deflated ribbon-like liner that can be inserted into a borehole and then pressurized to allow contact with the surface of the hole. A dye impregnated in the liner changes color when it comes in contact with the substance under investigation, for example, DNAPLs. The liner can be pulled from the hole inside out for determination of the zones that contain the contaminant.

portable gamma ray spectrometer: A hand-held instrument for detecting and analysing gamma ray emissions.

power (1-β): The probability of rejecting the *null hypothesis* when it is false. The power is equal to one minus the *Type II* error rate, *i.e.* (1-β).

PPE: personal protective equipment.

ppm: parts per million.

P_r: The probability that a measurement performed at a random location in the *survey unit* is greater than a measurement performed at a random location in the *reference area*.

practices: A human activity that can increase the exposure of individuals to radiation from an artificial source, or from a natural radiation source where natural radionuclides are processed for their radioactive, fissile or fertile properties, except in the case of emergency exposure. This is a Basic Safety Standard Directive definition.

precipitation: A standard chemical method that can be used in the treatment of liquid wastes where radionuclides are removed from the liquid by either forming or being carried by the insuluble product of a chemical reaction made to occur within the liquid.

precision: A measure of mutual agreement among individual measurements of the same property, usually under prescribed similar conditions, expressed generally in terms of the *standard deviation*.

preferred option: The option that is identified by an *owner/operator* as their preferred one following a comprehensive, systematic and consultative assessment in which all the *envisageable options* are considered.

preferred strategy: The strategy that is identified by an *owner/operator* as their preferred one following a comprehensive, systematic and consultative assessment of potential strategies derived by considering the *options* for the various areas on a site.

pregnant: Said of metal bearing leach solutions after contact with the ore.

PRG: preliminary remediation goal.

Primordial radionuclides: Radionuclides produced during the initial formation of the earth. Those of the radionuclides that remain have very long half-lives

problem definition: Step 1 in the process of moving from site characterization through remediation and closure with a focus on the determination of whether excessive risk exists and the determination of the nature and extent of the contamination leading to the excess risk.

process: A combination of people, machine and equipment, methods, and the environment in which they operate to produce a given product or service.

professional judgement: An expression of opinion, based on technical knowledge and professional experience, assumptions, algorithms, and definitions, as stated by an expert in response to technical problems.

profile maps: Graphic representation of traverse data as a plot with time or distance along the abscissa.

proposed option: The *option* that is formally submitted by an *owner/operator* to regulators and decision-makers for approval to implement, following the comparison of options, identification of a *preferred option*, and consideration of this preferred option in regulatory and other acceptance procedures.

proposed strategy: The strategy that is formally submitted by an *owner/operator* to regulators and decision-makers for approval to implement, following the comparison of strategies, identification of a *preferred strategy*, and consideration of this preferred strategy in regulatory and other acceptance procedures.

proton: Principle particle of an atom nucleus. The proton is a positively charged nucleon.

proton number: The number of positively charged nucleons (protons) in the nucleus of an atom.

PSA: Preliminary Site Assessment.

Pu: plutonium.

putrescible waste: Organic waste that may decompose or rot.

PVC: Polyvinyl Chloride.

PWR: Pressurised Water Reactor.

QA/QC: See *quality assurance /quality control*.

qualified data: Any data that have been modified or adjusted as part of statistical or mathematical evaluation, data *validation*, or data *verification* operations.

quality: The totality of features and characteristics of a product or service that bear on its ability to meet the stated or implied needs and expectations of the user.

Quality Assurance (QA): An integrated system of management activities involving planning, implementation, assessment, reporting, and quality improvement to ensure that a process, item, or service is of the type and quality needed and expected by the customer.

Quality Assurance Project Plan (QAPP): A formal document describing in comprehensive detail the necessary *QA*, *QC*, and other technical activities that must be implemented to ensure that the results of the work performed will satisfy the stated performance criteria. As defined for Superfund in the Code of Federal Regulations 40 CFR 300.430, the Quality Assurance Project Plan describes policy, organization, and functional activities and the Data Quality Objectives and measures necessary to achieve adequate data for use in selecting the appropriate remedy. The QAPP is a plan that provides a process for obtaining data of sufficient quality and quantity to satisfy data needs. It is a part of the *Sampling and Analysis Plan*.

quality assurance/quality control: The process by which a laboratory can determine the accuracy and precision of sample analysis techniques and analytical results.

Quality Control (QC): The overall system of technical activities that measure the attributes and performance of a process, item, or service against defined standards to verify that they meet the stated requirements established by the customer, operational techniques and activities that are used to fulfil requirements for *quality*.

quality factor: A factor applied to the absorbed dose in tissue to take account of the different levels of harm inflicted by different types of radioactive decay. Used to calculate equivalent dose.

quality indicators: Measurable attributes of the attainment of the necessary quality for a particular environmental decision. Indicators of quality include precision, bias, completeness, representativeness, reproducibility, comparability, and statistical confidence.

Quality Management Plan (QMP): A formal document that describes the quality system in terms of the organizational structure, functional responsibilities of management and staff, lines of authority, and required interfaces for those planning, implementing, and assessing all activities conducted.

quality system: A structured and documented management system describing the policies, objectives, principles, organizational authority, responsibilities, accountability, and implementation plan of an organization for ensuring quality in its work processes, products (items), and services. The quality system provides the framework for planning, implementing, and assessing work performed by the organization and for carrying out required QA and QC.

R: The rate of missing or unusable measurements expected to occur for samples collected in *reference areas* or *survey units*. See *missing or unusable data*. See n_f (Not to be confused with the symbol for the radiation exposure unit Roentgen.)

R&D: Research and Development.

R_A: The acceptable level of risk associated with not detecting an *area of elevated activity* of area A_{min}.

^{226}Ra: radium-226.

^{228}Ra: radium-228.

radiation: A flux of particles or energy originating at transitions of unstable atoms. A physical property of some sources.

radiation flux: See *radiation*.

