EUROPEAN COMMISSION
Community research

EURATOM

Monitoring Developments for Safe Repository Operation and Staged Closure

(Contract Number: 232598)

MoDeRn Monitoring Reference Framework report

MODERN DELIVERABLE (D-1.2)
Final

Author(s): **MoDeRn Partners**
(Edited by NDA, Nagra & NRG)

Date of issue of this report: 26/11/2013

Start date of the project: 01 May 2009 Duration: 54 months

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the 7th Framework Programme (2007-2013)		
Dissemination level		
PU	Public	X
RE	Restricted to a group specified by the partners of the MoDeRn project	
CO	Confidential, only for MoDeRn partners	

Distribution lists of the final version (email + acknowledgement of receipt): DD.MM.YYYY	
Steering Committee	X
Contributors	X
Project Officer	X
Administrative and financial teams	

Table of Contents

List of Acronyms

ASN:	Autorité de Sûreté Nucléaire (Nuclear Safety Authority), France
BFS:	Bundesamt für Strahlenschutz (Federal Office for Radiation Protection), Germany
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe, Germany
BMU:	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), Germany
CSEC	Centre for the Study of Environmental Change (CSEC), Lancaster University
CFR:	Code of Federal Regulations, USA
CEN:	Comité Européen de Normalisation (European Committee for Standardisation)
EBS:	Engineered Barrier System
EC:	European Commission
EDZ:	Excavation Disturbed Zone
EKRA:	Expertengruppe Entsorgungskonzepte für radioaktive Abfälle (Expert Advisory Group for Radioactive Waste Management), Switzerland
ENSI:	Eidgenössisches Nuklearsicherheitsinspektorat (Nuclear Safety Inspectorate), Switzerland
EPA:	Environmental Protection Agency, USA
ETN:	European Thematic Network
EIA:	Environmental Impact Assessment
EU:	European Union
EURATOM:	European Atomic Energy Community
FEPs:	Features, Events and Processes
FP7	Seventh European Community Framework Programme
FSC:	Forum on Stakeholder Confidence
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Germany
GSL	Galson Sciences Limited, UK
GRA:	Guidance on Requirements for Authorisation of Geological Disposal Facilities on Land for Solid Radioactive Wastes, UK
HADES:	High-Activity Disposal Experimental Site at Mol, Belgium
HLW:	High-level Waste
IAEA:	International Atomic Energy Agency
IBC:	Isoleren, Beheersen, Controleren (Isolation, Control and Monitoring)
ICRP:	International Commission on Radiological Protection
ILW:	Intermediate-level Waste
KTM:	Ministry of Trade and Industry, Finland
LLW:	Low-level Waste

MoDeRn:	EU-FP7 project "Monitoring Developments for Safe Repository Operation and Staged Closure"
NDA	Nuclear Decommissioning Authority, UK
NEA:	OECD Nuclear Energy Agency
NGO:	Non-governmental Organization
NIREX	United Kingdom Nirex Ltd., a UK organisation replaced by NDA, RWMD in 2008
NNC	NNC Ltd. (NNC), Knutsford
NRC:	National Research Council of the National Academies, USA
NSC:	Nuclear Safety Commission of Japan
OECD:	Organization for Economic Co-operation and Development
ONKALO:	Underground rock characterisation facility at Olkiluoto, Finland
R&D:	Research and Development
RTD:	Research and Technological Development
RWMD:	Radioactive Waste Management Directorate of NDA, UK
RWMC	Radioactive Waste Management Research Organisation, Japan
SAM:	Safety Assessment Management Ltd., United Kingdom
SEA:	Strategic Environmental Assessment
STUK:	Radiation and Nuclear Safety Authority, Finland
SUJB:	State Office for Nuclear Safety, Czech Republic
UK	United Kingdom of Great Britain and Northern Ireland
URL:	Underground Research Laboratory
US	United States of America
US DOE	United States, Department of Environment
US NRC	United States, Nuclear Regulatory Commission
WDP:	Waste Disposal Package
WMO:	Waste Management Organisations
WIPP:	Waste Isolation Pilot Plant, USA
WP:	Work Package

Glossary

This glossary provides definitions of terms that are used within this report and which are either specific to monitoring or have a specific meaning/definition within the MoDeRn Project.

Disposal Cell: The excavation in which waste is emplaced for disposal including any buffers and barriers (seals or plugs).

Disposal Unit/Disposal Area: A location or area, where a number of disposal cells are located, but separated from other units by accessways

Engineered Barrier System (EBS): The man-made components of the repository, typically comprising the wasteform, the waste container, the buffer, the backfill, and the plugs and seals.

Far field: The rock mass and surrounding geology but distant from the excavation as distinct from *near field*.

Main Objectives: The specific, high-level goals of a monitoring programme. The MoDeRn Reference Framework recognises four high-level goals for monitoring: to support the basis for repository performance evaluations, to support operational safety, to support environmental protection, and to support nuclear safeguards. Supporting the basis for repository performance evaluations includes the two different aspects of supporting the basis for the long-term safety case and supporting pre-closure management of the repository.

MoDeRn Reference Framework: An approach to developing a comprehensive monitoring programme by describing feasible monitoring activities, highlighting remaining technological obstacles, illustrating the possible uses of monitoring results and suggesting ways to involve stakeholders in the development and implementation of a monitoring programme

MoDeRn Monitoring Workflow: A process flowsheet that visualises the *MoDeRn Monitoring Reference Framework* process.

Near-field: The area of rock mass immediately surrounding and disturbed by the repository excavation in which disposal cells are located.

Overarching Goals: High-level statements that define the contribution of monitoring to the implementation of geological disposal. The MoDeRn Reference Framework recognises two overarching goals that all monitoring programmes will contribute towards: *to support confidence building* and *to support decision making*.

Pilot Facility: An area of an underground repository used to emplace and monitor a small but representative fraction of the waste in an early stage, i.e. prior to the disposal of the mayor part of waste. The waste in the pilot facility would be retrieved following operation of the facility and would be disposed of in the main repository.

Parameters: Numerical indicators of properties related to processes and events.

Preliminary Parameter List: A long list of possible monitoring parameters for which data could be collected to meet specific sub-objectives

Processes: On-going chemical and physical changes in a system.

Sub-objectives: Precise statements of the purposes of monitoring that allow the identification of processes and parameters to be monitored.

Stakeholder: An actor with an interest in repository monitoring. Can include, but is not limited to, members of a WMO, regulatory organisations, advisory bodies, and members of the public and/or their representative bodies.

Technical baseline: The level of technical development or the maturity of a specific technology at that time.

Trigger Values: Pre-defined values for monitoring results, which if reached would invoke further action.

List of MoDeRn Project Partners

The partners in the MoDeRn Project are listed below:

AITEMIN: Association for Research and Industrial Development of Natural Resources, Spain.

ANDRA: Agence nationale pour la gestion des déchets radioactifs, France.

DBE TECHNOLOGY: DBE Technology GmbH, Germany.

ENRESA: Empresa Nacional de Residuos Radiactivos, Spain.

ETH ZURICH: Eidgenössische technische Hochschule ETH Zürich, Switzerland.

ESV EURIDICE: European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment, Belgium.

GALSON SCIENCES: Galson Sciences Limited, United Kingdom.

NAGRA: Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle, Switzerland.

NDA: Nuclear Decommissioning Authority, United Kingdom.

NRG: Nuclear Research and Consultancy Group, Netherlands.

POSIVA: Posiva Oy, Finland.

RAWRA (now SURAO): Radioactive Waste Repository Authority, Czech Republic.

RWMC: Radioactive Waste Management Funding and Research Centre, Japan.

SANDIA: Sandia National Laboratories, United States.

SKB: Svensk Kärnbränslehantering AB, Sweden.

UNIVERSITY OF ANTWERP: University of Antwerp, Belgium.

UNIVERSITY OF EAST ANGLIA: University of East Anglia, United Kingdom.

UNIVERSITY OF GOTHENBURG: University of Gothenburg, Sweden.

1. Introduction

This report is the product of research activity carried out in the ***Mo**nitoring **De**velopments for Safe **R**epository Operation a**n**d Staged Closure* (MoDeRn) Project, within the Seventh European Atomic Energy Community Framework Programme (Euratom FP7/2007-2011). The project focuses specifically on repository monitoring for deep geological disposal of long lived radioactive waste and/or spent nuclear fuel.

> Based on prior (IAEA 2001, EC 2004) definitions, the MoDeRn project defines the term monitoring in the context of geological disposal of radioactive waste as:
>
> "*Continuous or periodic observations and measurements of engineering, environmental, radiological or other parameters and indicators/ characteristics, to help evaluate the behaviour of components of the repository system, or the impacts of the repository and its operation on the environment - and thus to support decision making during the disposal process and to enhance confidence in the disposal process*."

The purpose of this report is to present a ***Monitoring Reference Framework*** as guidance for the development of a geological disposal monitoring programme addressing the design of monitoring systems to implement such a programme; the use of monitoring results and their contribution to the governance of a stepwise disposal process; and the progressive updating of the monitoring programme within that stepwise process.

This guidance *Monitoring Reference Framework* draws on experiences and lessons learned from waste-management programmes in different countries and integrates new information from various stakeholder-engagement activities. It presents the MoDeRn partners' conclusions on:

- How monitoring objectives would be developed;
- Why and how they could contribute to verifying the basis for safety analyses;
- What options are available to support decision making in the stepwise disposal process.

The report also identifies and briefly discusses some aspects of the context within which geological disposal programmes take place that may influence decisions about monitoring and which therefore merit consideration when developing a monitoring programme.

1.1 Target audience for this report

The target audience for this report is assumed to have a good understanding of radioactive waste management. While it is written to provide guidance to waste management organisations (WMOs) on how to develop, implement, and use monitoring it is also envisaged that it could provide a basis for engaging with a range of stakeholders on the approach to monitoring. The report has been developed by the MoDeRn partners[1], which includes representatives of waste management organisations (WMOs), social scientists and experts in monitoring technology. It has also drawn on feedback from regulatory agencies, advisory bodies, monitoring experts for related industries and a small number of public stakeholders.

The project recognises that all stakeholders with an interest in a particular repository programme are likely to be interested in or have a specific role to play with respect to the development, implementation, and use of monitoring as a basis for receiving information on repository performance. Therefore the content of this report is intended to be informative to all stakeholders, including:

- Safety Authorities who supervise the monitoring approach and who may require some monitoring as a license condition;
- Designated Advisory Boards with responsibility for advising national decision makers on waste management issues;
- The local public and/or their representative bodies likely to take a particular interest in monitoring to verify that protection goals are met.
- Other interest groups such as local or national NGOs who are concerned about the (environmental) safety of a potential repository project.

1.2 Background on the MoDeRn project and this report

MoDeRn is a four year collaborative research project (2009 – 2013) addressing how repository monitoring can contribute to the technical safety strategy and the implementation of geological disposal for long lived radioactive waste and spent nuclear fuel, as well as contribute to public understanding of and confidence in repository behaviour.

Spent nuclear fuel and long-lived radioactive waste must be contained and isolated for very long periods, and current schemes for its long-term management assume disposal in deep geological repositories. The successful implementation of a repository programme for radioactive waste relies on both the technical aspects of a sound safety strategy and scientific and engineering excellence as well as on the way they relate to societal norms and values, and to various stakeholder expectations. Monitoring is considered key in serving both aspects.

Only limited prior experience is available for specific monitoring activities to compare with expected/predicted behaviour of the repository system. Most of this prior experience is based on analogous monitoring activities, e.g. in non-nuclear subsurface structures or the few operating low-level waste geological repositories.

---

[1] There are 18 MoDeRn project partners representing organisations responsible for radioactive waste management in 7 EU countries: Andra (France), DBE Technology GmbH (Germany), Enresa (Spain), NDA (UK), Posiva (Finland), SURAO (formerly RAWRA; Czech Republic), SKB (Sweden), Nagra (Switzerland), Sandia (US) and RWMC (Japan) as well as organisations with specialist expertise in monitoring (Aitemin (Spain), ESV Euridice (Belgium), NRG (The Netherlands), GSL (UK), ETH Zurich (Switzerland). Three partner organisations offer specialist experience in researching how people interact with technology and finding ways to engage all stakeholders (e.g. civil society, experts, technical safety organisations, industry) in highly technical issues: University of Antwerpen (Belgium), University of East Anglia (UK) and University of Gothenburg (Sweden).

MoDeRn focuses particularly on monitoring *in situ* repository system behaviour, as from a technical point of view monitoring of safety-relevant components of the disposal concept remains a significant challenge today, comprising many aspects that are unique to geological disposal.

The MoDeRn project aims to further develop the understanding of the role of monitoring in the staged implementation of geological disposal and to provide examples, guidance and recommendations that may be useful to Waste Management Organizations (WMOs) for their development of a monitoring programme and their understanding of how it could be implemented and used as part of the overall disposal process.

Other types of monitoring activity that will be called for in any geological disposal programme, such as operational safety, environmental and safeguards monitoring, are recognised as important but are likely to be similar to those already in use at other nuclear installations, based on standard tested and certified technology and their implementation can be planned and further developed based on prior experience. These monitoring activities do not pose the types of challenges discussed above and thus were not considered further within the MoDeRn project.

As part of the MoDeRn project previous (national and international) work addressing monitoring objectives has been reviewed and elaborated to better reflect the actual implementation of disposal monitoring activities, taking into account a variety of physical and societal contexts, available technology, and feedback from both expert and non-expert stakeholder interactions, obtained through dedicated workshops, and focussed social sciences research activity.

The project has furthermore defined the technical requirements of monitoring activities for repository system behaviour and has assessed the latest relevant technology (MoDeRn, 2010a, MoDeRn, 2013a). A technical workshop was hosted to learn about monitoring skills from technical applications outside of but relative to geological disposal (e.g. oil and gas industry, carbon capture and storage, mining and civil engineering) (MoDeRn 2010b). Innovative monitoring approaches specific to repository design requirements have been tested within underground research laboratories. These include non-intrusive techniques in mock-up disposal facilities in underground research laboratories (URLs) in Belgium, France and Switzerland (MoDeRn, 2013b & c).

In addition, several case studies were performed to illustrate the process of mapping objectives and strategies onto the processes and parameters that need to be monitored in a given context, to illustrate, in three case studies, the potential design of corresponding monitoring systems and possible approaches to prevent and detect measurement errors (MoDeRn, 2013g).

All detailed reports pertaining to the technology programme within MoDeRn are summarised within a Technology Summary Report (MoDeRn 2013h), presenting an overview of the current status of monitoring technology relevant to geological disposal and the project partners' advance understanding of monitoring systems, based on research, development and demonstration of appropriate monitoring techniques within the MoDeRn project.

Collectively, the activities within the MoDeRn programme discussed above contribute to a framework for developing and implementing various monitoring activities for deep geological repositories. This "Reference Framework", which is the subject of this report, proposes a systematic approach to developing a comprehensive monitoring programme by describing the steps from defining monitoring objectives to determining what parameters to monitor, designing and managing a monitoring programme, illustrating the possible uses of monitoring results and suggesting ways to involve stakeholders in the process of identifying monitoring objectives. The resulting 'framework' has been developed as guidance for radioactive waste management organisations to assist in progressing programmes for deep geological repositories that are safe and acceptable for all.

The output from the MoDeRn project is 18 published reports as illustrated in Figure 1-1 below.

Figure 1-1: MoDeRn Project Reports

A key factor in addressing a monitoring design is an understanding of the available and relevant technologies to address monitoring requirements. A significant component of the MoDeRn programme has been the management of a technical programme, which is summarised in MoDeRn Technology Summary Report (MoDeRn, 2013h). This technical programme includes:

- Identification of technical requirements report. Examples of specific requirements within the national programmes of the MoDeRn partners can be found in (MoDeRn, 2010a). However, it is recognised that many of the national programmes are at an early stage where sites and or specific host rock types have not yet been identified. These "technical requirements" are not therefore viewed as "mandatory - obligation to implement", recognising that as designs develop these requirements might change. Identifying these requirements then enables an assessment of applicable monitoring techniques which could be applied.

- Assessment of monitoring applications in technical fields outside of geological disposal. The MoDeRn project brought together monitoring specialists from a range of disciplines to present and discuss their work and experience in applying state-of-the-art techniques to monitoring (MoDeRn, 2010b).

- Identifying/defining the current technical state-of-the-art. Utilising the experience from this workshop (MoDeRn, 2010b) and drawing on the skills and practice of several project partners, MoDeRn has prepared a report on monitoring state-of-the-art (MoDeRn, 2013a) which identifies monitoring techniques which could have applications in geological disposal monitoring;

- RTD on relevant monitoring technologies. The MoDeRn project has also progressed 5 innovative research, development and demonstration programmes (MoDeRn 2013, b to f) where demonstrations have been progressed in underground research laboratories (URLs) monitoring mock-up disposal facilities in different geological environments. These programmes address the application of seismic tomography, remote wireless sensor networks, fibre-optic sensing (including distributed sensing) and microseismic techniques; wireless transmission of data underground to surface; and sensors embedded in liners to withstand construction and liner emplacement.

- Case studies on the development of monitoring programmes/set-ups. Specific examples of monitoring applications in a disposal situation in clay, salt and granitic rock and lessons learnt from these are presented in three Case Studies (MoDeRn 2013g).

1.3 Structure of the Report

Chapter 2 provides some background information and "sets the scene" for the MoDeRn Project programme and particularly for this *Monitoring Reference Framework*. This includes highlighting prior developments representing the understanding of repository monitoring at the international level and introducing key elements of the context within which a monitoring programme should be developed. It summarises some of the key findings and requirements arising from previous work and how these have provided the motivation for progressing the MoDeRn Project.

Chapter 3 introduces the *MoDeRn Monitoring Workflow*, a flow diagram which illustrates a systematic *process* for developing a monitoring programme for geological disposal. This process assists in (i) converting goals and objectives into identified processes and parameters to monitor; (ii) analysing requirements against available technology to design a monitoring programme; and (iii) conducting a monitoring programme and using the results to inform decision making.

Chapter 4 provides discussion and examples for identified processes and parameters to monitor.

Chapter 5 provides discussion and examples on a design of monitoring programmes, considering monitoring requirements and available technology.

Chapter 6 provides discussion for conducting a monitoring programme and using the results to inform decision making.

Chapter 7 provides discussion of contextual and decision-making issues related to designing and implementing a monitoring programme.

Chapter 8 provides a concluding summary of the MoDeRn *Monitoring Reference Framework*.

2. International developments in monitoring

This chapter provides some summary background information on key international developments in monitoring for geological disposal and describes the key driver for the MoDeRn project and, in particular, for developing this *Monitoring Reference Framework*.

Repository monitoring technologies have been developing over several decades and monitoring considerations have, in some cases, been included in national regulations. For example, the United States Code of Federal Regulations 10 CFR 60 (US NRC, 2012) includes specific requirements for monitoring to check performance.

This section briefly introduces key developments to date, reflecting the shared understanding of repository monitoring at the international level, in particular as reported in (IAEA, 2001; EC, 2004; IAEA, 2006, IAEA, 2012). It summarises several developments conducted over the last decade, where national repository programmes define their associated monitoring objectives and strategies and the corresponding monitoring programmes planned for implementation - or actually implemented, as in the case of Waste Isolation Pilot Plant (WIPP) monitoring (US NRC, 2012).

2.1 IAEA monitoring guidance

The IAEA Monitoring TECDOC (IAEA, 2001) discusses the possible purposes for monitoring geological repositories at the different stages of a repository programme, starting from surface exploration up to the post closure phase. It also discusses the use that may be made of the information obtained and the techniques that might be applied. It establishes general points of importance to the monitoring of geological repositories. It states that

> *"Monitoring will contribute essential information (…) and, in doing so, will strengthen confidence in long term safety"*.