Radiation Protection Adviser (RPA): An appointment required under some national regulations for all companies involved in work with ionising radiations. The RPA is registered with the HSE and provides advice on all aspects of radiological protection. The RPA will set dose constraints on workers and specify hold points for use during the work.

Radiation Protection Supervisor (RPS): An appointment required under some national regulations for all companies involved in work with ionising radiations. An RPS must have received training related to radiological protection and ensures that the specified safety restrictions are observed.

radiation survey: Measurements of radiation levels associated with a *site* together with appropriate documentation and data evaluation.

radioactive decay: The spontaneous transformation of an unstable atom into one or more different nuclides accompanied by either the emission of energy and/or particles from the nucleus, nuclear capture or ejection of orbital electrons, or fission. Unstable atoms decay into a more stable state, eventually reaching a form that does not decay further or has a very long *half-life*.

radioactive halos: In mineralogy and petrology, micro-areas around radioactive minerals, identifiable in rock thin sections, formed by radiation – particularly alpha radiation.

radioactive material: Often used to describe any material containing radionuclides. The statutory definition of radioactive material is given in the Radioactive Substances Act 1993.

radioactive minerals: Rock minerals containing natural radioactive elements.

radioactively contaminated land: Any land in, on or under (including groundwater) which there are radioactive contaminants above natural and artificial background levels that are typical of the area of the UK in which the site is located.

radioactivity: The mean number of nuclear transformations occurring in a given quantity of radioactive material per unit time. The International System (SI) unit of radioactivity is the Becquerel (Bq).

radioelements: A proxy term for measured K, U and Th in gamma ray surveys for geological purposes.

radiological survey: Measurements of radiation levels and radioactivity associated with a *site* together with appropriate documentation and data evaluation.

radio-luminescence: Light produced by the absorption of energy from ionizing radiation.

radiometric instrument: A measuring device having the capacity for detecting radiation.

radio-nuclide: An unstable nuclide that undergoes *radioactive decay*.

radon: A noble gas, having radioactive isotopes 222Rn, 220Rn, 219Rn (radon, thoron and actinon).

radon background: The component of background gamma radiation originating in disintegration and gamma radiation of short lived decay products of 222Rn in air, particularly ^{214}Pb and ^{214}Bi.

random error: The deviation of an observed value from the true value is called the error of observation. If the error of observation behaves like a random variable (*i.e.*, its value occurs as though chosen at random from a probability distribution of such errors) it is called a *random error*. See *systematic error*.

range: The concentration levels in samples over which useful measurements can be made. It is limited at the low end by the detection limit and at the high end by detector saturation.

RBE: Relative Biological Effectiveness.

RDX: Cyclotrimethylenetrinitramine (explosive).

reactive barrier: Groundwater permeable geochemical barriers installed across the flow path of the contaminant plume allowing it to flow through while at the same time removing the contaminant (e.g. radioactive species) through interactions with the reactive component of the barrier.

readily removable: A qualitative statement of the extent to which a radionuclide can be removed from a surface or medium using non-destructive, common, housekeeping techniques (*e.g.*, washing with moderate amounts of detergent and water) that do not generate large volumes of radioactive waste requiring subsequent disposal or produce chemical wastes that are expected to adversely affect public health or the environment.

real-time instrumentation: Sampling technologies that allow the collection of data in the field with the immediate return of results. This allows investigators to scan a site in order to map areas of contamination and the extent of contamination.

receptor: An entity (persons, living organisms, ecological systems, controlled waters, atmosphere, structures, utilities) that may be adversely affected by a contaminant.

records: Information including details of site characterisation work, the process of deciding on the land management option/strategy, implementing the option/strategy and validating its implementation, as well as interaction with stakeholders throughout the process. There is a key principle about the keeping of records.

reference area: Geographical *area* from which representative reference measurements are performed for comparison with measurements performed in specific *survey units* at remediation site. A site radiological *reference area* (background area) is defined as an area that has similar physical, chemical, radiological, and biological characteristics as the site area being remediated, but which has not been contaminated by site activities. The distribution and concentration of *background radiation* in the *reference area* should be the same as that which would be expected on the *site* if that *site* had never been contaminated. More than one *reference area* may be necessary for valid comparisons if a *site* exhibits considerable physical, chemical, radiological, or biological variability.

reference coordinate system: A *grid* of intersecting lines referenced to a fixed site location or benchmark. Typically the lines are arranged in a perpendicular pattern dividing the survey location into squares or blocks of equal areas. Other patterns include three-dimensional and polar coordinate systems.

reference radionuclide: A gamma ray emitting radionuclide used for instrument energy calibration or instrument sensitivity checks.

reference region: The geographical region from which *reference areas* will be selected for comparison with *survey units*.

regulation: A rule, law, order, or direction from federal or state governments regulating action or conduct. Regulations concerning radioisotopes in the environment in the United States are shared by the Environmental Protection Agency (EPA), the U.S. Nuclear Regulatory Commission (NRC), the U.S. Department of Energy (DOE), and many State governments. Federal regulations and certain directives issued by the U.S. Department of Defense(DOD) are enforced within the DOD.

relative shift (Δ/σ): Δ divided by σ, the *standard deviation* of the measurements. See *delta*.

relative standard deviation: See *coefficient of variation*.

relaxation mass, β (g/cm^2): A parameter specifying the vertical distribution of gamma emitting radionuclide in the ground, controlling the surface gamma activity.

release criterion: A regulatory limit expressed in terms of dose or risk.

rem (radiation equivalent man): The conventional unit of *dose equivalent*. The corresponding International System (SI) unit is the *Sievert (Sv)*: 1 Sv = 100 rem.

remedial action: Those actions that are consistent with a permanent remedy taken instead of, or in addition to, removal action in the event of a release or threatened release of a hazardous substance into the environment, to prevent or minimize the release of hazardous substances so that they do not migrate to cause substantial danger to present or future public health or welfare or the environment. See *remedy*.

remediation: Measures taken, including stabilization or isolation of the contamination in situ, to reduce human exposure or environmental damage from already contaminated land or water.

remediation control survey: A type of survey that includes monitoring the progress of remedial action by real time measurement of areas being decontaminated to determine whether or not efforts are effective and to guide further *decontamination* activities.

remediation of contaminated land: The taking of any actions to reduce the risks to humans or other organisms from contamination in, on or under land (including the groundwater).

remedy: See *remedial action*.

removable activity: Surface activity that is *readily removable* by wiping the surface with moderate pressure and can be assessed with standard radiation detectors. It is usually expressed in units of dpm/100 cm^2.

removal: The cleanup or removal of released hazardous substances, or pollutants or contaminants which may present an imminent and substantial danger; such actions as may be necessary taken in the event of the threat of release of hazardous substances into the environment; such actions as may be necessary to monitor, assess, and evaluate the threat of release of hazardous substances; the removal and disposal of material, or the taking of other such actions as may be necessary to prevent, minimize or mitigate damage to the public health or welfare or the environment.

replicate: A repeated analysis of the same sample or repeated measurement at the same location.

representative measurement: A measurement that is selected using a procedure in such a way that it, in combination with other representative measurements, will give an accurate representation of the phenomenon being studied.

representativeness: A measure of the degree to which data accurately and precisely represent a characteristic of a population, parameter variations at a sampling point, a process condition, or an environmental condition.

reproducibility: The precision, usually expressed as a standard deviation, that measures the variability among the results of measurement of the same sample at different laboratories.

residual radioactivity: Radioactivity in structures, materials, soils, groundwater, and other media at a site resulting from activities under the cognizant organization's control. This includes radioactivity from all sources used by the cognizant organization, but excludes background radioactivity as specified by the applicable regulation or standard. It also includes radioactive materials remaining at the site as a result of routine or accidental releases of radioactive material at the site and previous burials at the site, even if those burials were made in accordance with the provisions of 10 CFR Part 20.

restoration: Measures taken to return the environment in to approximately the same state in which it previously existed or to a state that is in agreement with future land use scenarios and all publically accepted agreements.

restricted use: A designation following *remediation* requiring radiological controls.

risk: An assessment of the potential for harm or damage posed by a contaminant or circumstance taking account of the likelihood, or probability, of occurrence. Risk is the product of hazard and probability.

risk assessment: A systematic process that establishes the existence, nature and significance of risk. Different methods are used to evaluate different types of risks. The approach to assessing risks to *people's health* and to the *environment* from non-radioactive contamination is largely described in regulatory guidance. The approach to assessing risks to people and the *environment* from radioactive contamination is different and an approach is outlined in the guidance.

RMBK: Light Water Cooled Graphite Moderated Reactor (Reaktor Bolschoi Moschtschnosti Kanalny).

^{222}Rn: radon-222.

robust: A statistical test or method that is approximately valid under a wide range of conditions.

roentgen, R: Unit of exposure, equal to 2.58 x 10-4 C/kg.

ROI: Region Of Interest.

RoT: Rules of Thumb.

RPA: Radiation Protection Advisor

RPE: Respiratory Protective Equipment.

RSS: Radiation Scanning System.

run chart: A chart used to visually represent data. Run charts are used to monitor a process to see whether or not the long range average is changing. Run charts are points plotted on a graph in the order in which they become available, such as parameters plotted versus time.

s: second.

s: The *arithmetic standard deviation* of the mean.

S+: The *test statistic* used for the *Sign test*.

SAFEGROUNDS: Safety and Environmental Guidance for Remediation of UK Nuclear and Defence Sites.

safety case: Documentation for a nuclear installation that demonstrates safety. Safety cases must be produced and maintained during the design, construction, manufacture, commissioning, operation and *decommissioning* of the installation.

sample: (As used in EURSSEM) A part or selection from a medium located in a *survey unit* or *reference area* that represents the quality or quantity of a given parameter or nature of the whole area or unit; a portion serving as a specimen.

sample: (As used in statistics) A set of individual samples or measurements drawn from a population whose properties are studied to gain information about the entire population.

sampling: Methods and techniques used to obtain a representative sample of the material under investigation.

sampling and analysis plan: A plan that provide a process for obtaining data of sufficient quality and quantity to satisfy data needs. The sampling and analysis plans consists of two parts: 1) the *Field Sampling Plan*, which describes the number, type, and location of samples and the type of analyses;

and 2) the *Quality Assurance Project Plan*, which describes policy, organization, functional activities, the Data Quality Objectives, and measures necessary to achieve adequate data for use in selecting the appropriate remedy.

sampling error: Error resulting from the collection or storage of samples.

SAP: Safety Assessment Principles

scanning: An evaluation technique performed by moving a detection device over a surface at a specified speed and distance above the surface to detect radiation.

scintillation counter: A sensor converting the energy photons or particles of nuclear radiation to voltage pulses, based on luminescence of scintillation matter.

scintillation detector: Radiation detector relying on the property of certain materials to fluoresce when ionised by radiation. The light produced is measured using a photomultiplier.

scintillation type crystals (NaI crystals): When hit by high-energy gamma rays, these crystals produce charged particles and give off low-energy photons that are collected by a photomultiplier tube. These crystals are a component of a device used in the real-time detection of radioactive constituents at remedial sites.

scoping survey: A type of *survey* that is conducted to identify: 1) radionuclide contaminants, 2) relative radionuclide ratios, and 3) general levels and extent of contamination.

secular equilibrium: Relationship in a parent/progeny radionuclide system where the half-life of the parent is much longer than that of the progeny; with time, the radioactivity of the parent becomes equal to that of the progeny within the series (e.g., radium-226 to radium-222).

self-assessment: Assessments of work conducted by individuals, groups, or organizations directly responsible for overseeing and/or performing the work.