In particular, it sets out five key purposes for monitoring, considered

> "*to be an important support to decision-making at all stages of the repository development programme."*

The five key purposes for monitoring (IAEA, 2001) are:

- To provide information for making management decisions in a stepwise programme of repository construction, operation and closure;
- To strengthen understanding of some aspects of system behaviour used in developing the safety case for the repository and to allow further testing of models predicting those aspects;
- To provide information to give society at large the confidence to take decisions on the major stages of the repository development programme and to strengthen confidence - for as long as society requires - that the repository is having no undesirable impacts on human health and the environment;
- To accumulate an environmental database on the repository site and its surroundings that may be of use to future decision makers;
- To address the requirement to maintain nuclear safeguards, should the repository contain fissile material such as spent fuel or plutonium-rich waste.

A key message from the IAEA TECDOC is that the probability of "unexpected readings" should be considered. It says:

> "*For critical parameters, the possible causes and consequences of unexpected readings need to be discussed and any actions that might then be required should be studied and planned for. The key issue is to be able to demonstrate an understanding of the implications of all types of monitoring results and an appropriate level of response*."

The document also stated that any monitoring system should not intrude into the barriers designed to contain radionuclides. Instead a part of the repository could be allocated as a demonstration facility, which could be heavily instrumented at least up to repository closure.

It concludes:

> "*It is widely accepted that the long-term safety of geological disposal should not rely on a continued capability to monitor a repository after it has been sealed and closed. Although future generations may wish to monitor, it would be presumptuous to speculate how and why they might do this. However, there are several more immediate applications of monitoring information obtained from the outset of a development programme, which the repository designers and operators can, and should, be required to consider*."

As a next step IAEA is currently developing a new Safety Guide on "Monitoring and Surveillance of Radioactive Waste Disposal Facilities" (DS 357).

The objective of this Safety Guide is to provide Member States with guidance and examples of good practice in relation to monitoring and surveillance programmes for disposal facilities for radioactive waste.

The Safety Guide will cover monitoring and surveillance during preoperational, operational and post-closure phases for all type of radioactive waste disposal facilities. It will consider the general criteria that need to be met by a monitoring and surveillance programme that is intended to assure radiological safety of the public, safety of the environment and specific criteria for each of the three phases of disposal facility development.

Guidance will be provided on how to implement such a programme and how to interpret and use the results, and storage of the data. It will cover guidance to the regulatory body on verification, independent control if needed and confidence on the information provided. General monitoring should be focused on the potential human exposure pathways (e.g., direct exposure, water bodies, soil, flora, fauna etc.). Each objective may require somewhat different types of information, or may use the same information in different ways. The extent and the nature of monitoring will change throughout the various stages of development of disposal facilities, and monitoring plans drawn up at an early stage of a programme will need to reflect this. It may also be expected that the plans will be revised periodically in response to technological developments in monitoring equipment, changing surveillance requirements, modifications to the facility design and changing societal demands for information.

2.2 European Thematic Network on monitoring

The European Thematic Network (ETN) on Monitoring (EC, 2004) built on the guidance on monitoring provided by the IAEA (IAEA, 2001) by considering the role of monitoring in a phased approach to the geological disposal of radioactive waste. The aim of the Monitoring ETN was to improve both the understanding of the role of and the options for monitoring within a phased approach to deep geological disposal of radioactive waste as well as to identify how monitoring can contribute to decision making, operational and post-closure safety and improve understanding of and confidence in repository performance.

The following reasons for monitoring that relate to the stepwise implementation of a geological repository (EC, 2004) were identified:

- Monitoring as part of the scientific and technical investigation programme, including environmental monitoring;
- Confirmation of key assumptions of the disposal concept;
- Maintaining the confidence of future generations.

The ETN noted that:

> "*Monitoring that is part of scientific and technical investigation programmes includes the collection of all necessary information related to site selection, site characterisation, design and construction of the facility and for safety assessment. It provides the basis to determine model parameters and to compare measured data with model predictions. This also includes monitoring of baseline conditions at potential repository sites to detect any potential negative impact on the environment caused by on-site activities during site characterisation, construction and operation of the underground repository, as well as for reasons of liability.*
>
> *The safety of the disposal system is usually demonstrated in terms of a safety case. This is defined as a set of arguments and analyses used to justify the conclusion that a specific repository system is safe. It includes a description of the system design and safety functions, illustrates the performance of engineered and natural safety barriers, and presents the evidence that supports the arguments and analyses and discusses the significance of any uncertainty or open questions. The safety case also presents the evidence that all relevant regulatory safety criteria can be met. Monitoring is, therefore, a means to assist in checking or confirming that key assumptions regarding the safety-related features of the disposal system are valid.*
>
> *The development of a repository for radioactive waste up to closure is a long-term process, possibly involving several generations. It is important to ensure that future generations will maintain confidence in the adequacy of the disposal system by confirming that the repository does not, at any time, pose a threat to the operating personnel and the public, and that the disposal system and the surrounding natural environment evolve as expected. Monitoring and the comparison of monitoring results with the predicted evolution of the system is a possible means of fulfilling this requirement. A related aspect is that the available information about the repository should be properly conserved and passed on from one generation to the next.*"

The main findings and conclusions of the Monitoring ETN (EC, 2004) can be summarised as follows:

- *"The importance of safety and the implementation strategy, where a spectrum of approaches can be recognised in different countries, have implications for the role of monitoring within a programme.*
- *It is important to understand the reasons for differences and the role played by monitoring within any safety and repository implementation strategy. Any differences in approach relate mainly to the extent to which monitoring is seen as confirming processes related to evolution of the repository and its long-term safety.*

- *The extent of monitoring should be limited to that which could reveal useful results for the decision-making process or for the confirmation of safety. That monitoring takes place must be explained to audiences and it is important not to give the impression that such monitoring indicates a lack of confidence in the safety of the disposal system.*
- *The technology that is necessary for much of the monitoring, e.g. of the surface environment and operational radiological parameters, is standard. Limitations exist, however, especially with regard to the longevity and reliability of monitoring equipment, especially under harsh environmental conditions, and calibration drift in remote locations may be a problem. False expectations should not be raised either with respect to what is practical over long timescales, or the utility of measurements and the ability (or need) to respond to the results of monitoring. That a parameter can be measured is not, however, a good reason for its measurement. Its measurement is justified only if it contributes to an increase in understanding or confidence in safety, and where it is possible to interpret the measurements.*
- *In summary, technologies exist or are being developed, that give good prospects for a level of monitoring that is appropriate for the issues at hand. The extent of monitoring that is either appropriate or useful to implement is, however, a sensitive question and depends on implementation strategies*."

2.3 IAEA safety requirements

Defining and carrying out a monitoring strategy has been listed as a Safety Requirement[2] for the geological disposal of radioactive waste by the IAEA in 2006. With these safety requirements, the IAEA wishes to set '*protection objectives and criteria for geological disposal*' and to establish '*the requirements to ensure the radiological safety ... during the operational period and especially in the post-closure period*' (IAEA 2006). Operational controls, monitoring and testing are seen as essential for assuring operational safety. They are seen as contributing to the further development of the post-closure aspects of the safety case during the period the repository remains operational, and are considered to provide baseline information for taking decisions on the closure of the facility. However, it is stressed that:

> "*Safety is ensured by passive means inherent in the characteristics of the site and the facility and those of the waste packages."* (IAEA 2006).

Therefore, monitoring and institutional controls are not considered a requirement to ensure post-closure safety. Nevertheless, a potential role in providing assurance is recognised for post-closure monitoring and institutional controls, particularly in relation to maintaining nuclear safeguards and to measures contributing to "social acceptability" (IAEA 2006).

With the presentation of these safety requirements, monitoring is explicitly recognised by the IAEA as playing an integral part in assuring the safety of a geological repository. Three specific requirements concerning monitoring programmes have been formulated (IAEA, 2006):

---

[2] "*Safety Requirements are to be situated in between Safety Fundamentals, which set out broad objectives, concepts and principles, and Safety Guides, which offer recommendations and guidance on how to operate in practice. Safety Requirements are expressed as 'shall' statements. Not meeting them means measures will need to be taken to restore the required safety level" (IAEA 2010).*

“A programme of monitoring shall be defined and carried out prior to and during the construction and operation of a geological disposal facility. This programme shall be designed to collect and update the information needed to confirm the conditions necessary for the safety of workers and members of the public and the protection of the environment during the operation of the facility, and to confirm the absence of any conditions that could reduce the post-closure safety of the facility.”

“Monitoring is carried out during each step of the development and operation of the geological disposal facility. The purposes of the monitoring programme include providing baseline information for subsequent assessments, assurance of operational safety and operability of the facility, and confirmation that conditions are consistent with post-closure safety. Monitoring programmes are designed and implemented so as not to reduce the overall level of post-closure safety of the facility.”

“Plans for monitoring with the aim of providing assurance of post-closure safety are drawn up before construction of the geological disposal facility to indicate possible monitoring strategies, but remain flexible and, if necessary, will be revised and updated during the development and operation of the facility.”

The IAEA also issued Safety Guide Standards relating to the development of safety cases and safety assessments for geological disposal (IAEA, 2012) which states:

“*The safety case and supporting assessment should also be used to establish a monitoring and surveillance programme for the site and the surrounding area that is appropriate for the specific disposal facility and for subsequent review of the programme. Surveillance and monitoring programmes should be developed and implemented to provide evidence for a certain period of time that the disposal facility is performing as predicted and that the components are able to fulfil their safety functions*.”

2.4 Developments within national programmes

Prior to, in parallel with, and following, the publication of the Monitoring ETN, several national programmes undertook programme-specific studies to develop national monitoring programmes associated with activities at specific sites. These include:

- A Compliance Monitoring Implementation Plan developed by the U.S. Department of Energy (US DOE) for monitoring activities to be conducted at the Waste Isolation Pilot Plant (WIPP) repository, in New Mexico, USA (Hansen, 2011),
- A programme of monitoring during the construction and operation of the ONKALO facility at Olkiluoto in Finland (Posiva, 2003),
- An approach to long-term monitoring for a nuclear fuel waste repository in Canada (OPG, 2003),
- A framework for monitoring during the stepwise implementation of the Swedish repository for spent fuel (SKB, 2004), and
- A comprehensive “performance confirmation” program for the Yucca Mountain Repository (Sandia, 2008).

A recent survey of these developments was produced by the project and the current status of national developments is presented in the MoDeRn Monitoring Context Summary Report and Annexes (MoDeRn, 2011a & b).

These programme-specific studies provide examples of monitoring objectives and the development of monitoring strategies. Organisations in two countries (Japan and the UK) with generic national disposal programmes undertook reviews of monitoring issues at the time of the work on the Monitoring ETN. The Radioactive Waste Management Funding and Research Centre (RWMC) in Japan provided a systematic review of studies into the approaches and technical possibilities of monitoring for understanding various aspects of HLW geological repositories (RWMC, 2005). This latter report has distilled five objectives for monitoring, and Table 2-1 provides the associated summary description of these objectives.

Table 2-1: The objective of monitoring of geological disposal and the description by RWMC

Objective	Description
1. Confirming safety performance and the adequacy of the repository's engineered measures	• Confirming whether or not disposal system components function as planned • Confirming design/construction assumptions • Verifying safety assessment models • Judging the need for facility improvements or repairs related to repository operation / construction
2. Confirming compliance with statutory requirements	• Confirming compliance with regulations after a closure of repository • Confirming compliance with safety regulations for workers and local residents during construction and operation • Confirming compliance with environmental impact assessment regulations
3. Providing information for making decisions on policy and operations	• Providing information for decision-making • Dealing with the retrievability of emplaced waste
4. Understanding the baseline characteristics of the geological environment at Preliminary Investigation Areas, etc.	• Clarifying the baseline characteristics of the geological environment
5. Providing information for public decision-making	• Enhancing the confidence that the public (particularly local residents) have in geological disposal • Compiling databases for future generations

United Kingdom Nirex Limited (Nirex) undertook strategic reviews of options for monitoring during the phased development of a repository for radioactive waste (SAM et al., 2002), the technical feasibility of post-closure monitoring (GSL & Golder, 2004) and development of an illustrative post-closure monitoring programme (GSL, 2004).

In 2007, both RWMC and Nirex organised an international workshop on repository monitoring in Geneva, Switzerland - the “Geneva Workshop” – (GSL, 2008). The objective of the Geneva Workshop was “*to identify the general basis for the development of effective repository monitoring programmes*”.

In general, the Geneva Workshop indicated that high-level national strategies for monitoring of geological repositories are broadly similar - differences in approach are largely at a detailed level. It did however note the value of further work on monitoring.

Key messages from the Geneva Workshop (GSL, 2008) were:

- Early planning of monitoring activities is essential. Monitoring programmes could be more intensive in the early stages of repository development, in order to obtain a good understanding of the system characteristics and confirmation of assumptions and data in the technical baseline.
- The extent of data collection should be planned in advance of initiating monitoring activities. Care should be taken to ensure that monitoring data requirements are sufficient to facilitate the desired understanding of the underlying properties and processes of a system, but not excessive in terms of needs, required resolution or precision. There should be appropriate overlap between monitoring techniques (e.g. measurement of a process by more than one technique).
- Monitoring is likely to play an important role in building stakeholder confidence.
- An effective strategy for communicating the results of monitoring activities to the public is essential.
- A variety of potentially relevant equipment and techniques have been developed outside the nuclear industry. The importance of identifying and exploiting the available technology on the market was highlighted.
- Gaps in the development of strategic planning of international and national monitoring programmes appeared to be greater than the perceived gaps from a technical perspective.

Two programmes for repository monitoring have been developed to a level of detail suitable for implementation: The Yucca Mountain Performance Confirmation Testing and Monitoring Plan (Sandia, 2008) and the WIPP Compliance Monitoring Implementation Plan (DOE 1996; Hansen 2011). The former - irrespective of its current project status - provides valuable information on the process followed to develop a monitoring programme and on how this is tied to the needs of the disposal process. The WIPP monitoring programme (see Chapter 5.1 and 7.6) was implemented and has been in operation for more than a decade, and as such provides valuable information including lessons learnt from evaluating and using monitoring results to inform the disposal process.

2.5 Monitoring throughout the repository lifecycle

The extent and nature of monitoring will change throughout the various stages of repository development. In the early stages of a repository programme, the results could be used to revise the way that geological disposal is implemented.

During the long period over which a repository will operate prior to closure, future operators and future generations will need to make decisions about how, when and if to implement various steps in the development of the repository system. Such decisions can be supported by information provided by monitoring results (IAEA, 2001; EC, 2004).

The geological disposal of radioactive waste is envisaged as a staged process, including development phases and stepwise repository implementation and closure. These are identified here to prepare further discussions on what types of decisions might be associated with each step of the process, what role monitoring might play and what stakeholders might be involved in making decision.

Most national disposal programs assume that repository construction, operation and staged closure will span a timescale of the order of a century. *In situ* monitoring of the actual repository (after site characterisation, but including any test or pilot facility monitoring) is assumed to begin at the start of construction and to accompany the disposal process at least until the decision to move to post-closure. It therefore provides the disposal process management with substantial added value through the *in situ* data made available over such a timescale. This will typically exceed the timescale that had previously been available to conduct experiments whose results also contribute to the basis of the safety case.

Earlier documents, such as the IAEA TecDoc 1208 (IAEA, 2001) or the US National Research Council (NRC, 2003), have structured the disposal process into a series of stages or phases. There are minor variations in how specific stages have been identified, however, in all cases the structure progresses from site selection and characterisation, through to post-closure.

The NEA R&R (Reversibility and Retrievability) project (NEA, 2011) identified phases and also distinct periods within each of these phases:

- Pre-operational phase
  - Siting decision
  - Construction decision
  - Decision to begin disposal
- Operational phase
  - Decision on partial backfilling (first sealing of the disposal cell; in a separate step sealing/backfilling of access galleries)
  - Decision to end emplacing waste
  - Decision on final closure (sealing and backfilling of remaining infrastructure)
- Post-operational phase
  - Period of indirect oversight
  - Period of no oversight

Consistent with the different phases discussed above, a series of decision points can be identified, located at the transition between the different periods and phases (NEA, 2011) i.e. where a decision is taken on whether to advance to the next phase/period. This series of decisions, as illustrated in Figure 2-1, could typically apply to most disposal programmes.

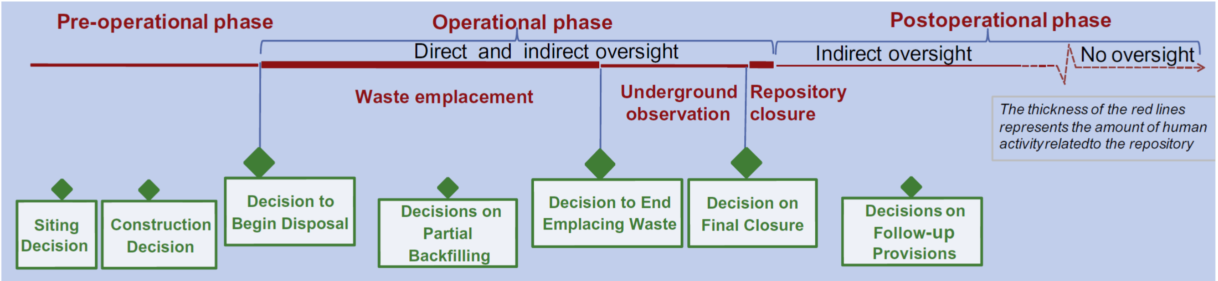

Figure 2-1: Repository life phases and examples of major decisions (from NEA, 2011 and ICRP, 2013)

A progression from siting to closure, as shown in Figure 2-1, may be considered as the reference path for implementing waste disposal. An obvious pre-requisite for progress is that the information provided by monitoring does not shed doubt on the robustness of the safety case, but rather confirms the basis for long term safety and provides confidence to progress to the next stage/activity. Possible alternative options, however, must also be provided at each step – otherwise there would be nothing to decide. The NEA R&R (Reversibility and Retrievability) project (NEA, 2011) proposed the following options:

- Follow the reference path;
- Continue on a modified path;
- Re-evaluate;
- Go back.

With respect to the option to "Go back", a consistent requirement encountered in most national contexts is for the disposal process to allow feasible waste canister retrieval operations. The degree of difficulty associated with such retrieval operations depends on the characteristics of the host geology; concept of operations and design; and more generally on the time and number of closure steps passed since waste emplacement.

Monitoring needs related to such decisions include information on the conditions of the waste package and of the environment in the disposal cell. This information can be used to relate actual conditions to those projected from scientific research and laboratory analysis. To this effect, it may be useful to consider the following series of stages of the waste lifecycle, identified in (NEA, 2011):

- Stage 1: Waste package in storage;
- Stage 2: Waste package in disposal cell;
- Stage 3: Waste package in sealed disposal cell;
- Stage 4: Waste package in sealed disposal zone;
- Stage 5: Waste package in closed repository;
- Stage 6: Distant future evolution, with progressive waste package degradation.

2.6 Need for further developments within the MoDeRn project

Previous developments on repository monitoring have laid down a solid foundation for understanding the key purposes for developing monitoring programmes. They identified the need for monitoring to provide information and thus support management decisions during the stepwise development of the disposal process. They put forward the assumption that monitoring is expected to contribute to strengthening confidence, specifically in long term safety and more generally in the disposal process overall. Furthermore, the IAEA Safety Requirements for geological disposal (IAEA, 2006) include specific safety requirements calling for the definition, planning and conducting of monitoring during each step of the disposal process. The Monitoring ETN (EC, 2004) was widely regarded as a useful starting point for the strategic planning of monitoring activities. However, it was perceived to provide insufficient detail regarding the degree of overlap and distinction between national monitoring programmes. It was also felt that the Monitoring ETN did not adequately address potential opportunities for international collaborative research in defining common elements in monitoring strategies. The findings of the Geneva workshop provided the basis for developing and defining the programme for this MoDeRn Project.

3. MoDeRn monitoring workflow

The previous developments at the international level (Chapter 2) express general requirements and describe how monitoring can support the implementation of geological disposal in a broad sense. However, project partners recognised that there is a need to develop and propose a more detailed and structured process description to provide guidance to national programmes on how to develop, implement and use a monitoring programme. The process description would build upon existing general guidelines but would be more focused on actual implementation of a monitoring programme. It would also incorporate lessons learnt from those national programmes which have already conducted monitoring or have commenced development of a monitoring programme.

The project proposes this *Monitoring Reference Framework* as a structured approach to follow in order to develop, implement and operate a monitoring programme. This is illustrated by the *MoDeRn Monitoring Workflow* (Figure 3-1) and the themes developed more specifically are:

- How specific monitoring objectives may be developed and how their role in the disposal process could be understood: to develop these objectives into clear information requirements which can then be related to key safety functions and thus to processes and parameters to be monitored.
- How monitoring systems may be designed and which strategies may help in attaining the monitoring objectives. These will include assessing technical feasibility; strategies to address technical limitations, with an outlook for further research and development (R&D), and more generally the potential for added value from a monitoring programme as well as an assessment of its limitations for informing the disposal process.
- How monitoring should be addressed as part of the overall governance of the disposal process by providing guidance on how monitoring results would inform and thus contribute to management decisions, how they would be evaluated against prior expectations, and how the particular case of monitoring results deviating from such prior expectations (unexpected or deviating results) could be addressed; and
- How monitoring might contribute to stakeholder confidence – to discuss how the evidence expected from testing the validity of the licence basis prior to closure, the process[3] overall and specifically the roles different stakeholders may play, could contribute to enhancing confidence in the disposal process.

This *Monitoring Reference Framework* develops the themes highlighted above in more detail and provides recommendations on how to progress them within the context of a national repository programme. This should enable implementers to build upon previously established understanding of monitoring, and apply the process, taking full advantage of the more detailed understanding already developed in certain national repository programmes.

[3] This aspect was not developed in detail during stakeholder research within MoDeRn, but the *MoDeRn Monitoring Workflow* is viewed as a tool for communicating monitoring process and programmes with stakeholders.

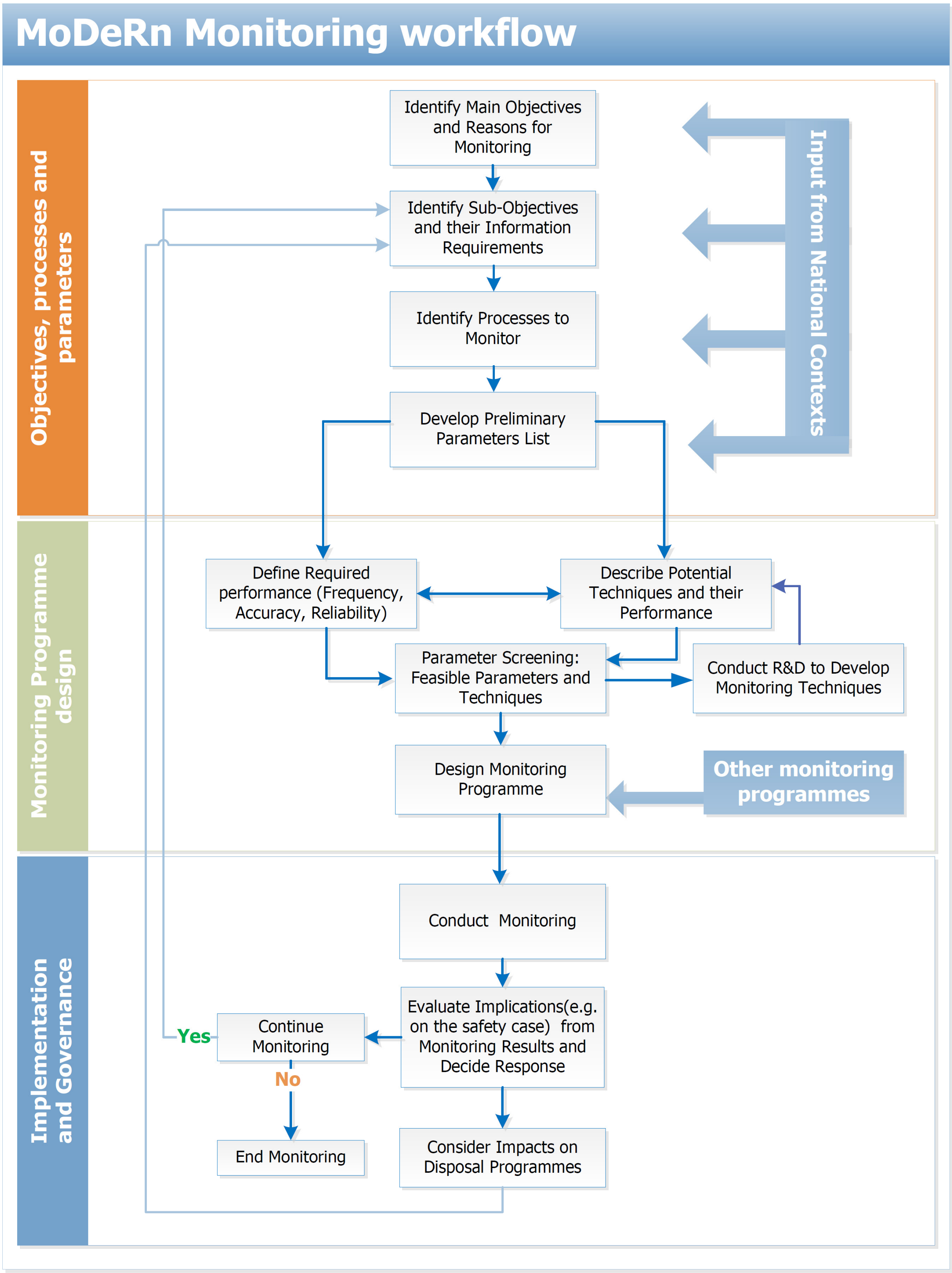

Figure 3-1: MoDeRn Monitoring Workflow

The *Monitoring Reference Framework* does not claim, nor aim to provide the description of a specific reference monitoring programme but some examples are provided in this report to illustrate specific aspects of the **process** presented in the *Reference Framework*. Indeed, the project clearly recognises the diversity of national contexts and the diversity of monitoring solutions that are thus likely to be developed.

The *MoDeRn Monitoring Workflow* (Figure 3-1) calls for a step-by-step process for identifying what is required from monitoring and developing those requirements into a defined programme through analysis of these requirements.

The Monitoring Reference Framework as depicted in the *MoDeRn Monitoring Workflow* identifies three key stages in developing and managing a monitoring programme:

1. Objectives and Parameters: Identification of objectives and sub-objectives, and relating these to processes and parameters to identify a preliminary parameter list for monitoring.
2. Monitoring Programme and Design: An analysis of: performance and technical requirements: available monitoring technology; and strategies to address potential technical failure to design a monitoring programme.
3. Implementation and Governance: Conducting a monitoring programme and using the results to inform decision making.

The MoDeRn Monitoring Workflow envisages an approach which starts with identifying high-level objectives, and through systematic analysis, develops clearly-defined monitoring requirements, leading to a programme of specific monitoring activities. This approach (often referred to as a "top-down" approach) can be used to ensure comprehensiveness, transparency and traceability. Developing this top-down process should also help ensure that a monitoring programme is properly focused on priorities. The systematic analysis also provides a basis for early engagement with interested parties to provide a transparent basis for ensuring that requirements (which will often be high-level) can be translated into a suitable and effective monitoring programme. A "bottom-up approach", i.e. a process that starts by defining detailed monitoring activities and attempting to link these to higher level objectives, is not recommended, as it can often be driven by technical preferences rather than programme needs and may not necessarily identify, or focus on, priorities.

Early development of monitoring programmes applying the process described in the *Workflow* should help the implementer and stakeholders to understand the approach to monitoring and provide a basis for engagement on monitoring programmes. The three key stages of the *Workflow* process are described in more detail in the sections below. Chapters 4, 5 & 6 discuss these stages providing examples and some discussion of how objectives might be developed through all the stages.

3.1 Objectives, processes and parameters

The Figure 3-2 below, as the first stage of the *MoDeRn Monitoring Workflow*, outlines the process from the identification of main monitoring objectives through to the development of a preliminary list of parameters for monitoring. The identification of sub-objectives, processes and parameters is a closely-linked and iterative process.

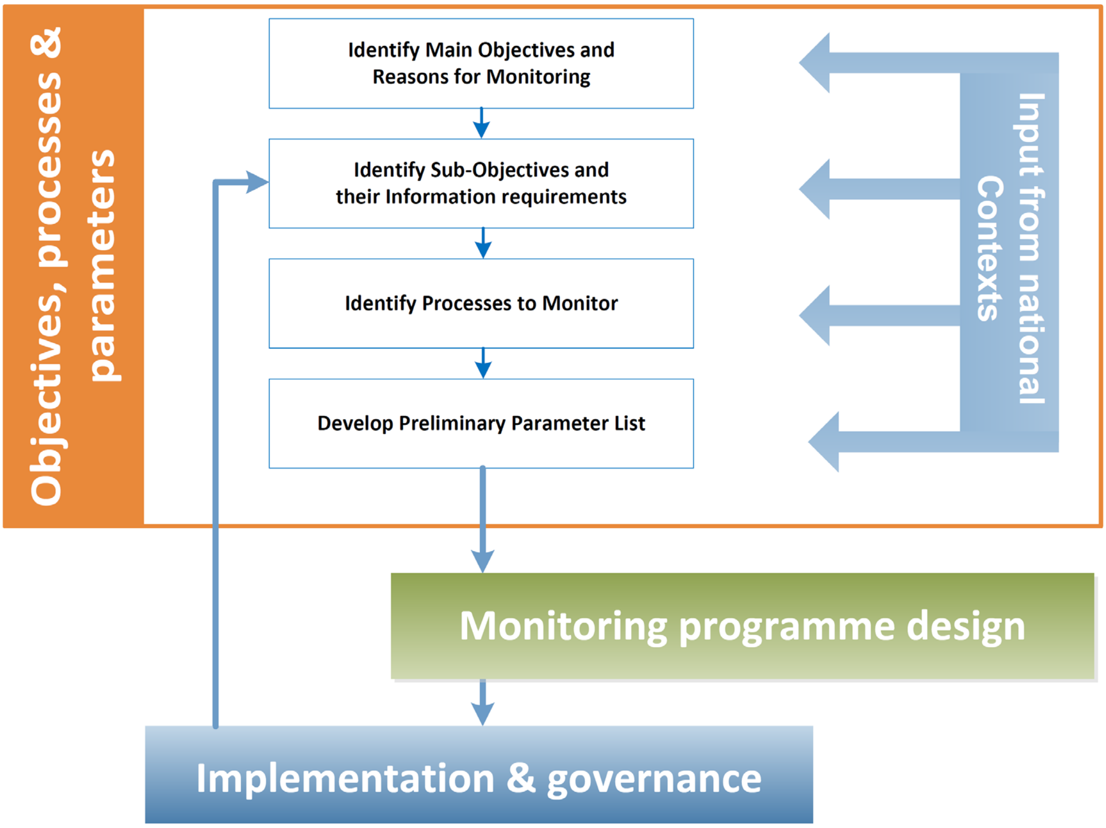

Figure 3-2: MoDeRn Monitoring Workflow – analysis of objectives, identification of sub-objectives and processes and development of a preliminary parameter list

There are two overarching goals that all monitoring programmes will contribute towards:

- *To support decision making,* which is associated with the use of information derived from monitoring in the context of a stepwise repository implementation process. Here, monitoring provides information to support management decisions required throughout the process.
- *To support confidence building*, which is associated with some of the more general added value that can be expected from monitoring. Monitoring provides a means to evaluate and verify the actual evolution of a repository and the surrounding environment, with the intent of checking that the disposal facility behaves within the bounds assumed in the safety case and that protection goals are met.

By defining the specific goals for monitoring, implementers could develop specific activities related to each goal. This makes the process for developing the monitoring programme more focused and efficient. These key drivers for conducting a monitoring programme should be clarified at the start of the process. These are referred to as *main objectives* in the *MoDeRn Monitoring Workflow*.

3.1.1 Identify main objectives and reasons for monitoring

Main objectives are statements describing the goals that call for the development, implementation and use of a specific monitoring programme. The MoDeRn Project recognised four fundamental main objectives (Figure 3-3):

- To support the basis for repository performance evaluations.
- To support operational safety.
- To support environmental protection / impact assessment.
- To support nuclear safeguards.

Monitoring related to these four main objectives would encompass any activities undertaken in support of stakeholder confidence. These stakeholders could include members of advisory bodies, members of local communities, members of the public, or representatives of other waste management organisations. Focused engagement may be undertaken with stakeholder groups to understand monitoring objectives and/or activities that they would like to see incorporated in a monitoring programme. The outcome of this engagement could result in the identification of specific sub-objectives.

Figure 3-3 illustrates the overarching goals and main objectives for monitoring.

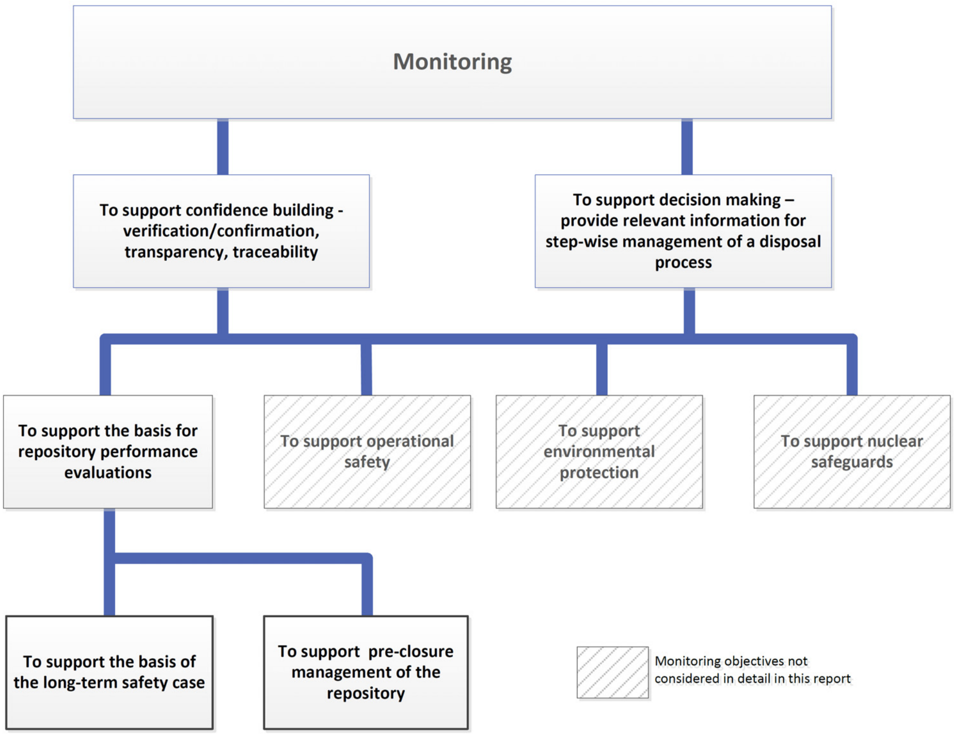

Figure 3-3: Overarching goals and main objectives for monitoring.

The main objective on which most work in the MoDeRn Project focuses is "*to support the basis for repository performance evaluation"*, however, it was recognised, as shown in Figure 3-3, that this could split into "*to support the basis of the long-term safety case*" and "*to support the basis for pre-closure management*". Although throughout this report reference is made to *main objectives* and *sub-objectives* (see below), these could be split into a number of steps.

National regulations may also include requirements to monitor specific processes. In addition, as a programme evolves regulatory review of preliminary safety cases or conditions imposed in regulatory approvals may specify monitoring activities that must be undertaken in the monitoring programme. These monitoring activities are covered by the four fundamental main objective and could be expressed directly in terms of processes and parameters (i.e. without further definition of sub-objectives as described in the sections below).

3.1.2 Identify sub-objectives

Main objectives are of a more general nature, therefore the next step in developing a monitoring programme is the development of more detailed objectives, referred to here as "sub-objectives". The specific sub-objective(s) would necessarily take account of the national context; this could include specific legal and regulatory requirements; stakeholder views and should also be specific to the particular waste, geology type and setting.

The identification of sub-objectives can be a complex process, when it involves national context and stakeholder view. This may require more than one step as a sub-objective should be a precise statement setting out the purpose of monitoring to allow the identification of processes and parameters to be monitored to address that sub-objective. Examples of types of sub-objectives are:

- Tracking of parameters representative of safety functions of different repository components
- Confirmation of short-term behaviour of the repository
- Confirmation of the near-field system behaviour
- Assessment of transferability of monitoring results from the pilot facility to the main facility
- Assessment of decisions concerning reversibility / retrievability
- Considerations on flexibility for extended operation

The identification of sub-objectives would be based on specific aspects of the disposal programme, including development and analysis of the safety case, design work, regulations and stakeholder engagement. For example if an objective was to *support the basis for pre-closure management* then a sub-objective could be *monitor ground support stability to maintain access* – this would require information from monitoring about the stability of tunnel, shafts and other accesses. (See Section 4 for worked example).

3.1.3 Identify processes

The main approach and starting point to identify processes involves the screening of a previously developed list of features, events and processes (FEPs), compiled in a FEP catalogue, that provides a comprehensive list of on-going processes in and around the repository. For each sub-objective, one or more features or processes (physical, chemical, biological, geological and/or other processes) should be identified that can provide information in support of the sub-objective. Sub-objectives collated from independent consideration of the safety case, regulations and stakeholder views may overlap with other sub-objectives - any overlaps should be considered carefully to minimise duplication and help optimise monitoring plans in a later stage.

As part of the safety case, which is the basis of the license application, safety functions would be defined. By a careful assessment of the FEPs and the corresponding evaluation of the repository evolution scenarios those processes affecting a particular safety function can be identified. Those processes are then considered worth monitoring to confirm that the safety functions are not jeopardized.

The process of identifying the list of candidate processes should be an iterative process to check that these respond to the specific sub-objectives; this process should also ensure that sub-objectives are clear and unambiguous. Screening of the list of FEPs may be only one way of deriving relevant processes to be monitored. Other methods may include the involvement of stakeholders. The development of the resulting monitoring programme can include cross-disciplinary discussions, with experts on the performance assessment and monitoring technology, in order to identify the more technically-relevant processes on the list and to determine parameters to be monitored relevant to those processes (e.g. parameters that significantly affect the safe confinement of the waste or safety functions of individual disposal components).

This process of identifying the *candidate list* is developed in a number of steps. First, the safety strategy and underlying safety functions for the identified processes should be made clear in order to provide a solid basis for justifying their inclusion. Then, more specific processes and parameters related to these safety functions are identified and an analysis made of how these processes impact safety performance.

Further analysis should then be performed to identify the “most significant” processes. This analysis may be required to establish the degree of confidence available in expected future evolutions. The implementer should evaluate what provides this degree of confidence and assess whether monitoring of a process evolution is required, or whether the outcome is known with a high degree of certainty. This selection of a most significant set of processes would thus also provide the core information for decision making.

The selection or rejection of a process with the evaluation of the role of each FEP with respect to a certain safety function needs to be clearly justified. Experts in safety case development, with an overall understanding and analysis of those processes likely to influence the expected repository performances, are best placed to develop these justifications, and this would result in a list of processes to be considered. The justification could be a statement describing the assumptions behind expert judgement, a link to a specific section of a report or a link to a particular model result. Specific regulatory requirements and stakeholder views should also be addressed at this stage.

Those processes, not included could be evaluated in a separate step to establish whether their monitoring also holds potential to enhance the basis for model and parameter development, as used to present the safety case. They could still contribute to reducing model and parameter uncertainties, possibly leading to enhanced understanding and opportunities to revisit some initial and potentially conservative assumptions. In general, they would not be expected to substantially influence iterative updates of performance assessments, but should reflect on the robustness of the overall understanding of the underlying processes.