semi-conductor counter: A sensor converting the energy photons or particles of nuclear radiation to voltage pulses, based on induced conductivity in a part of a semiconductor by radiation.

semiconductor-type crystals (e.g. HPGe crystals): Crystals that are composed of an element with four available electrons, such as those in column IVa of the periodic table, with an introduced impurity. Elements like carbon and germanium can form four covalent bonds with neighbouring like atoms to form a crystal structure. When an impurity element with either three or five available electrons is introduced, the extra or missing electron allows for the creation of electron-hole pairs that offer partial resistance to electricity.

sensitivity: The efficiency of the detector response to radionuclide concentration.it is the slope of the detector signal.

shape parameter (S): For an elliptical area of elevated activity, the ratio of the semi-minor axis length to the semi-major axis length. For a circle, the shape parameter is one. A small shape parameter corresponds to a flat ellipse.

shift: See *delta (Δ)*.

shine: Radiation originating from sources other than the material directly under a detector. Shine is of concern in remedial surveys because it can bias results.

Sievert (Sv): The special name for the International System (SI) unit of *dose equivalent*. 1 Sv = 100 *rem* = 1 Joule per kilogram.

Sign test: A *nonparametric* statistical test used to demonstrate compliance with the release criterion when the radionuclide of interest is not present in background and the distribution of data is not symmetric. See also *Wilcoxon Rank Sum test*.

single-blind measurement: A measurement that can be distinguished from routine measurements but are of unknown concentration. See *non-blind measurement* and *double-blind measurement*.

site: Any installation, facility, or discrete, physically separate parcel of land, or any building or structure or portion thereof, that is being considered for survey and investigation.

site reconnaissance: A visit to the *site* to gather sufficient information to support a site decision regarding the need for further action, or to verify existing site data. Site reconnaissance is not a study of the full extent of contamination at a facility or site, or a risk assessment.

size (of a test): See *alpha*.

snow-water equivalent: A term describing the thickness of a snow or water absorbing layer having the same attenuation of gamma rays of the specified energy.

soil: The top layer of the earth's surface, consisting of rock and mineral particles mixed with organic matter. A particular kind of earth or ground - *e.g.*, sandy soil.

soil activity (soil concentration): The level of radioactivity present in soil and expressed in units of activity per soil mass (typically Bq/kg or pCi/g).

soil corings: A soil sample obtained by driving a hollow tube into the ground. The tube is removed along with a narrow soil sample that reflects the soil profile and, if present, contamination with depth.

sorption A broad term referring to the interaction of an atom, molecule or particle within pores or on the surfaces of a solid, the 'substrate'. Absorption is generally used to refer to interactions taking place largely within the pores of solids, in which case the absorption capacity of the solid is proportional to its volume. Adsorption refers to interactions taking place on solid surfaces, so that the capacity of a substrate is proportional to the effective specific surface area. Chemisorption refers to actual chemical bonding with the substrate. Physisolption refers to physical attraction, e.g. by weak electrostatic forces.

source: A contaminant which is in, on or under the land and which has the potential to cause harm to an identified receptor or to cause pollution of controlled waters.

source-detector geometry: Description of mutual geometric relationship between the detector of an instrument and a source of radiation, involving distance, spatial angle of source radiation and source shape and dimensions.

source term: All residual radioactivity remaining at the *site*, including material released during normal operations, inadvertent releases, or accidents.

spatial uncertainty: Error in a sampling plan associated with the incomplete coverage of a contaminated area.

specific activity: A measure of activity of a unit mass, expressed in becquerel per kilogram.

spectrum drift: Phenomenon caused by non-linearity between pulse amplitudes at the detector output and energy of impacting particles into the detector, at very high count rates.

split: A sample that has been homogenized and divided into two or more aliquots for subsequent analysis.

^{90}Sr: Strontium-90.

stakeholder: A person or organisation that has an interest in the management of the *contaminated land*. There are various groups of stakeholders: institutional stakeholders include the *owner/operator*, regulators, government departments and local authorities. External stakeholders are all those outside the owner/operator organisation. Those stakeholders involved in decisions on the management of contaminated land are participating stakeholders and may include local residents, CBOs and NGOs.

standard: A reference radiation source of known radioelement composition, concentration or activity, with a defined shape, dimensions and matrix composition.

standard normal distribution: A *normal (Gaussian) distribution* with mean zero and variance one.

standard operating procedure (SOP): A written document that details the method for an operation, analysis, or action with thoroughly prescribed techniques and steps, and that is officially approved as the method for performing certain routine or repetitive tasks.

standardization the data: The reprocessing of gamma ray data to the correct level and correct units.

statistical control: The condition describing a process from which all special causes have been removed, evidenced on control chart by the absence of points beyond the control limits and by the absence of non-random patterns or trends within the control limits. A special cause is a source of variation that is intermittent, unpredictable, or unstable.

strategy: A broad plan for the management of all the *contaminated land* on a *site*, probably comprising of several *options*.

stratification: The act or result of separating an area into two or more sub-areas so as each sub-area has relatively homogeneous characteristics such as contamination level, topology, surface soil type, vegetation cover, *etc*.

stripping correction: The correction applied to an elemental window count rate to correct for interference from gamma rays due to other elements in that window.

stripping ratios: Numerical parameters, defined by ratios of gamma ray spectrometer sensitivities, applied in the stripping method.

subsurface soil sample: A soil sample that reflects the modeling assumptions used to develop the *DCGL* for subsurface soil activity. An example would be soil taken deeper than 15 cm below the soil surface to support surveys performed to demonstrate compliance with 40 CFR 192.

supervised area: Any area where the annual effective dose to persons working there is likely to exceed 1 mSv or one-tenth of the appropriate dose limit.

surface contamination: *Residual radioactivity* found on building or equipment surfaces and expressed in units of activity per surface area (Bq/m^2 or $dpm/100\ cm^2$).