3.1.4 Develop preliminary parameter list

The next step is to develop on the basis of the candidate list of processes a preliminary list of parameters to monitor. This preliminary list is expected to identify parameters that, when monitored, may provide useful information on safety and to enhance our knowledge basis as well as to reduce uncertainties and enhance our ability to model and assess the future repository evolutions. This approach is illustrated by specific examples and based on lessons learnt in the development of specific case studies (MoDeRn, 2013g).

It was agreed by all MoDeRn partners that the process of identifying parameters should be transparent and traceable. This is not only useful for the implementer itself to keep track of the knowledge and the rationale for their identification but also for the discussions with the authorities and justification for the decision to monitor that parameter. Transparency is also important for the public and expert stakeholders giving them the opportunity to provide their views and influence decisions. A formal and thus regular involvement of stakeholders is viewed as essential. Figure 3-4 illustrates the identification process starting with the monitoring sub-objectives as indicated in the MoDeRn Monitoring Workflow.

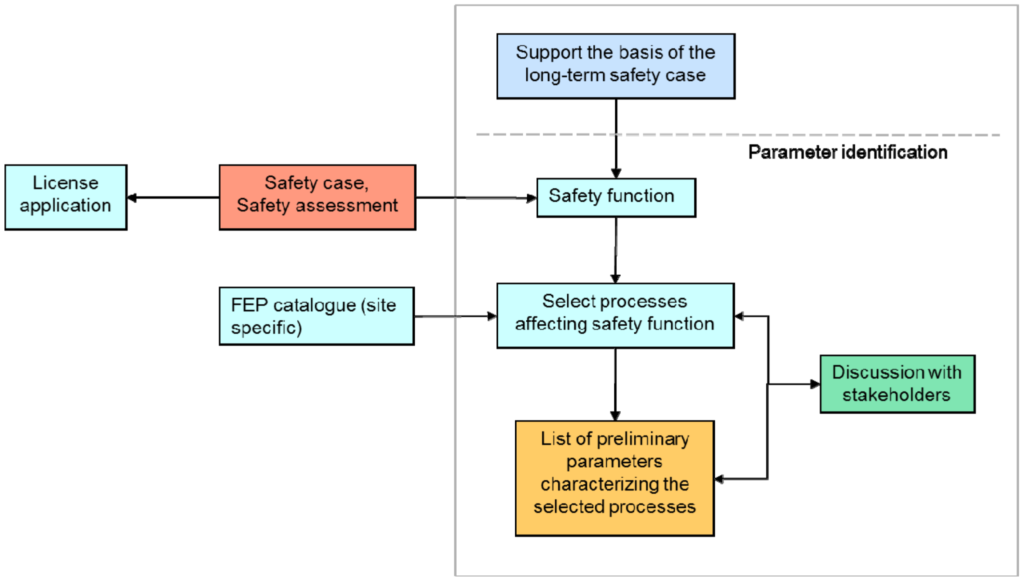

Figure 3-4: Principle of parameter identification process

The next step is then to determine the parameters characterizing the individual processes. This process would lead to the development of a *Preliminary Parameter List* for further evaluation prior to implementing a monitoring programme. The selection of processes and the setup of the preliminary parameter list should be discussed with those involved stakeholders to ensure that all their requirements are considered.

3.2 Monitoring programme design

Development of the monitoring programme should include cross-disciplinary discussions, with experts on the performance assessment and monitoring technology, in order to identify the technically-relevant processes on the list and to determine parameters to be monitored relevant to those processes (e.g. parameters that significantly affect the safe confinement of the waste or safety functions of individual disposal components; see Chapter 3.1).

The *Preliminary Parameter List* must undergo a screening prior to the design of the monitoring programme to evaluate the feasibility and to ensure that the proposed monitoring technology will not have adverse effects on the disposal system. The screening (Figure 3-5) will also ensure that the proposed techniques will provide meaningful data.

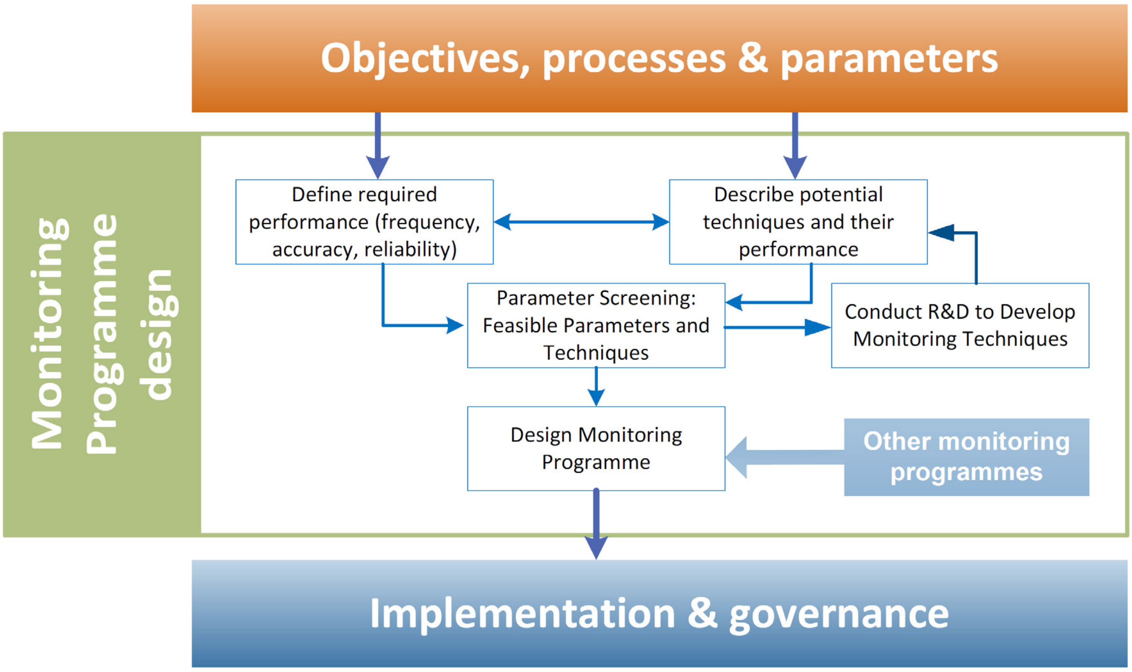

Figure 3-5: MoDeRn Monitoring Workflow – Monitoring programme design

3.2.1 Define required performance

In order to assess the feasibility of a technology, for each of the parameters identified by the parameter selection process, an initial description should be prepared of what, when and where the parameter could be monitored, together with a description of the required accuracy and frequency. The details would be specified in a general sense (e.g. "where" would describe a generic location for the measurement). Specific details of the monitoring programme would be defined in developing the monitoring design.

In order to assess the technical and performance requirements of the parameters to be monitored, the information needs for each of the entries in the Preliminary Parameter List must be defined. Through analysis of the role of a parameter in the safety of a disposal design, requirements on the frequency, placement and performance (e.g. accuracy) for monitoring each parameter should be specified.

More detailed information on technical requirements on monitoring systems are reported in (MoDeRn 2010a). From some of the overarching requirements for monitoring, such as placing emphasis on monitoring systems not compromising safety, areas for RTD have already identified as e.g. nonintrusive monitoring techniques, some of which have been addressed in the MoDeRn project (MoDeRn, 2013 b to f).

3.2.2 Describe potential techniques

It will then be necessary to evaluate the available monitoring technologies to assess whether they can meet the required performance. That evaluation will also need to consider whether the proposed approach to monitoring a parameter (location, technique, etc.) would affect the safety case or impact on other monitoring measurements. Of key importance here is considering whether application of the technique would affect the passive safety of the disposal facility; monitoring programmes should be designed and implemented so as not to reduce the overall level of post-closure safety of the facility. In selecting a monitoring technique, factors such as the timespan over which it required to operate, the reliability, durability and robustness of the technique would also need to be considered – given the requirement to ensure that barriers are not disturbed, consideration should be given to the use of non-intrusive techniques.

The MoDeRn project has compiled a state-of-the-art report (MoDeRn, 2013a) on applicable and related monitoring techniques which could be employed in repository monitoring. The state-of-the-art is continually developing particularly in repository monitoring and designers should continually research to establish the latest advances in monitoring technology in both geological disposal and other related industries (e.g. nuclear, mining & civil engineering).

3.2.3 Parameter screening

For each parameter, an assessment of whether there are one or more techniques of suitable maturity (technical readiness) available to monitor that parameter. The technical and performance requirements on the parameters in the *Preliminary Parameter List* should be checked against available techniques to identify methods for collecting the data required. This will include consideration of the operating conditions under which the technology can perform, and known reliability of the technology and accuracy of data collected using the technology. This process should also recognise situations where the expected parameter evolution would be so small or so slow, that existing technologies would not be sufficiently sensitive to provide useful information within realistic timescales for monitoring.

Figure 3-6 illustrates the suggested process for parameter screening. This proposes the following systematic analysis of each parameter on the Preliminary Parameter List:

1. A preliminary specification would be developed for each parameter identify what monitoring information is required; what accuracy and over the timeframes. This would also specify the conditions under which the monitoring system would operate (temperature and physical and chemical environment).
2. An analysis of whether there is an available monitoring technique to address that requirement.
3. If a technique is available then it would be assessed to check if it would have an adverse impact on safety (or on other monitoring systems).
4. If a technique is not available or has limitations in relation to required level of sensitivity and accuracy, durability or would have a potential impact on safety, then research and development of alternative techniques or improvement of existing techniques could be initiated.

5. In situations where a technique is unavailable and unrealisable through research and development then it must be accepted that that specific parameter cannot be monitored and the parameter should be removed from the parameter list and the justification recorded.
6. Once the analysis is complete a final parameter list would be developed together with potential locations for monitoring systems.

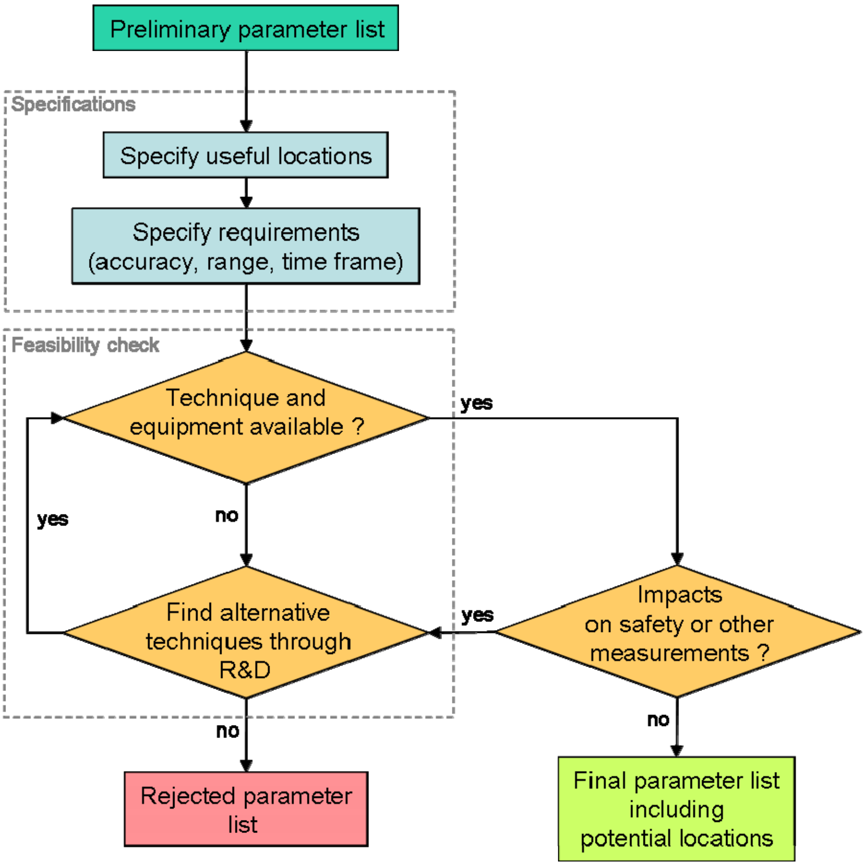

Figure 3-6: Parameter screening process

A parameter would be kept in the parameter list if there is a suitable technique for monitoring the parameter, and if there is no impact on the safety case, and undertaking monitoring is practical from a time and cost perspective.

Screening could be referred to as an iterative assessment what options for technical implementation of monitoring are available. Where techniques to monitor a parameter are not available and the parameter is viewed as important then a case may be made for additional research and development. Where more than one technique has been identified as suitable for monitoring a specific parameter, options would be retained until the design of the monitoring programme has been completed.

Most national radioactive waste disposal programmes are in an early stage of development, where a complete set of quantitative safety assessment results and corresponding parameter sensitivity analysis are not yet available. However, the benefits in attempting early development of a monitoring programme is that the process of evaluating and screening processes and parameters, assists in establishing their relative importance with respect to safety. This could be used to define monitoring research and development priorities; recognising that the monitoring programme would need to be revisited as a specific safety case develops. This is particularly important as a number of technical challenges (MoDeRn 2013a, MoDeRn 2013h) have been identified for monitoring of geological disposal.

3.2.4 Design monitoring programme

Once the parameter screening is performed and a list of all feasible parameters, including one or several technical options of monitoring technologies is derived, an analysis of available monitoring techniques can be conducted to identify which techniques could be most effectively applied to monitor a specific parameter.

The MoDeRn project has compiled a state-of-the-art report (MoDeRn, 2013a) on applicable and related monitoring techniques which could be employed in repository monitoring. The state-of-the-art is continually developing particularly in repository monitoring and designers should continually research to establish the latest advances in monitoring technology in both geological disposal and other related industries (e.g. nuclear, mining & civil engineering).

In cases no mature technology exists that fulfils the requirements, there may be good prospects for developing techniques, either to monitor processes that cannot currently be monitored using existing techniques, or to monitor processes more effectively. Therefore, R&D could be undertaken to improve the options for repository monitoring. The basis for early analysis of monitoring requirements is to identify where such R&D on monitoring techniques could be progressed for the benefit of future monitoring programmes.

Some of the overarching requirements for monitoring, such as placing emphasis on monitoring systems not compromising safety have already identified areas for RD&D of non-intrusive monitoring techniques, some of which have been addressed in the MoDeRn project (MoDeRn, 2013 b to f).

The design of the monitoring systems should commence with specification of the details of the monitoring programme, including the location of monitoring sensors, the amount of redundancy in terms of the use of different techniques, and of the application of the same technique in multiple locations. The design of the monitoring programme should include consideration of the feasibility, time and cost of monitoring to that specification.

The design of the monitoring programme would consider:

- Performance requirements (e.g. sensitivity, accuracy, reliability/durability) for the monitoring system and compatibility with disposal barriers.
- Selection of monitoring locations.
- Management of uncertainty in the performance of the chosen monitoring techniques.
- Assessment of data quality and management of potential technical failures.
- Data management.
- Post-processing of data, quality assessment and communication of monitoring results.
- Performance measures and trigger levels for the monitoring programme, including agreement on response plans to be undertaken, should data exceed trigger levels or not evolve as expected.
- Integration with other repository monitoring programme that might be collecting data of relevance (e.g. national groundwater quality monitoring programmes).

As the design of monitoring systems progresses, these can be discussed and reviewed with regulators and involved stakeholders to provide the opportunity for some input and feedback. This provides a chance to discuss: whether the design approach is consistent with expectations; to discuss issues of scope and cost; to communicate areas where there are challenges to the effectiveness of the design and where there are plans to address those challenges; and to refine how future monitoring programmes are developed and communicated.

3.3 Implementation and governance

Once a monitoring programme has been implemented it is important that a well-developed process for collecting monitoring information, evaluating and communicating that information and responding to the findings, as appropriate. This process (see Figure 3-7) of implementation and governance should include a wider consultation with key stakeholders to ensure that the monitoring process is transparent and acceptable to provide the basis for later decision making and for the evaluation of implications. In the next sections, the three steps of implementation and governance as depicted in Figure 3-7 are discussed. To put the topic of implementation and governance into perspective, in the last two sections the role of monitoring in decision-making and a description of the role of monitoring for the stepwise implementation of waste disposal are presented.

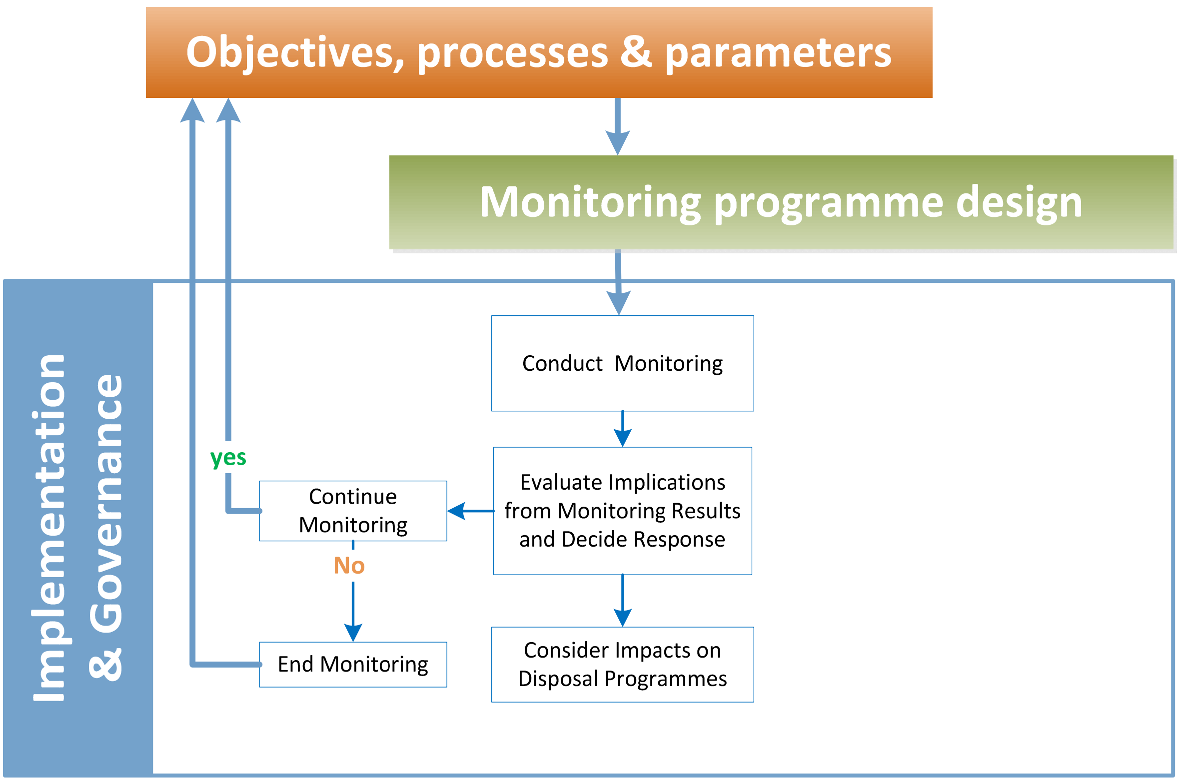

Figure 3-7: MoDeRn Monitoring Workflow – Implementation and governance

3.3.1 Conduct monitoring

Monitoring activities should be undertaken by suitably qualified and experienced personnel, working to specific quality assurance and reporting procedures. Data will be delivered to qualified personnel for analysis and validation. The processes for data analysis and management should be accessible to key stakeholders to allow checking and to increase confidence in the quality of information provided. Where third parties checks/reviews are required, the information provided should include detail relating to the methods employed, the raw data and processed information.

Following acquisition of monitoring data, the first step would be to verify the quality of the data. The design of a monitoring system should address potential failures and methods to detect these e.g. by redundancy or by applying the use of more than one technology to monitor a critical parameter. In a large long-term monitoring programme, equipment failure cannot be excluded and this needs to be anticipated in advance by suitable measures to detect failure. In addition to traditional quality assurance, assessment of data during a monitoring programme would include consideration of consistency of data collected by the same technique or by other techniques.

For certain monitoring techniques, it is expected that the instruments will cease to operate or malfunction over time. Some of these devices may not be accessible. It will not be possible to predict the exact time at which the instruments fail, although minimum operating timescale objectives may be defined based on testing and demonstration undertaken prior to the start of the monitoring programme. Therefore, pre-defined criteria need to be developed to justify decisions to reject data that give spurious results.

Taking suitable measures (e.g. redundancy) in design should mean that it is unlikely that all instruments will fail at the same time. Redundant equipment, or equipment using alternative technology, would provide a basis for analysis of inconsistent data. It is important to be able to analyse effectively whether inconsistent data is a result of failure of instrumentation rather than unacceptable performance of the repository. Where the operating life for a monitoring system is known to be limited, a key requirement is that measurements are taken more frequently than the expected rate of equipment failure.

Further details on sensor failure detection methods and possible improvements of monitoring systems in this regard are elaborated in the Case Study Report in Chapter 7 (MoDeRn 2013g).

3.3.2 Evaluate implications

When monitoring outcomes are in line with (predefined) expectations, the outcomes will be reported periodically and monitoring will continue as planned. Prior to commencing a monitoring programme, a response plan should be developed, where potential actions are defined in case results exceed pre-defined "trigger values" Trigger values will be a combination of limiting values, ranges, and observations that are based on the parameter produced and reported by the various monitoring activities. Trigger values should be set to provide a warning that one or more readings are not in line with expectations and that further action is required (risk management).

Definition of a trigger value and parameter evolution could be undertaken using the following steps:

- *Step 1:* The expected range including the uncertainties of each parameter has to be established as part of the licence application. For certain monitoring parameters this will require specific calculations to define the expected evolution in a parameter value. A principal investigator (safety case specialist) is the subject matter expert on the process model to which the parameter applies.
- *Step 2:* Define the expected performance of a monitoring system in terms of accuracy, precision, drift, etc.
- *Step 3:* Derive trigger values by identifying monitoring results that would initiate evaluation processes defined in the test plan.

3.3.3 Consider impacts on disposal programmes

Monitoring is an activity undertaken in support of the wider context of management of radioactive waste. Therefore, conclusions from the monitoring programme are provided as support to decision making, which could take account of other factors as well as monitoring results. Periodic assessment of monitoring results will allow decisions to be made on revising the monitoring programme, which may impact on how monitoring is achieved. The decision may also be taken to end a monitoring programme. The monitoring programme will end when determined by an implementing organisation, and agreed with regulators and other stakeholders.

In the case of deviating monitoring results, one should check first if a technical failure can be excluded. However, in case a malfunction of a sensor cannot be excluded, a range of risk management approaches exist, which would only be invoked if certain trigger values are exceeded:

- Additional analysis of the safety case/assumptions underpinning the monitoring and setting of the trigger value.
- Invoke additional monitoring to check/confirm results.
- Engineering intervention.
- Retrieve the waste.

Within the risk management approach, the significance (to the safety of the repository) of data which exceeds a trigger value should be assessed. This might be achieved by the additional analysis of performance assessment or supporting calculations. This would allow the data to be classified as either:

- "Not associated with risk": monitoring outcome does not affect basic assumptions of the safety case. These data would indicate that the repository is continuing to operate within a tolerable safety margin (data not affecting safety case).
- "Associated with risk": monitoring outcomes may affect basic safety assumptions of the safety case. These data would indicate that the repository is behaving in a manner that may affect safety (safety-related data).

This analysis and resulting response plan should be discussed and agreed with regulatory authorities. The response plan should include a programme of communication and engagement with other stakeholder groups to ensure transparency. Where monitoring data are consistent with performance measures (trigger values) the monitoring programme should continue with data acquisition based on the planned programme, until a periodic assessment of the overall results from the monitoring programme is required. A decision-making process for use in evaluating data from a monitoring programme is shown in Figure 3-8.

Following the identification of data “Potentially associated with risk”, the possible responses identified in the safety strategy should be considered and a preferred risk management option selected. Applying the selected risk management option may include significant changes to the basis for safety which could cause changes to the monitoring programme and/or the disposal programme.

Monitoring is an activity undertaken in support of the wider context of management of radioactive waste. Therefore, conclusions from the monitoring programme are provided as support to decision making, which could take account of other factors as well as monitoring results.

Periodic assessment of monitoring results will allow decisions to be made on revising the monitoring programme, which may impact on how monitoring is achieved. The decision may also be taken to end a monitoring programme. The monitoring programme will end when determined by an implementing organisation, and agreed with regulators and other stakeholders.

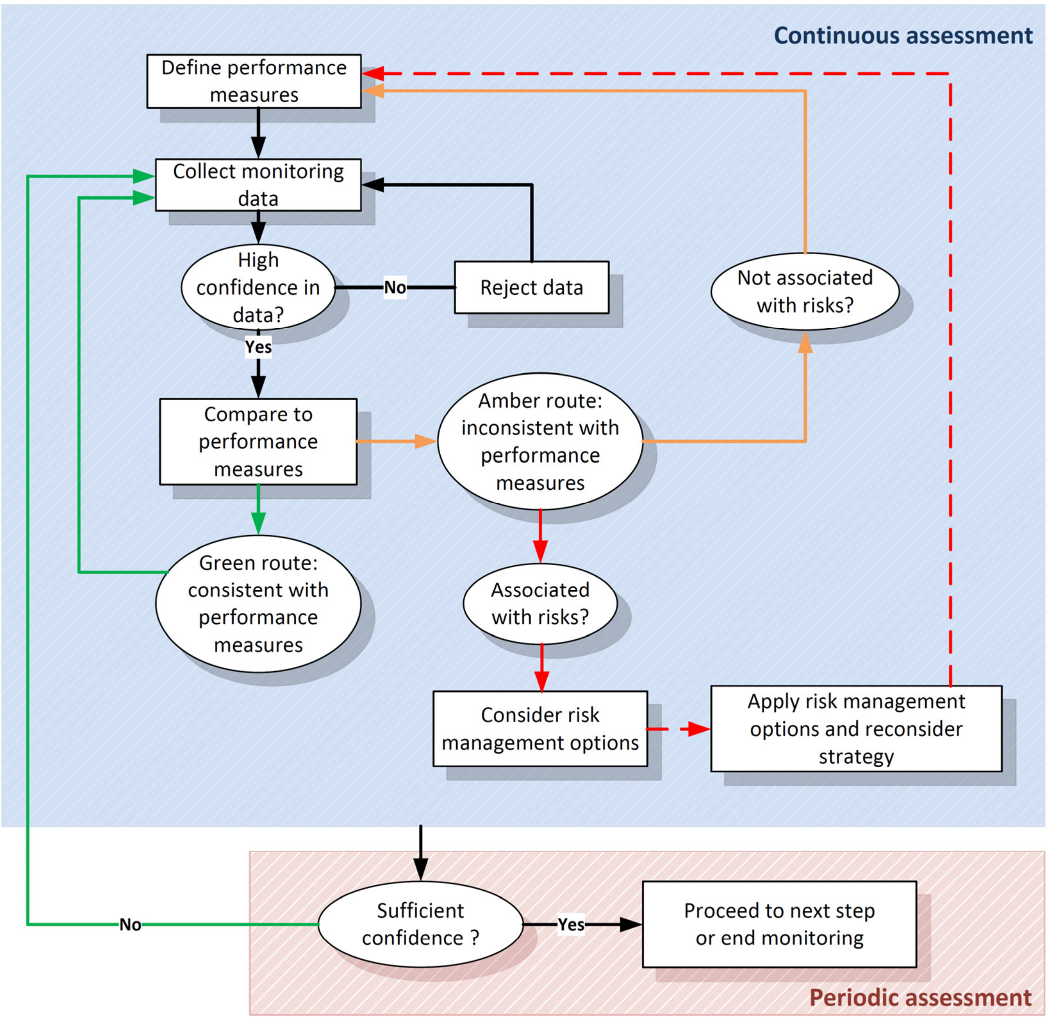

Figure 3-8: An example of a decision-making process for use in evaluating data collected during a monitoring programme (from GSL, 2004)

3.3.4 Role of monitoring in decision-making

This report does not aim nor claim to address overall governance of the disposal process. To the extent, however, that "*To support decision making*" (Figure 3.3) as an overarching goal for monitoring, it is necessary to discuss monitoring in relation to the overall governance. The emphasis will be on the possible role and indeed contribution that monitoring might make to governance, as evidenced at major decision points. The IAEA (IAEA, 2001) considers that "*the primary objective of monitoring is to provide information to assist in making those decisions"*.

"*To support decision making*" may refer to both a process of predominantly technical/ scientific considerations (traceability, competence) whereas "*To support confidence building*" addresses predominantly political considerations (transparency, accountability and acceptance). Both relate to stakeholder confidence: the former to the implementers' and safety authorities' confidence, primarily based on technical/scientific considerations; and the latter to other 'non-expert' stakeholders' confidence in the transparency and competence of the process.

The respective roles in process governance of the waste management organisation, the safety authorities, evaluation boards and government, as well as other involved stakeholders, are known for those countries which have already taken the major decisions for site selection and, in the case of the US and Swedish programme, for licence application. Similar roles may be in place to influence decisions during the operational phase and for the major decision to close the repository.

The provision in most national programmes for a stepwise process for decision-making before advancing to the next stage is recognition of the complexity of geological disposal. Therefore the approach required in pre-closure management is to be able to retain the ability for different options to support the decision-making process. It seems prudent to ensure that the structural integrity and environmental conditions in the repository continue to provide for safe operations over a sufficient time period, to prevent these factors becoming a driver to move to closure. The options considered would need to provide for the time it might take – even if initially unplanned – for the operational phase to progress through the stepwise decision process.

Previous consideration has been given to how decision points should be managed within a disposal process. By way of example, the US National Research Council (NRC, 2003) proposed an overall process to be initiated by the programme implementer at each decision point:

- "*Systematically gather, synthesize, evaluate, and apply the information acquired to date*
- *Develop options for the next stage, including explicit consideration of reverting to an earlier stage*
- *Evaluate and update the assessment of the safety of the repository system, in light of the options*
- *Make the findings publicly transparent and available*
- *Engage in dialogue with stakeholders*
- *Decide on the next stage based on all of the above*
- *Disseminate decisions and their rationale*"

Among the information of interest to management of the disposal process are: (i) verification of the adequacy of the licence basis for long term safety and (ii) options available to continue the disposal process.

Information pertaining to the licence basis for safety should confirm the long-term passive safety of the repository, in order to contribute to a decision to continue the initial process path towards closure. Information pertaining to pre-closure management should inform decision-makers on options available, and on the conditions in which those options would be carried out. This informs process governance (i) on the relative flexibility available to implement decisions, especially delays (technical or otherwise) in emplacement and closure, and (ii) on options to improve on the disposal process through design optimisation.

3.3.5 Monitoring as part of the stepwise implementation

The developments within MoDeRn focus on this operational and closure phase from initial construction until final closure of the repository. Therefore, this discussion focuses on the possible contribution and use of monitoring data to support decisions that may be taken during the stepwise management of that operational and closure phase.

From the moment a licence basis has been established and a licence is granted, monitoring plays a role in evaluating progress compared with that licence basis. It is expected that monitoring will either provide information that confirms prior understanding or that may refine or introduce new understanding. If monitoring results are satisfactory, they are expected to support decisions to pursue a reference path or, if enhanced knowledge supports the potential for optimisation. If, on the other hand, monitoring results challenge prior understanding, this could call for a re-evaluation of the licence basis.

The licence to move to final closure would be based on a decision sometime in the distant future (in the order of a century after initial granting of a licence). Some national contexts have identified legal provisions governing the process of authorising closure, which would include review by safety authorities and possibly call for a dedicated “repository closure” law, followed by a period of institutional control of a closed repository.

When and how the decision points during the operational phase will be set strongly depends on the specific national context and could be based on: specific expectations of stakeholders; specific licence conditions (e.g. a mandated periodic (10-year or other) safety review); as well as specific design considerations (e.g. to repository layout and efficient schedules for construction and waste emplacement). Therefore decision points could be planned for, both in referring to a set calendar, as well as referring to clearly defined modifications of the repository configuration.

- “Calendar-driven” (i.e. related to an agreed timetable) steps might be imposed by periodic safety inspections and/or periodic safety reviews possibly requiring the update of the safety case integrating any new knowledge.
- “Configuration-driven” (i.e. relating to stages in development of the repository) steps might refer to decisions pertaining to progressive closure, as well as to progressive construction and waste emplacement.

Some decision points may also arise for unexpected reasons, either from societal factors or as a result of technical or monitoring information. These cannot be planned as for routine activities but the process needs to accommodate them should they arise.

From the beginning of operations until the decision to close the repository, waste would be emplaced and disposal cells and disposal areas would be progressively closed. Corresponding decisions gradually bring the repository closer to its passive configuration, which provides the basis for long-term safety. As the duration of a monitoring programme increases, monitoring should provide more information relating to the evolution of the repository and thus assist in decision making about moving to subsequent stages. In parallel, pre-closure management options, in particular the option of waste retrieval, become increasingly difficult to implement. Decisions informed by monitoring should thus be based on conclusions that there is increased confidence that the basis for safety evaluation is robust, and that retrievability is increasingly less likely to be needed. This concept is illustrated by Figure 3-9, developed within the NEA retrievability and reversibility project (NEA, 2011), classifying the progressively reduced ease of retrieval by an R-scale.

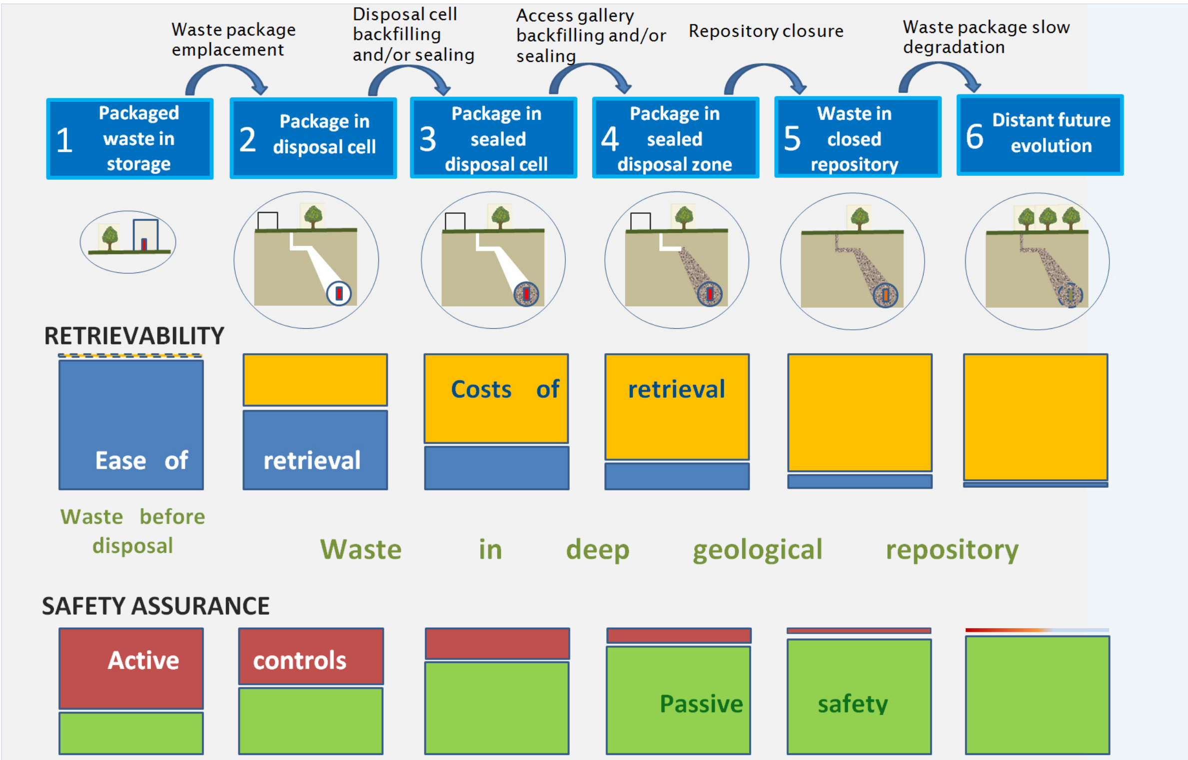

Figure 3-9: The NEA R&R project graphic presentation of the R-scale (NEA, 2011)

4. Process and parameter identification

The *MoDeRn Monitoring Workflow* (Figure 3-1) summarised in the previous chapter, identifies three key stages in developing and managing a monitoring programme. This chapter considers the first stage of analysis (Figure 3-2) required to translate main objectives and sub-objectives into parameters, citing examples to assist in explaining the basis for analysis.

The role of monitoring in support of long-term safety of geological disposal requires a different approach from what would be expected at facilities whose performance expectations span the more common timescales of decades or centuries. While barrier and environmental monitoring can directly confirm the adequate protection of human and the environment provided by a (near-surface) disposal of short lived waste, for the time that the waste presents a threat, this is not the case for geological disposal.

The ability to check/confirm behaviour through direct evidence is likely to be limited to initial evolutions and the near-field response, as well as to verifying that no unexpected early evolutions take place. The extents (and limitations) to which this can contribute to "*support the basis for the safety case*" are important considerations within this framework.

Generally it can be stated that the overall safety function of the disposal system could be labelled *provide adequate containment and isolation of radionuclides from the accessible environment*. Its performance measure would be breakthrough curves of radionuclide concentrations at the horizon of the accessible environment, or more commonly the effective dose this induces to humans living in that environment. Such a metric can be simulated based on the development of a scenario, associated modelling and overall system performance assessment. For example, a repository sealing system which may include disposal unit plugs or seals, gallery seals and access shaft/ramp seals is emplaced to restrict water flow and radionuclide transport through the repository. Monitoring activities may consider the mechanical and hydraulic properties of such seals and possibly confirm an adequate chemical environment consistent with expected seal material swelling.

The analysis required must link overall system performance to local barrier performance. It could be carried out by functional breakdown. The system safety function can be broken down into several functions providing e.g. (i) containment at the source, (ii) limiting the transport vector (water) from the source to the accessible environment, and (iii) preventing or retarding transport of radionuclides by this vector. To each of these would be associated specific performances, consistent with what is used in the reference scenario for the safety assessment. Consistent with the example above, these would be e.g. (i) initial delay and release rate at the source, (ii) permeability of the engineered structures and seals, as well as permeability of the host formation, and (iii) dissolution potential and retardation factor for radionuclides.

This can be further broken down, until a specific safety function is attributed a performance that has to be met by a specific repository component. Therefore, while the analytical tool provides for several levels of functions and corresponding expected performances, in the end a specific safety function can be related to a specific components performance. More detailed examples are provided in the remainder of this chapter.

4.1 National context

Differences in waste types, designs and host formations may lead to different performance objectives for repository components. Where this *Reference Framework* is used as a basis for developing a monitoring programme, the user should first consider the specific national context including these differences to enable these specific factors to be taken into account from the outset. For example, copper, steel or concrete overpacks contribute differently to the overall safety case and are influenced by different degradation processes. Any associated monitoring sub-objectives need to be developed specifically for each case. The design of the monitoring system needs to be adapted to address the relevant processes and parameters, as well as to the design of the component to be monitored. The use of monitoring results and the relative weight they carry when informing decision making would depend on the contribution that the component (e.g. buffer) being monitored provides to the performance of a safety function and/or the performance of the repository system overall.

In some national contexts, performance assessment models do not rely upon short-term transients and emphasise evolutions from an initial equilibrium between the repository and its environment (resaturation, thermal field...). This equilibrium is expected to occur much later than the monitoring period envisaged, thus monitoring cannot directly track any parameters considered in that performance assessment. They can, however, be used to confirm that assumptions underlying the development of these simplified performance assessment models were indeed appropriate or conservative, and thus that long term simulations of performance still provide a valid argument for long term safety.

4.2 Sub-objectives related to processes and parameters

A specific sub-objective will call for information from monitoring to support the evaluation of a safety function.