surface soil sample: A soil sample that reflects the modelling assumptions used to develop the *DCGL* for surface soil activity. An example would be soil taken from the first 15 cm of surface soil to support surveys performed to demonstrate compliance with 40 CFR 192.

surveillance (quality): Continual or frequent monitoring and verification of the status of an entity and the analysis of records to ensure that specified requirements are being fulfilled.

survey: A systematic evaluation and documentation of radiological measurements with a correctly calibrated instrument or instruments that meet the sensitivity required by the objective of the evaluation.

survey plan: A plan for determining the radiological characteristics of a *site*.

survey unit: A geographical area consisting of structures or land areas of specified size and shape at a remediated site for which a separate decision will be made whether the unit attains the site-specific reference-based cleanup standard for the designated pollution parameter. *Survey units* are generally formed by grouping contiguous site areas with a similar use history and the same classification of contamination potential. Survey units are established to facilitate the survey process and the statistical analysis of survey data.

Sv: Sievert, a unit of dose from ionising radiation.

SVOC: Semivolatile Organic Compounds.

systematic error: An error of observation based on system faults which are biased in one or more ways, *e.g.*, tending to be on one side of the true value more than the other.

T+: The *test statistic* for the *Wilcoxon Signed Rank test*.

tandem testing: Two or more statistical tests conducted using the same data set.

TCA: Trichloroethane.

TCE: Trichloroethylene (a solvent).

technical review: A documented critical review of work that has been performed within the state of the art. The review is accomplished by one or more qualified reviewers who are independent of those who performed the work, but are collectively equivalent in technical expertise to those who performed the original work. The review is an in-depth analysis and evaluation of documents, activities, material, data, or items that require technical verification or validation for applicability, correctness, adequacy, completeness, and assurance that established requirements are satisfied.

technical systems audit (TSA): A thorough, systematic, on-site, qualitative audit of facilities, equipment, personnel, training, procedures, recordkeeping, data validation, data management, and reporting aspects of a system.

TEDE (total effective dose equivalent): The sum of the effective dose equivalent (for external exposure) and the committed effective dose equivalent (for internal exposure). TEDE is expressed in units of Sv or rem. See *CEDE*.

TENORM: Technologically Enhanced Natural Occuring Radioactive Material

ternary maps: K, U, Th three component colour presentation of natural radioelement concentration in the ground.

terrestrial radiation: Radiation originating from natural radionuclides in the ground.

test statistic: A function of the measurements (or their ranks) that has a known distribution if the *null hypothesis* is true. This is compared to the *critical level* to determine if the *null hypothesis* should be

test-line: A selected airborne traverse used for daily and temporal control of instrument function and stability of environmental radiation.

^{230}Th: thorium-230.

^{232}Th: thorium-232.

transfer factor: a factor for a radionuclide between different environmental compartments, for example soil and plants. Unit depends on the original (activity) concentration units for the respective compartments.

thermal energy of the Earth: Thermal energy of the Earth is mainly generated by the disintegration of natural radionuclides in the Earth. Thermal energy can be described by the heat production (μW/m3) of unit rock volume, or by heat flow (mW/m^2).

threshold gamma ray spectrometer: Radiometric instrument selecting and registering gamma rays of energy exceeding an energy discrimination threshold.

tied measurements: Two or more measurements that have the same value.

tie-line: Airborne profiles, generally flown perpendicular to regular survey lines - used to level regular survey line data.

topographical survey: A survey of the physical features of a site in three dimensions.

ToR: Terms of Reference.

toxic: Waste and material that contain certain substances determined to be harmful to human health in very small concentrations

TPA: Tri-Party Agreement.

TPP: Technical Project Planning.

traceability: The ability to trace the history, application, or location of an entity by means of recorded identifications. In a calibration sense, traceability relates measuring equipment to national or international standards, primary standards, basic physical constants or properties, or reference materials. In a data collection sense, it relates calculations and data generated throughput the project back to the requirements for quality for the project.

Triad: The U.S. Environmental Protection Agency.s environmental data collection design program consisting of three primary components: 1) systematic project planning, 2) dynamic work plan strategies, and 3) the use of real-time data.

triangular sampling grid: A grid of sampling locations that is arranged in a triangular pattern. See *grid*.

TRU: transuranic.

two-sample t test: A parametric statistical test used in place of the *Wilcoxon Rank Sum (WRS) test* if the *reference area* and *survey unit* measurements are known to be *normally (Gaussian) distributed* and there are no *less-than measurements* in either data set.

Type I decision error: A decision error that occurs when the *null hypothesis* is rejected when it is true. The probability of making a *Type I decision error* is called *alpha* (α).

Type II decision error: A decision error that occurs when the *null hypothesis* is accepted when it is false. The probability of making a *Type II decision error* is called *beta* (β).

^{238}U: uranium-238.

UNGG: Untreated Natural Uranium Graphite Gas Cooled Reactor.

unity rule (mixture rule): A rule applied when more than one radionuclide is present at a concentration that is distinguishable from background and where a single concentration comparison does not apply. In this case, the mixture of radio-nuclides is compared against default concentrations by applying the unity rule. This is accomplished by determining: 1) the ratio between the concentration of each radionuclide in the mixture, and 2) the concentration for that radionuclide in an appropriate listing of default values. The sum of the ratios for all radio-nuclides in the mixture should not exceed 1.

unrestricted area: Any *area* where access is not controlled by a *licensee* for purposes of protection of individuals from exposure to radiation and radioactive materials - including areas used for residential purposes.

unrestricted release: Release of a *site* from regulatory control without requirements for future radiological restrictions. Also known as unrestricted use.

uranium equivalent: The amount of uranium that will give the same measured gamma radiation as a particular radionuclide; for example: uranium equivalent of potassium (ppm U/1% K), uranium equivalent of thorium (ppm U/1ppm Th).

UXO: Unexploded ordnance.