Analysis of safety functions and the contribution of repository components to the expected performances of those safety functions provide a more detailed list of how these components should perform to support the basis for the long term safety case.

An example of this is that the safety function of a waste canister is to provide containment of its radionuclides. The performance indicator that can be associated to this safety function is water tightness for a period of time described in the safety assessment. This performance has to be realised by the physical barrier (container) in its environment (disposal cell and near field). The sub-objective related to this safety function is to provide information supporting the evaluation of the containers' performance, i.e. duration of water tightness. Containment is provided as long as the canister is not pierced by corrosion and mechanical stress. The sub-objective therefore aims at providing information relevant to the evaluation of corrosion and applied mechanical stress. The available understanding provided by safety assessments should allow those features, events and processes, which influence container corrosion and applied mechanical stress, to be identified.

It is not always possible to follow such an approach and at the same time incorporate differences arising from national contexts, where there might be very specific monitoring requirements. For this reason, the approach to developing a monitoring programme, as set out in this report, must always be viewed as generic and operators should always consider specific national context, including waste type and geological environment, as they develop their monitoring plans.

For the purpose of defining a comprehensive monitoring programme, it may be necessary to regroup all processes and parameters expected for a specific component into a unique monitoring plan – the worked examples in the 3 *case studies* (MoDeRn, 2013g) show how this has been addressed. The relationship between each process and parameter and the function and performance that motivated it should not be forgotten, as it will be important when evaluating monitoring results.

4.3 Examples of sub-objectives related to safety functions

The following are examples relating specific safety functions to monitoring sub-objectives:

- *Safety function: Avoid or limit water or brine inflow from the environment through the access drifts to the canisters*

  Depending on the host rock, canister corrosion can significantly be limited by ensuring that there is no water inflow from the environment to the canisters. In case of salt being the host rock, this is the main safety function of the geotechnical barriers and a key topic within the safety case. The sub-objective would thus be to demonstrate the proper functioning of the geotechnical barriers, in the early phase, after barrier emplacement.

- *Safety function: Contain radionuclides at the source*

  Expected performances typically relate initially to a more or less substantial period of total containment of radionuclides, followed by a period of release rates controlled by the waste matrix and the conditions in the disposal cell. The physical components which are required to provide these performances are the disposal container and the waste matrix, within their disposal cell environment. The sub-objective associated with this safety function would thus be to support the basis for evaluating: (i) watertightness and gas tightness over a given period and (ii) release rates thereafter.

- *Safety function: Limit the transport vector from the source to the accessible environment*

  This safety function could be further broken down to consider specifically (i) the transport vector from the disposal cell to the repository infrastructure or near field, (ii) the transport vector through the closed repository to the accessible environment, and (iii) the transport vector through the host formation to the accessible environment.

  - *Expected performance from the disposal cell* (i) typically relates to the water flux entering and leaving the disposal cell. This may refer to maximum or localised influx rates and the permeability of a cell plug (seal) and/or buffer. The sub-objective would thus be to support the basis for evaluating: (a) the permeability of the cell plug or buffer; and (b) the local hydraulic conditions driving the flux.

  - *Expected performance through the closed repository* (ii) relates to the water flux through a repository infrastructure towards the repository shafts or ramps. This may refer to average flow rates and to the permeability of gallery, shaft or ramp seals. The sub-objective would thus be to support the basis for evaluating: (a) the permeability of the gallery, shaft, and/or ramp seal; and (b) the local hydraulic conditions driving the flux.

- *Expected performance through the accessible environment* (iii) refer to the unperturbed permeability of the host formation. This unperturbed permeability was first established during site characterisation. Its spatial variability throughout the repository may have been verified during construction. The expected performance thus refers to the extent that repository construction and operation may have altered the baseline permeability. The sub-objective would thus be to support the basis for evaluating the extent and influence of perturbations on host formation permeability.

- *Safety function: Limit the dissolution potential and provide retardation for radionuclides*

  Another example for retaining radionuclides at source could be to limit the dissolution potential and provide retardation for radionuclides. As for the previous safety function, this could also be further broken down to reflect specific performances expected in the disposal cell, in the infrastructure and from the host formation. Such a breakdown would make sense if the safety case were to rely on such specific features, e.g. *providing for a reducing environment in the disposal cell*. The transport properties of the host formation would be established during site characterisation. The expected performance thus refers to the extent that repository construction and operation may have altered the baseline permeability. The sub-objective would thus be to support the basis for evaluating the extent and influence of perturbations on host formation transport properties.

4.4 Examples of sub-objectives related to pre-closure management

The following are broad examples to relate pre-closure management to monitoring sub-objectives. These consider the need to be able to assure a repository infrastructure to retain the flexibility to keep a repository open. Emphasis is on several levels of flexibility to provide operational options for future decisions:

- *Flexibility over the time period between key stages* - e.g. relating to lifetime and functionality of key structures to assure safe operations without negative impact on long term safety.
- *Design flexibility* - potential for updates in design and overall layout as the numerical uncertainty of the repository properties and evolution decrease in time.

Examples of sub-objectives for pre-closure management are:

- Condition of waste disposal packages (WDPs) are to provide information on the ability to safely retrieve waste canisters, if, in future, such a decision is taken. This leads to considerations of the canisters mechanical stability for adequate handling and safe retrieval, and for its integrity for radioprotection and prevention of any risk of dissemination;
- Structural support of disposal units and all infrastructure to enable access to those units to verify if operations are possible under safe conditions; update estimates of structural lifetime;
- Environmental conditions in disposal units – verify if operations are possible under safe conditions, for how long;

- Informing in advance if future maintenance is required to allow this to be factored into decision-making without time pressures.
- Ensure operations do not modify near field and tunnel support in a manner inconsistent with emplacing seals to the required design and performance.

Monitoring efforts are generally intended to confirm that subsurface conditions and geotechnical parameters are, or can be maintained, as anticipated and that changes to these conditions are within acceptable limits applied in the design and licensing process. Sub-objectives relating to the natural environment that might be further developed are likely related to:

- Confirmation that the hydrogeological environment remains consistent with the licensing baseline;
- Verification that favourable rock properties, taken into account in the safety case and characteristic of the undisturbed host rock are preserved, minimally altered, or understood sufficiently during construction and operation;
- The thermo-hydro-mechanical response in the near field to construction, operation and partial closure, with respect to the safety case and to support disposal process management prior to closure;
- Far field response, if any, due to construction, operation and closure.

5. Design of monitoring programme

Chapter 3.2 sets out the screening process to be applied to develop from a preliminary list of parameters to be monitored into a list of feasible parameters and techniques which could be developed and would allow a monitoring programme to be designed. Figure 3-5 illustrates the process to be applied to design a monitoring programme.

For each parameter, identified through the screening process, an estimate should be made of the projected timescales for any significant and monitorable change as a consequence of the evolution of the disposal system. The required performance of any monitoring system would then be assessed to include the required:

- sensitivity,
- accuracy,
- monitoring intervals and
- time span for operating effectively.

A quantitative analysis, based on modelling results and performance assessment can assist in selecting those processes and parameters most significantly influencing expected performances. The key challenges in developing and using monitoring systems to monitor geological disposal are:

- Avoiding damage or disturbance to multiple barriers;
- Being able to operate effectively and accurately in harsh environments (temperature, humidity, radiation and induced stress);
- Achieving the required accuracy where the basis for safety is often related to very small changes over long timescales;
- Ensuring the monitoring information from selected locations is demonstrably representative;
- Reliability and durability of the monitoring systems particularly over the long timescales envisaged;
- Access to in situ sensors is not possible without disturbing barriers
- Defining criteria/methods for identifying sensor failures.

Although it is theoretically possible to perform monitoring exhaustively on all components of the repository, this approach is neither realistic not appropriate. Risk and/or costs, added difficulty to construction and operations, possible interference between monitoring and stepwise operations, and financial burden must be balanced with added value of: safe management of the operational phase; information for sound decisions in stepwise construction; operation and closure; as well as any required or perceived needs for monitoring to confirm the scientific basis supporting the long term safety case.

5.1 Experiences from the United States

An example of a complete, stepwise development of a monitoring programme is the Yucca Mountain Project (YMP) performance confirmation plan (Hansen, 2011) in the US. The monitoring activities proposed as part of the licence application are shown in Figure 5-1.

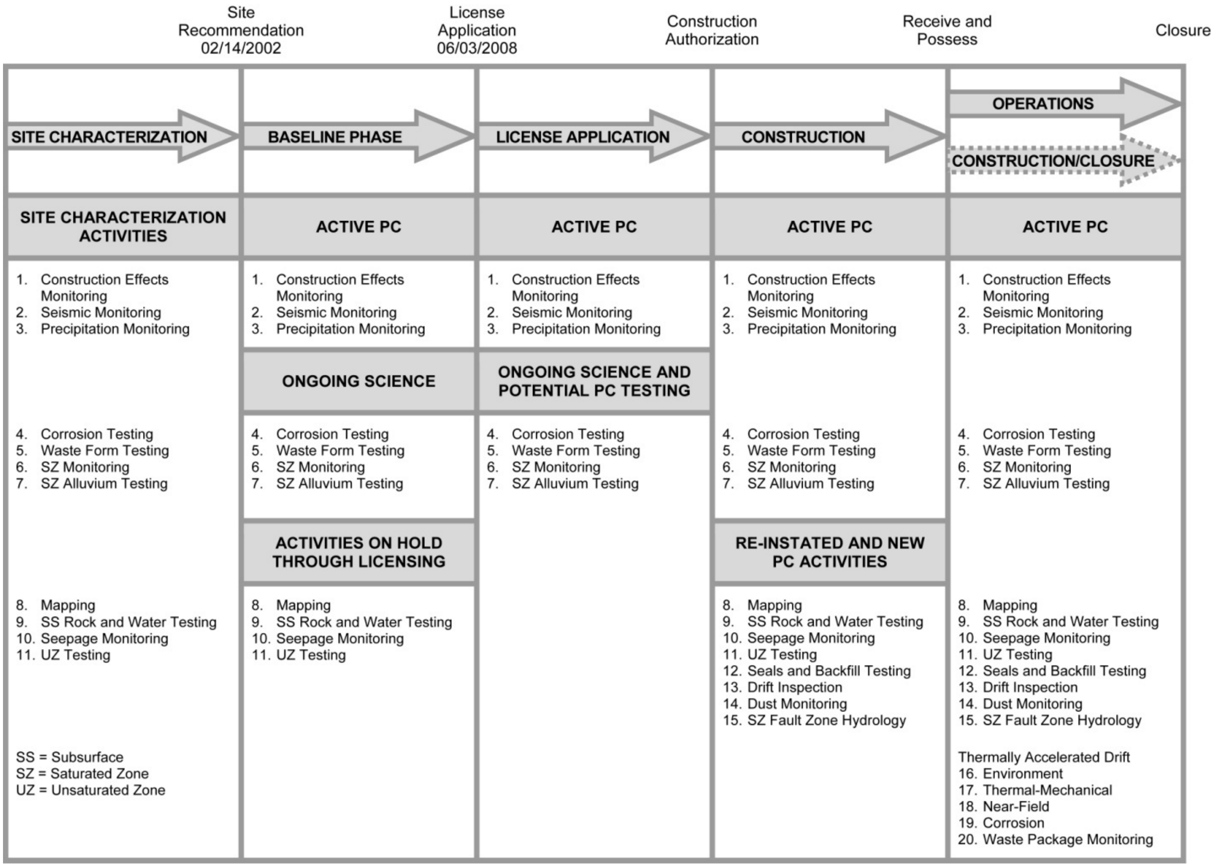

Figure 5-1: Yucca Mountain Performance Confirmation Testing and Monitoring Schedule

Eleven activities undertaken for site characterisation were to be continued as part of the performance confirmation program and are listed in the first column A. Subsurface activities would be supportable when underground space is made available during the construction period. The performance confirmation activities that require waste in the drifts can only be realised during the operational period. During the licensing process, performance confirmation activities would be guided by ongoing science programs and regulatory review of the licence application. The staged approach and schedule are consistent with the regulatory requirements.

The example from Yucca Mountain illustrates how a long-term performance monitoring program can be developed in-step with a sequential licensing process dictated by the Nuclear Regulatory Commission. The successful monitoring program developed and deployed at WIPP followed regulatory guidelines of the Environmental Protection Agency (EPA) standards. In the WIPP experience stakeholder and state authorities were involved by formal agreement between the Department of Energy (DOE) and the State of New Mexico in 1981. These agreements included, among other things, a list of experimental activities, waste limitations and monitoring requirements that were to become elements of a performance confirmation program.

Compliance monitoring was included as an assurance measure to add confidence that the repository would perform as predicted (see also Chapter 7.7). The WIPP experience included performance evaluations during the site-characterization phase, which helped focus experimental activities toward repository performance and public assurance considerations. The EPA included requirements in its disposal standards for a monitoring program that met the common definition of performance confirmation, which uses various techniques to continually challenge the certification basis. The monitoring program thereby provides assurance that the repository safely isolates waste from the biosphere as predicted.

DOE used EPA guidance to develop the following criteria to assess performance confirmation parameters:

- Address significant disposal system parameters,
- Address an important disposal system concern,
- Obtain meaningful data in a short time period,
- Not violate disposal system integrity, and
- Complement other existing environmental monitoring programs.

The DOE qualitatively and quantitatively analysed potential parameters to determine what aspects of the system could be monitored to meet the EPA guidelines. The parameters chosen relate to human activities in the surrounding area, groundwater hydrology, geotechnical performance, waste activity and overburden subsidence. The confirmation program prepares formal reports on these ten monitoring parameters annually. The program has been verified by the EPA to meet their assurance requirements and is reassessed at each five-year recertification cycle. The program has proven beneficial in identifying conditions that are outside PA expectations. Specific changes have been made to performance assessment models as a direct result of this performance confirmation monitoring program (Wagner, 2012).

WIPP confirmation monitoring consists of the following ten activities:

- *Creep Closure and Stresses* - Closure rate increase signals potential de-coupling of rock.
- *Extent of Deformation* - Coalescence of fractures at depth in rock surrounding drifts will control panel closure functionality and design, as well as discretization of performance assessment models.
- *Initiation of Brittle Deformation* - A qualitative parameter and not related to performance.
- *Displacement of Deformation Features* - Lateral displacement of boreholes allows global interpretation of rock mass behaviour.
- *Culebra Ground Water Compositions* - Provide validation of the various conceptual models, potentially significant with respect to flow, transport, and solubility and redox assumptions.
- *Change in Culebra Ground Water Flow* - Provides validation of transmissivity models and the groundwater basin model.
- *Drilling Rate* - Direct-release calculations are influenced by drilling rate changes.
- *Probability of Encountering a Castile Brine Reservoir* - EPA conducted analyses that indicate a lack of significant effects on performance from changes in this parameter.
- *Subsidence Measurements* - Predictions are of low consequence to the calculated performance of the disposal system.
- *Waste Activity* - May affect human intrusion scenarios, so a substantial change in average activity of intersected waste is potentially significant.

It is noteworthy, that long-term repository performance requirements for compliance certification comprises only ten parameters. Of these, four parameters pertain to rock mechanics phenomena, which are derived from ongoing (continuous) operational safety ground support of the WIPP disposal facility. These geotechnical data are gathered though out the year as part of regular ground-support engineering and reported annually.

For example a water-well monitoring program encompasses testing hydrostatic head and water chemistry as shown in Figure 5-2. Monitoring wells are tested and sampled on a periodic basis in accordance with Test Plans developed by the Principal Investigator. Interpretations of the flow fields such as shown in Figure 5-3 are compiled in annual reports that include all ten compliance monitoring parameters. Other monitoring parameters include industry drilling rate in the WIPP area and radioactivity of the waste being placed in the underground. These parameters provide input to repository performance calculations, but are essentially logistical in nature.

Figure 5-2: Monitoring well at the WIPP site

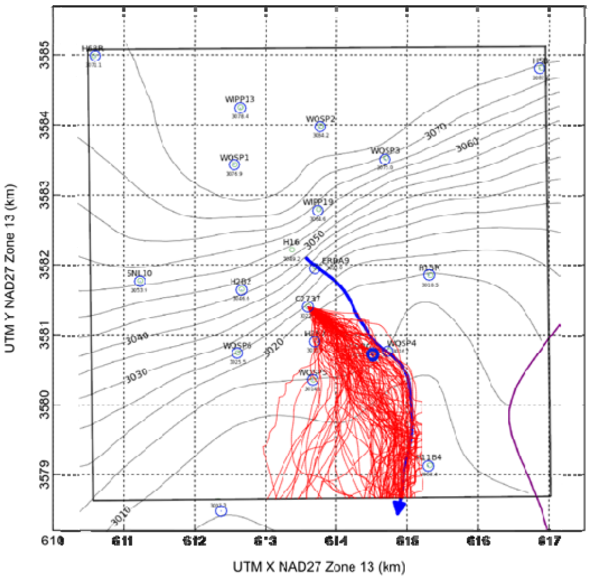

Figure 5-3: Flow field from ground water conceptual model for WIPP

The experiences drawn from the work descripted above have assisted in developing this framework report.

5.2 Realistic time period for monitoring

The monitoring techniques proposed should have the capacity to provide meaningful information from monitoring. In many situations the change to some barriers is expected to be too slow to give useful information on system evolution during realistic timeframes for monitoring. If significant changes are not expected within typical monitoring timeframes, monitoring may still be carried out to check whether any unexpected system behaviour or events occurs, i.e. for checking that the disposal system *has not failed* and the situation is consistent with expectations. This expectation should be clearly communicated to stakeholders. Therefore, in light of the expected evolution and monitoring system performance, careful evaluation should be made of the limitations of a chosen monitoring set-up to provide significant information.

It is also important that this understanding of the expected evolution is recognised in considering the amount of monitoring activities which should be conducted, respecting the fact that significant cost and resource could be employed in monitoring parameters with limited added value. The most important consideration is whether the parameter can be related to a relevant aspect of the safety functions, rather than if some evolution can be monitored within the envisaged timeframes, e.g. it makes sense to monitor for brine intrusion in salt even if it is not expected. This fact needs to be confronted within the screening process while taking due account of a specific national context.

The following barriers are briefly revisited to illustrate this point:

- Waste disposal package corrosion rates could be too slow to monitor *in situ*, but providing evidence of total containment of the waste, e.g. by monitoring the absence of water, might attribute to confidence.
- Seal resaturation could be too slow to monitor *in situ* but if resaturation cannot be monitored, consideration should be given to whether other elements could provide the basis for evaluation of long term performance.
- The hydro-mechanical equilibrium in the near-field could be too slow to monitor.
- Repository layout: Overall evolutions could be too slow to monitor at larger scales.
- Far-field: Hydro-thermo-mechanical evolutions at a large scale could be too slow for surface subsidence/heave to be detected.

It is important, however, that monitoring can be employed to check that the performance of key components of the repository (i.e. barriers) meet expectations. This approach can be used to support the basis for safety and provide stakeholders with information on actual performance against expected performance albeit over short timescales in the overall evolution. This approach also applies to monitoring to support pre-closure management where the flexibility of reversibility and retrievability is required.

5.3 Planning for implementation

For each of the processes and parameters that were selected using the process described in the *MoDeRn Monitoring Workflow*, specific plans for the implementation of suitable monitoring methods need to be developed, while keeping track of their expected contribution to repository performance. This requires more detailed considerations of available monitoring solutions, the achievable accuracy of a certain set-up, the duration of data acquisition and the required reliability, i.e. the design a suitable monitoring system.

- In the first instance, this requires an understanding of available monitoring technology and the associated technical limitations pertaining e.g. to durability, reliability, or resistance to environmental conditions.
- Secondly, it requires an understanding of possible implementation strategies, i.e. the possible approaches to instrumenting the repository in order to provide information which adequately contributes to meeting a specific monitoring objective.
- Finally, it requires an understanding of the specific technical performance requirements associated with a specific monitoring activity.