V: volt.

vadose zone: Subsurface zone extending from the surface to the top of the capillary fringe overlying the groundwater.

validation: Confirmation by examination and provision of objective evidence that the particular requirements for a specific intended use are fulfilled. In design and development, validation concerns the process of examining a product or result to determine conformance to user needs.

verification: Confirmation by examination and provision of objective evidence that the specified requirements have been fulfilled. In design and development, verification concerns the process of examining a result of given activity to determine conformance to the stated requirements for that activity.

VLLW: Very Low Level (radioactive) Waste.

VOC: Volatile organic compound.

WAC: waste acceptance criterion.

waste acceptance criteria (WAC): Level of contamination set by a waste disposal facility that defines the type of waste it will accept.

weighting factor (W_t): The fraction of the overall health risk, resulting from uniform, whole-body radiation, attributable to specific tissue. The dose equivalent to tissue is multiplied by the appropriate weighting factor to obtain the effective dose equivalent to the tissue.

whole body dose: See *effective dose*.

Wilcoxon Rank Sum (WRS) test: A *nonparametric* statistical test used to determine compliance with the *release criterion* when the radionuclide of concern is present in background. See also *Sign test*.

working level: A special unit of radon exposure defined as any combination of short-lived radon daughters in 1 litre of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha energy. This value is approximately equal to the alpha energy released from the decay of progeny in equilibrium with 100 pCi of ^{222}Ra.

W_r: The sum of the ranks of the adjusted measurements from the reference area, used as the *test statistic* for the *Wilcoxon Rank Sum test*.

W_s: The sum of the ranks of the measurements from the survey unit, used with the *Wilcoxon Rank Sum test*.

Xrays: Electromagnetic radiation of low energy (E > 40 keV, approximately).

XRF: x-ray fluorescence.

yd^2: square yard.

$Z_{1-\varphi}$: The value from the standard normal distribution that cuts off 100 φ % of the upper tail of the standard normal distribution. See *standard normal distribution*.

Appendix F: Examples of report formats, checklists and files

F.1 Example of a historical site assessment report format

1 Glossary of terms, acronyms and abbreviations

2 Executive summary

3 Purpose of the historical site assessment

4 Property identification

- 4.1 Physical characteristics
  - 4.1.1 Name of the site, owner/operator name, address
  - 4.1.2 Location -street address, city, county, state, geographic coordinates
  - 4.1.3 Topography minute quadrangle or equivalent
  - 4.1.4 Stratigraphy
- 4.2 Environmental Setting
  - 4.2.1 Geology
  - 4.2.2 Hydrogeology
  - 4.2.3 Hydrology
  - 4.2.4 Meteorology

5 Historical site assessment methodology

- 5.1 Approach and rationale
- 5.2 Boundaries of site
- 5.3 Documents reviewed
- 5.4 Property inspections
- 5.5 Personal interviews

6 History and current usage

- 6.1 History -years of operation, type of facility, description of operations, regulatory involvement; permits & licenses, waste handling procedures
- 6.2 Current usage -type of facility, description of operations, probable source types and sizes, description of spills or releases, waste manifests, radionuclide inventories, emergency or removal actions
- 6.3 Adjacent land usage -sensitive areas such as wetlands or preschools

7 Findings

- 7.1 Potential contaminants
- 7.2 Potential contaminated areas
  - 7.2.1 Impacted areas - known and potential
  - 7.2.2 Non-impacted areas
- 7.3 Potential contaminated media
- 7.4 Potential problematic and hazardous materials and waste
- 7.5 Related environmental concerns

8 Conclusions

9 References

10 Appendices

A. Conceptual model and site diagram showing classifications

B. List of documents

C. Photo documentation log

Original photographs of the site and pertinent site features

D List of actions that have never been performed and a list of radionuclides that have never been present at the site.

F.2 Example of scoping survey checklist

Scoping survey design

____ Enumerate DQOs: State the objectives of the survey; survey instrumentation capabilities should be appropriate for the specified survey objectives.

____ Review the Historical Site Assessment for:

- ____ Operational history (*e.g*., problems, spills, releases, or notices of violation) and available documentation (*e.g*., radioactive materials license).
- ____ Other available resources - site personnel, former workers, residents, etc.
- ____ Types and quantities of materials that were handled and where radioactive materials were stored, handled, moved, relocated, and disposed.
- ____ Release and migration pathways.
- ____ Areas that are potentially affected and likely to contain residual contamination. Note: Survey activities will be concentrated in these areas.
- ____ Types and quantities of materials likely to remain on-site - consider radioactive decay.

____ Select separate DCGLs for the site based on the HSA review. (It may be necessary to assume appropriate regulatory DCGLs in order to permit selection of survey methods and instrumentation for the expected contaminants and quantities.)

Conducting surveys

____ Follow the survey design documented in the QAPP. Record deviations from the stated objectives or documented SOPs and document additional observations made when conducting the survey.

____ Select instrumentation based on the specific DQOs of the survey. Consider detection capabilities for the expected contaminants and quantities.

____ Determine background activity and radiation levels for the area; include direct radiation levels on building surfaces, radionuclide concentrations in media, and exposure rates.

____ Record measurement and sample locations referenced to grid coordinates or fixed site features.

____ For scoping surveys that are conducted as Class 3 area final status surveys, follow guidance for final status surveys.

____ Conduct scoping survey, which involves judgment measurements and sampling based on HSA results:

- ____ Perform investigatory surface scanning.
- ____ Conduct limited surface activity measurements.
- ____ Perform limited sample collection (smears, soil, water, vegetation, paint, building materials, subsurface materials).
- ____ Maintain sample tracking.

Evaluating survey results

____ Compare survey results with the DQOs.

____ Identify radio-nuclides of concern.

____ Identify impacted areas and general extent of contamination.

____ Estimate the variability in the residual radioactivity levels for the site.

____ Adjust DCGLs based on survey findings (the DCGLs initially selected may not be appropriate for the site).

____ Determine the need for additional action (*e.g.*, none, remediate, more surveys).

____ Prepare report for regulatory agency (determine if letter report is sufficient).

F.3 Example of characterization survey checklist

Characterisation survey design

____ Enumerate DQOs: State objective of the survey; survey instrumentation capabilities should be appropriate for the specific survey objective.

____ Review the Historical Site Assessment for:

- ____ Operational history (*e.g*., any problems, spills, or releases) and available documentation (*e.g*., radioactive materials license).
- ____ Other available resources - site personnel, former workers, residents, *etc*.
- ____ Types and quantities of materials that were handled and where radioactive materials were stored, handled, and disposed of.
- ____ Release and migration pathways.
- ____ Information on the potential for residual radioactivity that may be useful during area classification for final status survey design.
  Note: Survey activities will be concentrated in Class 1 and Class 2 areas.
- ____ Types and quantities of materials likely to remain on-site - consider radioactive decay.

Conducting surveys

____ Select instrumentation based on detection capabilities for the expected contaminants and quantities and a knowledge of the appropriate DCGLs.

____ Determine background activity and radiation levels for the area; include surface activity levels on building surfaces, radionuclide concentrations in environmental media, and exposure rates.

____ Establish a reference coordinate system. Prepare scale drawings for surface water and ground-water monitoring well locations.

____ Perform thorough surface scans of all potentially contaminated areas, (*e.g*., indoor areas include expansion joints, stress cracks, penetrations into floors and walls for piping, conduit, and anchor bolts, and wall/floor interfaces); outdoor areas include radioactive material storage areas, areas downwind of stack release points, surface drainage pathways, and roadways that may have been used for transport of radioactive or contaminated materials.

____ Perform systematic surface activity measurements.

____ Perform systematic smear, surface and subsurface soil and media, sediment, surface water and groundwater sampling, if appropriate for the site.

____ Perform judgment direct measurements and sampling of areas of elevated activity of residual radioactivity to provide data on upper ranges of residual contamination levels.

____ Document survey and sampling locations.

____ Maintain chain of custody of samples when necessary.

Note: One category of radiological data (*e.g*., radionuclide concentration, direct radiation level, or surface contamination) may be sufficient to determine the extent of contamination; other measurements may not be necessary (*e.g*., removable surface contamination or exposure rate measurements).

Note: Measuring and sampling techniques should be commensurate with the intended use of the data because characterization survey data may be used to supplement final status survey data.

Evaluating survey results

____ Compare survey results with DCGLs. Differentiate surfaces/areas as exceeding DCGLs, not exceeding DCGLs, or not contaminated.

____ Evaluate all locations of elevated direct measurements and determine the need for additional measurements/samples.

____ Prepare site characterization survey report.

F.4 Example of a 'Project Records File'

1. Overview document
2. Document management information
3. Land referencing information
4. Past, current and future land use and related licenses
5. Surrounding land
6. Surface and groundwater
7. History
8. Desk study and factual investigation information
9. Live index of areas of potential concern
10. Time series monitoring results
11. Interpretations and assessments
12. Management of contaminated land
13. Management of removed materials

Annex 1 Record of regulatory information relevant to the land

Annex 2 Record of site owner requirements/contractual information

Annex 3 Record of desk studies, investigations, characterisation and remediation activities, and final results

Annex 4 Record of removed material

Annex 5 Record of stakeholder involvement

Annex 6 Other references

Annex 7 Copies of other key documents

A fixed structure for a 'Project Records File' as indicated in the table above may be proposed for use across an organisation to capture the required information and to allow any gaps in information to be readily identified. For smaller or more straightforward sites not all the sections may be relevant and its use in these instances should be appropriate to the issues concerned. The file could comprise thirteen sections and seven annexes. The file may be used either as a source of information to feed into site characterisation (Sections 3 to 7), or as a repository for site characterisation acquired data and its interpretation (Sections 8 to 11).

The overall aim of Sections 8 to 11 should be to build up a comprehensive body of information including a realistic conceptual model and a robust risk-based analysis of the data. Section 9 should be a living document that keeps track of knowledge on areas of potential concern, some of which may have been identified in a desk study then closed out in subsequent investigation or remediation.

Section 10 should enable build-up of a time-series picture of the changes in land quality on sites that have a monitoring programme. The results should be used to update, confirm or challenge the interpretations and assessments in Section 11. Section 11 should contain the records that document the site's understanding of the significance of ground contamination. Iterations of the conceptual model and other assessments and interpretations should be recorded so that developments of thinking can be recorded over time and tracked through the initial overview document.

In Section 12 further supplementary characterisation information may be included as part of the implementation and verification of the site management options. As well as providing relevant background on the site, the annexes should provide a logical and comprehensive record of the processes used to characterise and manage the site quality interest. Appendix 3 should hold all the desk study and investigation data.

In Section 13, an overview should be given of the management and the final destination of the removed materials as a technical link to possible disposal sites.

F.5 Example of remedial action support survey checklist

Survey design

____ Enumerate DQOs: State the objectives of the survey; survey instrumentation capabilities should be able to detect residual contamination at the DCGL.

____ Review the remediation plans.

____ Determine applicability of monitoring surfaces/soils for the radio-nuclides of concern.
Note: Remedial action support surveys may not be feasible for surfaces contaminated with very low energy beta emitters or for soils or media contaminated with pure alpha emitters.

____ Select simple radiological parameters (*e.g.*, surface activity) that can be used to make immediate in-field decisions on the effectiveness of the remedial action.

Conducting surveys

____ Select instrumentation based on its detection capabilities for the expected contaminants.

____ Perform scanning and surface activity measurements near the surface being decontaminated.

____ Survey soil excavations and perform field evaluation of samples (*e.g.*, gamma spectrometry of undried/non-homogenized soil) as remedial actions progress.

Evaluating survey results

____ Compare survey results with DCGLs using survey data as a field decision tool to guide the remedial actions in a real-time mode.