Considering those three jointly (Figure 5-4) will allow the development of a basic design of monitoring systems to meet a specific duty. To ensure that monitoring system designs can be accommodated within the overall design of the repository, these need to be developed in the early stages of design and could influence the overall design configuration, with the clear requirement that the monitoring system does not compromise the effectiveness of the disposal system design.

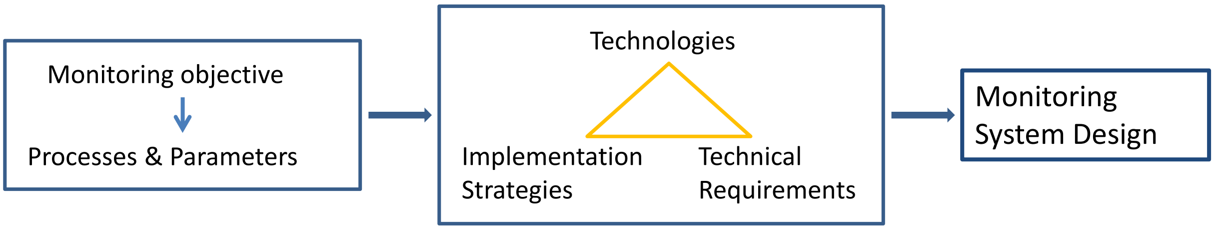

Figure 5-4: Preparing for implementation – From objectives to design

An implementation strategy should be developed in order to enhance the ability of the implementer to monitor and provide information in response to the monitoring objectives. This strategy should include evaluation of the ability to:

- Provide representative locations for monitoring without the risk of monitoring having a negative impact on long term safety;
- Provide alternatives for monitoring where this would otherwise not be technically feasible *in situ* in the main disposal facility;
- Provide alternatives to enable monitoring for as long as possible, without being constrained by the disposal process, especially due to closure of the disposal cells and disposal areas;
- Provide options for monitoring to minimise or suppress interference with operation, construction and waste emplacement activities.

In addition to these considerations, the design for monitoring should take account of any site specific factors particularly related to the geology, planned layout and emplacement strategy to ensure that number of monitoring installations and their arrangement can provide results which are demonstrably representative. The design will also need to address how monitoring will be achieved as areas of the repository are progressively closed. The process for developing an implementation plan for monitoring will necessarily require several iterations to ensure that the objectives will be achieved both effectively and efficiently.

It is necessary to develop a clear understanding of how monitoring is achieved for the entire repository, while respecting the technical requirements for monitoring: durability, reliability, resistance to environmental conditions, and non-interference with expected barrier performances. It is recognised that not every component can be monitored.

Monitoring can only be conducted in select locations and on specific components of the repository. Even when selected monitored components and/or monitored near field evolutions are distributed throughout the repository layout, it is important to be able to demonstrate that the monitoring results are representative for the repository. This will typically be based on consideration of homogeneity of the natural environment and of the controlled homogeneity of manufacture and construction of engineered components, such that these components can be assured to perform within the required standard (e.g. saturated density of bentonite buffer). The impact any heterogeneities may have on repository functions should be accounted for by addressing these within the design.

Some natural evolutions, however, occur over typical timescales which are substantially higher than the period of circa one century envisaged for most repositories. By the time any evolution is expected to occur, access would not be available for direct monitoring. This consideration could be addressed in prior experiments, by providing for artificially accelerated transients (e.g. forced resaturation). Assuming that *in situ* repository evolutions will not be subjected to any artificial acceleration, monitoring of very slow natural evolutions would at best provide information limited to detecting initial evolutions, which might in certain cases provide confirmation that adequate process models were selected, or confirm the absence of significant evolution. This is the case e.g. for far field responses in host rocks having very small transmissivity. It is also the case for near field and engineered barrier evolution to their long-term, post-closure configuration (e.g. very slow seal resaturation and swelling).

5.4 Considerations for monitoring system designs

This section provides a few specific examples of how some of the challenges may be addressed in considering monitoring system designs. Its content is based on and refers to the MoDeRn Case Studies Report (MoDeRn, 2013g) which provides case studies for monitoring system designs for three generic rock types.

Waste disposal packages (WDP)

The design, relative stability and environmental conditions of the WDPs pose significant challenges to monitoring. No clear picture has yet emerged as to whether this is best done *in situ* on actual packages, whether representative long term tests (e.g. on metal corrosion samples) can provide the required information, or whether prior quality assurance and monitoring in a transfer store can be considered to provide sufficient information to confirm their expected performances.

Disposal unit, including near-field

The design of a disposal unit, i.e. cavern, drift, long or short borehole disposal, associated with a given buffer, plug and/or structural component, may create specific technical challenges for monitoring. Monitoring designs, in particular pertaining to disposal unit monitoring, need to be adapted to construction procedures, to environmental conditions and levels of accessibility of these units. Detailed technical solutions for instrumentation are still under development and will generally require development specific to the disposal design. In all cases monitoring system designs must not impact the safety functions of the disposal system design. Where longer-term monitoring is required, the use of remote wireless transmission or other remote techniques may be appropriate, particularly as disposal units are closed and sealed.

Seals, including near-field

Detailed monitoring design need to take into account the timescales at which natural seal resaturation may operate. For example, for crystalline rock, the interception by seals of water bearing features may lead to natural resaturation offering the potential for monitoring, whereas for an argillaceous host rock this is likely to be limited to the contact zone between seal material and the rock.

Design of monitoring systems

The Technology Summary Report (MoDeRn 2013h) and underpinning reports (MoDeRn 2013, a to f) provide useful reference to the current state-of-the-art for monitoring technology. The design and application of monitoring systems has advanced over recent years and the RD&D conducted under MoDeRn provides reference to state-of-the-art at 2013. It is expected as geological disposal programmes advance that there will be further developments in these techniques, particularly in the use of non-intrusive techniques.

5.5 Example for designing a monitoring programme

For designing a monitoring programme the relation between the protection goals and the components of the safety case or the safety assessment is assumed as a design basis. In the MoDeRn Case Studies (MoDeRn, 2013g) monitoring programme designs are illustrated for three different disposal concepts and host rocks. As an example the monitoring option for considering a specific safety function in one of the cases is illustrated in the following.

The ultimate aim of the German safety assessment concept in a salt host rock is to meet the protection goals stipulated in the regulations. These can be divided into conventional (non-radiological) and radiological protection goals. The protection goals are:

- Protection of the surface against repository induced changes (conventional protection goal)
- Protection of groundwater against contaminants (conventional protection goal)
- Protection of the biosphere against radionuclides (radiological protection goal)
- Criticality safety (radiological protection goal)

In the case of an undisturbed repository evolution, the protection of the groundwater is realized by the safe confinement of the radioactive waste. The safe confinement of the waste must be demonstrated for several scenarios. Next to the reference scenario, several alternative scenarios have to be assessed. For example, in case of an abandonment scenario, intrusion of brine has to be considered. In addition to the "safe confinement", the "negligibility of subsidence and uplift" and the "compliance with the container design" have to be assessed, too.

Figure 5-5 shows the protection goals and their relation with the safety assessment components. The core element "safe confinement" comprises the components "integrity of the geologic barrier", "sufficient compaction of the backfill material", and "integrity of the geotechnical barrier". The latter comprises the individual barriers shaft seal, drift seal, borehole seal, and containers. The safety functions allocated to the individual barriers are listed as well. While most of the components support the isolation of the waste, the component "sufficient compaction of the backfill material" is linked to three different safety functions according to the physical processes behind it. In addition to a decrease of the hydraulic permeability, the support of the rock mass (mechanical) as well as the dissipation of the container heat (thermal) has to be provided.

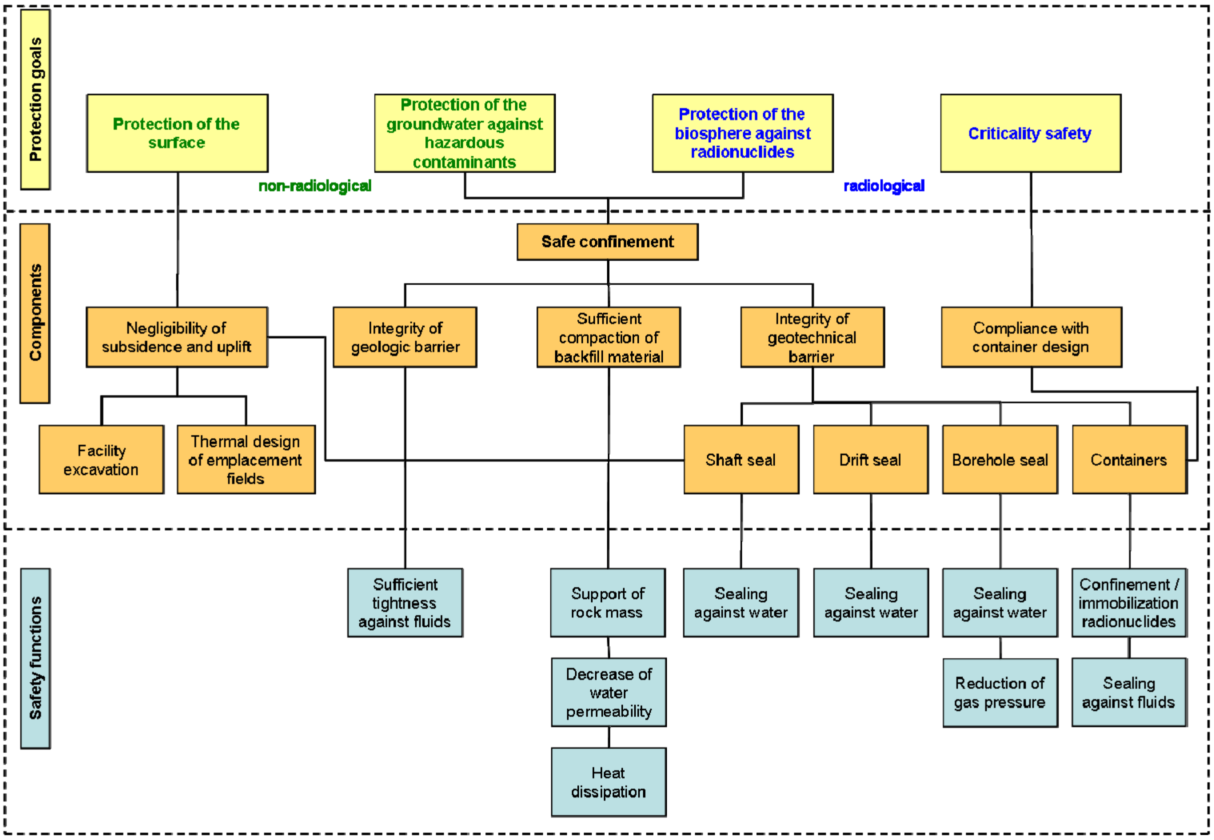

Figure 5-5: Connection between protection goals, safety assessment components, and safety functions

The safety functions of the assessment components are connected with processes taking place in a repository that have to be taken into account in the safety assessment.

Design for the safety component “Sufficient compaction of backfill material”

The primary function of the crushed salt backfill is to reduce the void volume in the drifts of the repository structure. Furthermore, it is to mechanically stabilise the geologic barrier (support of the rock mass) and to thus contribute to maintaining its integrity. In the emplacement drifts and boreholes, the backfill material also serves to dissipate the heat from the disposal containers into the surrounding rock. All these functions depend on the degree of compaction and on the compaction-dependent porosity of the backfill material; the latter also determines the decrease in fluid permeability.

As the reference periods may be as long as 1 million years, compliance with the safety functions is mainly demonstrated by means of model calculations. Models that are robust and cover the significant effects are a prerequisite for a high degree of accuracy in the predictions. Based on recent laboratory investigations, calculations of the compaction of crushed salt showed that after a period of 1000 years the compacted crushed salt has similar hydraulic properties as the undisturbed rock salt.

The process (FEP) determining compaction in connection with the safety functions mentioned before is the

- Drift convergence.

This process thus determines the development of the porosity, permeability, and thermal conductivity of the backfill material. Porosity and permeability will decrease during compaction, and the thermal conductivity will increase due to smaller void volumes. Additional factors influencing compaction are (i) the humidity development in the backfill changing its capability to be compacted and (ii) the temperature development in the backfill material and surrounding rock salt. Higher temperature of the backfill allows faster compaction. Higher temperature in the rock increases the creep velocity of the rock salt and thus the convergence. Parameters characterising the compaction process are the:

- *porosity* (absolute and effective) of the backfill
- *permeability* of the backfill (linked to the effective porosity)
- thermal conductivity of the backfill
- *temperature* of the backfill and surrounding rock salt
- *total pressure* in the backfill
- *displacements* of the rock salt in the vicinity of the cavities
- *humidity* of the backfill
- *pore pressure* in the backfill

The first two parameters are important for evaluating the increasing tightness of the backfill. However, they cannot be measured continuously in-situ. The thermal conductivity is hard to measure/monitor in-situ, especially within a moving granular material. In addition, the measurements must be very precise to evaluate the porosity via an empirical relationship between porosity and thermal conductivity. Thus, only the last five parameters remain suitable and are possible to be monitored. The most effective measurements characterizing the compaction process are the pressure measurements.

In order to be able to detect brine flow through the backfill material, the last two parameters should be measured at different locations in the backfill and, most suitable, on both sides of a drift sealing. This would allow the evaluation of the backfill compaction as well as of the barrier tightness at the same time. A change in moisture and/or in pore pressure would indicate fluid migration. The measurement points for the mechanical parameters stress and deformation could each be restricted to only one side of the sealing construction. A suitable distribution of the sealing constructions across the emplacement field (Figure 5-6) could yield representative information on the compaction behaviour of the crushed salt across the whole field. Furthermore, transmission of the measuring data will only be allowed by means of wireless transmission as the routing of cable along the backfill material or even through the sealing construction possibly create an undesired pathway for fluids. With regard to timing, the sensors should be installed at the same time as the sealing construction is built, and monitoring should last until it is decided they are not necessary any more. The decision should be a joined decision of implementer, regulator, and stakeholders involved.

Monitoring design option related to the other safety functions as well as details on proposed equipment are described in the MoDeRn (2013g).

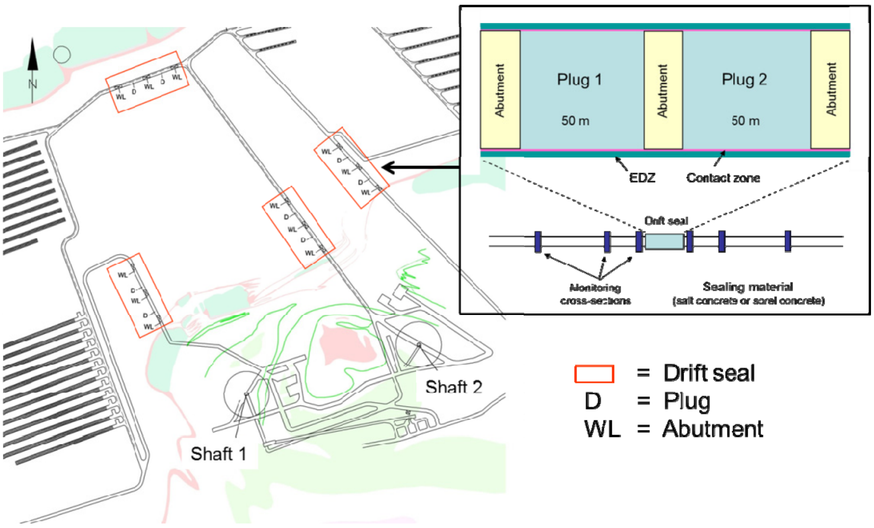

Figure 5-6: Potential position of sealing constructions (indicated in red) – Note: Their exact positioning will have to be determined in accordance with the closure concept (after Bollingerfehr et al., 2012).

5.6 Alternative approaches for monitoring design

A number of options could be considered as an alternative to direct monitoring of a disposal facility to address some of the challenges identified in this section. These include monitoring performed in a test facility or a pilot facility. Such facilities could be incorporated into the overall repository layout either:

- separate from the main repository, or
- distributed throughout the main repository.

Each combination of options would then be evaluated to identify associated advantages and disadvantages with respect to achieving useful monitoring results. Such evaluation considers the potential for:

- providing representative results;
- providing adequate information on processes that evolve over long timescales;

- circumventing technical challenges of direct *in situ* monitoring; and
- not interfering with expected performance in the repository.

Within the MoDeRn project, a number of potential monitoring techniques have been identified, developed for repository applications and evaluated in URLs (MoDeRn, 2013 b to f). These are either based on placing sensors *in situ* for remote sensing and non-intrusive sensing or measuring evolutions by sampling at discrete intervals/points.

One of the significant benefits provided by having underground research laboratories (URL's) available is that these can be used to conduct testing and development of monitoring systems in advance of a disposal programme. These URL's and pilot facilities also provide opportunities to commence longer-term evaluation of monitoring systems and of monitoring evolutions of mock-up disposal designs related to the design and safety case.

6. Implementation and governance

Chapter 3.3 outlined the processes to be considered in addressing implementation and governance. This chapter discusses a few general considerations on how the results provided by a monitoring programme might be used within the overall governance of the disposal process, from construction to closure. This provides a basis for discussion, particularly with stakeholders, on how the information from monitoring might be analysed and used, in particular to support decision-making. It also recognises the limitations of monitoring, which need to be acknowledged, and provides a more realistic view of how much monitoring can contribute to decision making, after a safety case has been presented and accepted for a licence.

The role of monitoring in informing decisions for overall process governance is discussed. The need to have a plan in place to respond to monitoring results is also discussed. The need for assurance of reliable monitoring results is stressed. Finally, ways of addressing and responding to situations where monitoring results deviate from prior predictions are discussed. Figure 3-7 illustrates this third stage (Implementation and Governance) from the *MoDeRn Monitoring Workflow*.

6.1 Failure detection in monitoring systems

A potentially relevant role in support of decision making and confidence building is attributed to monitoring. The results from monitoring activities can be used to check whether the models and assumptions used to demonstrate safety concur with the predicted behaviour of the monitored repository components. It is important to recognise that monitoring outcomes may deviate - for whatever reason - from predicted ones. Such deviation may, for example, result from a technical failure of one of the many sensors placed and does not necessarily mean that the long-term safety of a repository is impaired. However, if monitoring results are used to support decision making or are part of licence application conditions, it is important to consider how deviating monitoring outcomes should be analysed, and, in order to be able to design a robust implementation process for geological waste disposal, this needs to be done *a priori*.

The ability to identify failures is an important feature and the incorporation of such considerations into the selection of monitoring techniques would be a relevant contribution to the robustness of the implementation process. The installation of additional monitoring equipment, that enables potential failure of other monitoring equipment to be identified, will ensure improved reliability of monitoring information and should be considered where such monitoring is used as a basis for evaluating safety.

Methods available to detect errors and failures vary with respect to the degree of reliability that can be achieved. Failure detection strategies have been identified focussing on failure detection that includes failures of all parts of the monitoring chain including signal/data transmission (MoDeRn 2013g). Failure of sensors can be detected by means of:

- Redundancy,
- Known relations (diversity),
- Electrical stimulation,
- Reliability indicators,

- Local sensor validation (LSV),
- Correlation.

For example, the so-called "local sensor validation" (LSV) of a sensor system, detects errors by analysing characteristic signal components of the unfiltered signal of the system. This method is based on the assumption that errors or failures may occur at various locations in the system and that it would be highly efficient to monitor all possible sources of errors. The exact sources of the errors can only be determined if all sensor components and their interactions are known in detail. Nevertheless, certain signal characteristics in the unfiltered output signal of a sensor system may be used to trace a failure.

The relationship of failure detection to failure modes and measurement principles gives some idea of which failures modes lead to problems (because they may stay undetected) and which modes are less "challenging" (e.g. a simple sensor breakdown is easily identified for example by redundancy). It also shows which measures/techniques are effective in addressing failure modes. It will help to select principal techniques that are favourable with respect to failure detection, and it may help to identify additional monitoring techniques or measures that can be applied in order to be able to address as many failure modes as possible (MoDeRn, 2013g, Chapter 7).