____ Document survey results.

F.6 Example final status survey checklist

Survey preparations

____ Ensure that residual radioactivity limits have been determined for the radio-nuclides present at the site, typically performed during earlier surveys associated with the decommissioning process.

____ Identify the radio-nuclides of concern. Determine whether the radio-nuclides of concern exist in background. This will determine whether one-sample or two-sample tests are performed to demonstrate compliance. Two-sample tests are performed when radio-nuclides are present in the natural background; one-sample tests may be performed if the radionuclide is not present in background.

____ Segregate the site into Class 1, Class 2, and Class 3 areas, based on contamination potential.

____ Identify survey units.

____ Select representative reference (background) areas for both indoor and outdoor survey areas. Reference areas are selected from non-impacted areas and

- ____ are free of contamination from site operations,
- ____ exhibit similar physical, chemical, and biological characteristics of the survey area,
- ____ have similar construction, but have no history of radioactive operations.

____ Select survey instrumentation and survey techniques. Determine MDCs (select instrumentation based on the radio-nuclides present) and match between instrumentation and DCGLs - the selected instruments should be capable of detecting the contamination at 10 – 50 % of the DCGLs.

____ Prepare area if necessary - clear and provide access to areas to be surveyed.

____ Establish reference coordinate systems (as appropriate).

Survey design

____ Enumerate DQOs: State objective of survey, state the null and alternative hypotheses, specify the acceptable decision error rates (Type I (α) and Type II (β)).

____ Specify sample collection and analysis procedures.

____ Determine numbers of data points for statistical tests, depending on whether or not the radionuclide is present in background.

- ____ Specify the number of samples/measurements to be obtained based on the statistical tests.
- ____ Evaluate the power of the statistical tests to determine that the number of samples is appropriate.
- ____ Ensure that the sample size is sufficient for detecting areas of elevated activity.
- ____ Add additional samples/measurements for QC and to allow for possible loss.

____ Specify sampling locations.

____ Provide information on survey instrumentation and techniques. The decision to use portable survey instrumentation or in-situ techniques, and/or a combination of both, depends on whether or not the radiation levels are elevated compared to natural background, and whether or not the residual radioactivity is present at some fraction of background levels.

____ Specify methods of data reduction and comparison of survey units to reference areas.

____ Provide quality control procedures and QAPP for ensuring validity of survey data:

  ____ properly calibrated instrumentation,

  ____ necessary replicate, reference and blank measurements,

  ____ comparison of field measurement results to laboratory sample analyses.

____ Document the survey plan (e.g., QAPP, SOPs, *etc*.).

Conducting surveys

____ Perform reference (background) area measurements and sampling.

____ Conduct survey activities:

  ____ Perform surface scans of the Class 1, Class 2, and Class 3 areas.

  ____ Conduct surface activity measurements and sampling at previously selected sampling locations.

  ____ Conduct additional direct measurements and sampling at locations based on professional judgment.

____ Perform and document any necessary investigation activities, including survey unit reclassification, remediation, and resurvey.

____ Document measurement and sample locations; provide information on measurement system MDC and measurement errors.

____ Document any observations, abnormalities, and deviations from the QAPP or SOPs.

Evaluating survey results

____ Review DQOs.

____ Analyze samples.

____ Perform data reduction on survey results.

____ Verify assumptions of statistical tests.

____ Compare survey results with regulatory DCGLs:

  ____ Conduct elevated measurement comparison.

  ____ Determine area-weighted average, if appropriate.

  ____ Conduct WRS or Sign tests.

____ Prepare final status survey report.

____ Obtain an independent review of the report.

F.7 Example data interpretation checklist

Convert data to standard units

____ Structure activity in Bq/m^2 ($dpm/100\ cm^2$)

____ Solid media (soil, *etc.*) activity in Bq/kg (pCi/g)

Evaluate elevated measurements

____ Identify elevated data

____ Compare data with derived elevated area criteria

____ Determine need to remediate and/or reinvestigate elevated condition

____ Compare data with survey unit classification criteria

____ Determine need to investigate and/or reclassify

Assess survey data

____ Review DQOs and survey design

____ Verify that data of adequate quantity and quality were obtained

____ Perform preliminary assessments (graphical methods) for unusual or suspicious trends or results - investigate further as appropriate

Perform statistical tests

____ Select appropriate tests for category of contaminant

____ Conduct tests

____ Compare test results against hypotheses

____ Confirm power level of tests

Compare results to guidelines

____ Determine average or median concentrations

____ Confirm that residual activity satisfies guidelines

Compare results with DQOs[*]

____ Determine whether all DQOs are satisfied

____ Explain/describe deviations from design-basis DQOs.

[*] ALARA may be included in the DQOs.

Appendix G: Reviewers of the report

Draft Report

Teunckens, Lucien	AF-Colenco Ltd	Switzerland
Van Gemert, Frank	Nuclear Research and consultancy Group	The Netherlands
van Velzen, Leo	Nuclear Research and consultancy Group	The Netherlands
Vaško Marek	DECOM a.s.	Slovak Republic

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Expert Review Meeting

Arnhem, The Netherlands: 13–15 May 2008
Organised by Nuclear Research and consultancy Group

Expert Review Meeting

Baden, Switzerland: 06 June 2008
Organised by AF-Colenco AG

Expert Review Meeting

Trnava, Slovak Republic: 24–25 June 2008
Organised by DECOM a.s.

Expert Review Meeting

Arnhem, The Netherlands: 29 July 2008
Organised by Nuclear Research and consultancy Group

Revised Report

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Vaško Marek	DECOM a.s.	Slovak Republic

Expert review meeting, Trnava, 10 September 2008

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Revised draft report

Teunckens, Lucien	AF-Colenco Ltd	Switzerland
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Expert review meeting, Trnava, 9 December 2008

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Revised report

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Quality review

Teunckens, Lucien	AF-Colenco AG	Switzerland