When monitoring data is planned to be used as part of decision making, robust methods and procedures that qualify all aspects of the performance of the applied monitoring systems, are essential. One means of increasing the reliability of sensor readouts is the use of "fail-safe" sensors. Since sensors will be implemented for repository monitoring purposes, especially for long-term monitoring of disposal cells after their closure, the focus could be put on the use of fail-safe sensors. These systems make use of error detection methods described in the previous section and apply these methods in a predefined, automated manner.

It is recognised that this area of monitoring merits further development to ensure that implementers and stakeholders can have confidence in monitoring systems.

6.2 Basic guidelines on using monitoring results for evaluation

Making good use of monitoring results requires a good understanding of how data relate to the safety assessment. If prior steps in identifying objectives - deriving them from safety functions and linking them to the basis for evaluating expected performances – were followed as recommended by this *Reference Framework*, this should already be understood and documented.

At the outset a plan needs to be in place for how to respond to the type of information – confirmatory or diverging – that monitoring provides. Both confirmation and challenge of the licence basis will enhance the technical baseline.

Monitoring results will be compared to prior understanding and expectations as provided for the licence basis. Direct confirmation or discrepancies arising from monitoring results provide important information; however, the real basis for decision making is not the individual monitoring result, but its implications, if any, on the safety assessment. If the monitored parameter is established as a direct *performance indicator*, i.e. as providing a direct measure with which to appreciate a positive or negative finding with respect to the safety assessment, then results that exceed a trigger value require further evaluation and decision on behalf of disposal process management (response plan). An example for a potential decision-making process to address monitoring outcomes is illustrated in Figure 3-8 and discussed in Chapter 3.3.4.

Guidelines if monitoring results "confirm" the prior basis

The response plan would be expected to provide for two actions: the first would inform the decision makers that monitoring results confirm the basis for evaluating performances, thus enhancing confidence in the basis for safety; and the second would be improving the actual evaluation of performances by incorporating any new data to reduce model and parameter uncertainties.

Monitoring would not merely serve to confirm expected behaviour, but also to reduce uncertainties by measuring parameters *in situ* (which might previously have been measured in laboratories or test facilities remote from the main disposal facility). In particular with regard to the latter, *in situ* monitoring over long durations may contribute to enhancing the characterisation of local and/or of slow processes (e.g. transient groundwater pressure). These may allow predictions to be updated and a re-evaluation of the performance of the repository system, and thus allow an update of the "performance measures" against which acceptable system conditions and evolutions are compared.

If monitoring results provide sufficient evidence to allow reduction of previously conservative assumptions, this might be used as a basis for considering the relaxation of overly conservative design requirements, where these could be demonstrated to be unnecessary. This could trigger decisions to follow more optimised approaches for the implementation of the disposal process.

Guidelines if monitoring results do "not confirm" the prior basis

A prepared response plan should be available to apply in the event monitoring results indicate difference from prior expectations.

In case, a failure of the monitoring system cannot be demonstrated, potential effects on the (long-term) safety should be assessed. By analysing the site specific FEP and the corresponding reference and altered repository evolution scenarios the monitoring results could be used to analyse if an altered scenario has to be assumed. This would help to select suitable measures, if necessary (see for example Chapter 8 of the Case Study Report in which, an example of the detection of an alternative scenario is illustrated; MoDeRn 2013g).

Preparing a response plan calls for an expected range of monitoring results to be defined, such that, results outside the bounds of these expectations would trigger a need for action. Those bounds would be established in relation to performance measures.

Trigger values could be set for each parameter being monitored to provide warning that results were exceeding the normal range of expectations. A trigger value is a value recorded through monitoring that would invoke risk management activities to be undertaken. Trigger values will be a combination of limiting values, ranges, and observations that are directly comparable to the data produced and reported by the various monitoring programs. Trigger values should be set to provide a warning that expected observations are not consistent with the technical baseline and that further risk management is required.

Given that monitoring refers to the basis for evaluating long term safety, the consequences of data deviating from prior expectations require further analysis, to assess the implications for the safety assessment.

As a first step, any failure of monitoring components should be excluded. Although (partially automated) methods for failure detection are applied, there is still a possibility that the reason for an unexpected reading lies in a failure not covered by predefined methods for failure detection. This can be done by consistency check, performed by trained experts. Additional evidence for a failure might be established by additional measurement, lab simulations, or analysis of timelines.

Sometimes the evolution of a parameter over time (e.g. a stress evolution within a barrier) could be less than expected. This may mean that certain expected values, which are important to the safety case, will not be reached. An example of this would be a sealing element where if the pore pressure in a sealing element in the lower part of a shaft sealing system increases earlier than expected that could mean the upper sealing elements have failed. This would be an important indication that an alternative scenario is to be assumed instead of the reference scenario (see Chapter 8 of Case Study Report; MoDeRn 2013g).

6.3 Monitoring case studies related to altered scenarios

In principle, it is assumed that, after closure, the repository will evolve as predicted in a ‘reference scenario’ which describes the most likely future evolution of the disposal. In order to assess the ability for monitoring to detect the presence of altered scenarios, i.e. future evolutions that are less likely and significantly different to the reference scenario, MoDeRn (MoDeRn, 2013g) provides *Case Studies* including an example of a qualitative and quantitative evaluation of the ability of a designed monitoring system, as foreseen to be installed in a salt-based repository to detect potential alternative scenarios of the repository’s evolution. The evaluation treats, in a qualitative manner, the impacts of alternative scenarios on the readouts of monitoring equipment in a generic repository design in rock salt. For one of the alternative scenarios, a quantitative assessment has been performed to evaluate the impact of a reduced performance of the shaft sealing system on potential monitoring readouts of a safety relevant parameter.

The alternative scenarios have been derived from the German Safety Case (BGR et al., 2012). By combining the readouts obtained from the different monitoring devices installed at different locations in the repository, indications could be derived on whether the evolution of the repository develops as assumed in the reference case, i.e. in the line of the “normal evolution scenario”, or an alternative route is followed, i.e. one of the “alternative evolution scenarios”.

For one of the scenarios, “early failure or reduced performance of shaft sealing”, a quantitative assessment has been made to determine whether it would be possible to detect this alternative scenario on the basis of monitoring results. Calculations assuming reduced performances of the various seal elements of the complex shaft sealing system clearly show that significant changes in the pore pressure can be detected within the timeframe of the assumed monitoring period, viz. 100 years after emplacement of the shaft seals. The quantitative results for this alternate scenario were in line with the qualitative expectations.

When designing a monitoring system, a detailed assessment (using performance assessment calculation) should be made to understand to what extent, and when, changes can be expected for the different parameters compared to the reference scenario, in order to link the actual observations to a specific scenario. In particular, it is necessary to determine at which quantitative sensor readings an altered scenario has taken place and to evaluate if and under which conditions this alternative scenario may lead to an impairment of the repository safety. Therefore when analysis of the specific parameters have been taken into account and are considered representative, they may in principle provide indications of the occurrence of alternative scenarios. Such an analysis should include the performance of the monitoring system (accuracy, precision, long-term drift), the sensor placement and expected uncertainties in system parameter evolutions (MoDeRn 2013g).

6.4 Monitoring information and governance

The role of monitoring in decision-making is discussed in Chapter 3.3. The overall governance of the disposal process is not addressed here but the focus is on the role of monitoring in support of the overall governance process. Monitoring will provide information to support all parties involved in governance in the various decision-making steps discussed in Chapter 2.5.

Most national programmes provide for a stepwise process where decisions will be taken before advancing to the next stage in the process. To this end, the processes developed for monitoring need to take account of when and how monitoring information will be used. This will require the implementer to provide, in agreement with regulators and in consultation with other stakeholders, a clearly defined monitoring plan which should include:

- Detail of what is being monitored and what monitoring should achieve;
- How the monitoring information will be presented and how raw data can be accessed;
- Pre-defined trigger levels and an action plan should trigger levels be reached;
- A routine cycle for reporting and agreed arrangements for reporting unexpected information;
- An agreed cycle for reviewing the monitoring plan;
- A process for communicating any changes to the monitoring plan.

Monitoring plans should be reviewed on a regular basis to take account of learning from the active monitoring programme and addressing changes to the monitoring design, utilising where appropriate advances in monitoring technology to update approach on new monitoring installations, and judging the effectiveness of the monitoring programme.

7. Discussion

This chapter provides discussion of some important issues and challenges associated with the context, the process and the role of monitoring which arose during the development of the *MoDeRn Monitoring Workflow* from discussions within the project team, and during engagement with expert and public stakeholders during the MoDeRn project. These have been compiled as a number of topics.

7.1 National contexts

The relative importance of the national context in developing a monitoring programme is recognised but it is not considered feasible to develop a single and definitive set of technical monitoring objectives and approaches for implementing these. The factors affecting national context were broadly structured into societal boundary conditions and physical boundary conditions. The former was further broken down into the legal and regulatory framework relevant to monitoring, expert stakeholders (e.g. safety authorities) expectations and public stakeholders' (e.g. local residents) expectations. The latter was further broken down into the waste inventory, the natural environment and the engineered system. The MoDeRn project conducted a review of national contexts for monitoring (MoDeRn, 2011b).

The project concluded that a detailed monitoring programme is not likely to be directly transferrable from one context to the other, and that a "specific reference programme" does not exist. The *MoDeRn Monitoring Workflow* does, however, provide a framework to follow as guidance for national programmes that integrates national contexts and three *Case Studies* (MoDeRn, 2013g) which provide examples which can assist in developing a specific monitoring programme. The understanding gained from developing a monitoring programme for each case study, and from comparing them, provided lessons that enabled the project to propose a generally applicable approach, independent of national context.

7.2 Legal and regulatory requirements

When looking at the legal and regulatory requirements described in the national context report (MoDeRn, 2011b), the level of detail in which monitoring requirements and approaches are specified varies considerably. Even though some of these national frameworks provide a basis for what needs to be included in the monitoring programme, this tends to be described in relatively general terms, without much (if any) specification of how the act of monitoring is defined. Reference may be made to a stepwise implementation process, but few, if any, details are provided in existing national regulations on how decisions at each intermediate step should be taken, and what the specific role and relative importance of monitoring should be. Some regulations or legal frameworks do, however, provide clear guidelines that the decision to close the repository would require confirmation that conditions are consistent with the licence basis (e.g. US NRC, 2012).

Some regulations may include specific requirements for implementation strategies, e.g. the Swiss regulator calls for monitoring to be conducted in a pilot facility (ENSI, 2009). The French guidelines also address monitoring to inform reversible disposal management (ASN 2008), which implies: monitoring the condition and integrity of excavations and structures to avoid operational considerations imposing constraints on step-wise closure decisions; as well as monitoring waste disposal package and disposal cell conditions to verify conditions for a potential waste retrieval.

Several regulations or guidelines make explicit mention of post-closure monitoring, e.g. the new German safety requirements (BMU 2010) call for a post-closure monitoring programme (for a certain period of time) which, in addition to surface-based environmental monitoring, is able to provide information about the thermo-hydro-mechanical response of the host rock due to the heat generating waste. Other regulations do not specify whether post-closure monitoring should be a form of environmental surface monitoring, or a form of below surface repository monitoring; whether it is about monitoring the construction; or the possible migration of radionuclides from the facility; or whether access control ("no excavations") for nuclear safeguards and large scale evolutions such as indicated by surface subsidence would respond to potential monitoring expectations.

It appears that safety authorities and other expert stakeholders such as national review boards are gradually placing greater emphasis on monitoring. At this stage, it does not appear, however, that these expectations have been expressed in any detail, recognising the difficulty to be specific until detailed disposal designs have been prepared. A number of general considerations can be identified: such as the longevity of monitoring programmes and thus the need to address related technological difficulties; and the preservation of safety functions in a monitored repository. There seems to be agreement amongst expert stakeholders that *in situ* monitoring offers some added value and possible reassurance for long term safety, which is a prerequisite to obtaining an authorisation to close the repository.

7.3 Safety case and monitoring

The safety case presented with the licence application, and the processes of evaluation and decision-making following that application, are to provide adequate assurance that long-term goals of protecting man and the environment will be met. It is implicit that the involved stakeholders should have confidence in the lines of evidence provided by the safety case, and in the associated decision-making processes, in order to proceed with the disposal process.

Because it is not possible to directly confirm long-term safety through direct monitoring of the associated performances (e.g., transport properties in a distant future, radionuclide concentrations, dose rates...), the objectives of monitoring should be linked to check/support/confirm/re-evaluate the basis for the safety case. The term 'basis' refers to the full set of arguments that were used to develop models that underpin the safety case.

Associated monitoring activities should be developed consistent with the presentation of a safety case and the underlying safety assessment. This presentation would include:

- description of the system design and safety functions;
- illustration of the performance of engineered and natural safety barriers;
- presentation of the evidence that supports the arguments and analyses; and
- discussion on the significance of any uncertainty or open questions.

The safety case also presents the evidence that all relevant regulatory safety criteria can be met. Associated monitoring is to test the adequacy of assumptions, data, and analyses that support the findings used to permit construction of the repository and direct subsequent waste emplacement operations. This provides information, where practicable, to check/confirm that subsurface conditions encountered and changes in those conditions during construction, waste emplacement, closure operations and also post closure are within expected and acceptable bounds. It also provides information to assess whether the natural and engineered systems and components, which were designed or assumed to operate as barriers after closure of the repository, are functioning as intended.

By a careful assessment of the FEPs that characterize all processes related to the possible future repository evolutions, and the corresponding evaluation of the repository evolution scenarios, those processes adversely affecting a particular safety function can be identified. Those processes are then considered worth monitoring to check/confirm that the safety functions are not jeopardized.

The long-term safety of a geological repository must be assured through passive means thus it should not need to rely on monitoring or any other activity (IAEA, 2001). However, monitoring to check the performance against expectations will provide the most important information to support pre-closure decisions. If those monitoring results were not to provide a confirmation of the basis for safety, then a re-evaluation of the disposal process would be required.

7.4 Site characterisation and monitoring

Monitoring should be conducted across all phases, from site characterisation through to, and after closure.

Site characterisation is conducted to collect data to enable the properties of the geological environment of a radioactive waste facility to be determined and to establish baseline environmental conditions prior to constructing a disposal facility. A site characterisation programme will include repeated measurement of some parameters to monitor change; this is effectively monitoring. The data can also be used as part of monitoring programmes, and the integration of site investigation activities and monitoring should be part of an overall monitoring strategy. The important distinction between site characterisation and monitoring is that: site characterisation is the collection and measurement of spatial data on features and properties of a site; whereas monitoring is the repeated measurement of a parameter to determine change over time.

Some monitoring activities that were started during initial site characterisation, e.g. related to the local hydrogeology, and continued as part of baseline monitoring of the host formation and throughout the construction/operation/closure, may also be pursued after repository closure as part of a post-closure monitoring plan. Monitoring plans should be structured to identify with key phases in the disposal process and monitoring activities could be related to major decision points, such as the selection of a particular site, the beginning of construction, waste emplacement, and closure. It should, however, also be acknowledged that some monitoring activities, in particular those related to the host formation, may remain unchanged through these decision points.

7.5 Monitoring of different host rocks and wastes types

The safety case is built on the robust combination of safety functions, realised through the performances of natural and man-made barriers, to ensure that the long term protection goals for man and the environment are met. Differences in waste types, designs and host formations may lead to different safety functions for repository components. Where this reference framework is used as a basis for developing a monitoring programme, the user should first consider the specific national context including the host rock and the specific disposal design to enable these specific factors to be taken into account from the outset. The physical environment of the selected host formation, the waste type and form, and the engineered barriers will all influence the priorities for monitoring. It is for this reason that monitoring programmes should be developed to inform on changes which are demonstrably relevant to the specific safety case.

For example, a copper, steel or concrete overpack contributes differently to the overall safety case and is influenced by different degradation processes. Any associated sub-objectives need to be developed specifically for each case. The design of the monitoring system needs to be adapted to the relevant processes and parameters, as well as to the design of the component to be monitored. The use of monitoring results and the relative weight they may carry when informing decision making will depend on the contribution this component provides to the performance of a safety function and/or the performance of the repository system overall.

Where repository development makes use of the favourable properties offered by the host formation, it is important to establish which of these particular properties are made use of in a given safety concept, prior to deciding which ones might be subject to monitoring. These are influenced by the specific properties of the waste, and the combination of overall repository layout, engineered barrier design and host formation properties, to contribute to expected repository performances.

In crystalline rock, the long-term integrity of the waste containers and the behaviour of the bentonite buffer are most significant, therefore monitoring of the near-field groundwater flow and groundwater chemistry are emphasised. This type of formation is characterised by blocks of tight rock suitable for waste deposition surrounded by fractures or fracture zones. Monitoring may thus also contribute to the knowledge of host rock heterogeneities. In sedimentary or saline rock, the concept relies more on the relative homogeneity, sorption capability, and extremely low hydraulic conductivity of the host formation. In the latter case, therefore, the average hydraulic properties on larger scale, and of the backfilled and sealed access tunnels, ramps, and shafts, are most important. This may be associated with a monitoring activity establishing the extent to which heterogeneities of the host formation properties should be taken into account, and with a monitoring activity confirming the self-healing properties of clay, or salt, that was fractured during construction and operation.

7.6 Existing monitoring programmes

In a mature geological disposal programme, the most significant parameters would already be identified. Where this is not the case it would first be necessary to determine these, in order to be able to develop a preliminary monitoring programme. In an ideal scenario, the development of monitoring objectives would be carried out in parallel with the development of performance assessments, safety assessments and the preparation of the safety case. Knowledge of relevant features, events and processes likely to influence the performance of a safety function (and associated components) would be established, as would understanding of which processes and parameters most significantly influence an expected performance.

Only three repository programmes for long-lived wastes have already submitted a licence application: the Waste Isolation Pilot Plant (WIPP) at Carlsbad, New Mexico, USA, which has been operational since 1999; the applications for a US repository at Yucca Mountain (now withdrawn); and application for a Swedish repository at Forsmark (SKB, 2011).

The WIPP repository is obligated by provision of its Compliance Certification Application (DOE, 1996; Hansen, F.D & Wagner, S.W, 2013) to monitor ten performance metrics. These measures for confirmation purposes are distinct from the many other monitoring practices involved with environmental permits and repository operations. Periodic review of these monitoring parameters is necessary to meet the intent of the Environmental Protection Agency's (EPA) assurance requirements applicable to WIPP. The WIPP facility has been safely disposing of the United States defence-related transuranic radioactive waste since March 1999.

The WIPP repository monitoring programme (Hansen, 2011) is based on assumptions and regulations for the disposal concepts and waste types. Monitoring requirements derive from the functional, operational, and post-closure goals and comprise a program of tests, experiments, and analyses to evaluate the adequacy of the information used to demonstrate compliance with the site specific performance objectives.

Monitoring WIPP performance is an "assurance requirement" of the governing regulations to protect the public and environment. In the WIPP licensing process, the DOE made commitments to conduct a number of monitoring activities to comply with regulatory criteria and to ensure that deviations from the expected long-term performance of the repository are identified at the earliest possible time. The monitoring implementation plan (DOE, 2007) describes the overall monitoring program and responsibilities for the compliance monitoring parameters, which are assessed and reported annually.

The DOE oversees and directs the monitoring program to ensure compliance with the EPA monitoring and reporting requirements. Observations beyond the acceptable range of trigger values represent a condition that requires further evaluation. The original ten monitoring parameters have been continuously monitored without modification since the WIPP opened.

Periodic review of monitoring parameters meets the intent of assurance requirements (DOE, 2007):

> "*Disposal systems shall be monitored after disposal to detect substantial and detrimental deviations from expected performance. This monitoring shall be done with techniques that do not jeopardise the isolation of the wastes and shall be conducted until there are no significant concerns to be addressed by further monitoring*."

7.7 Stakeholder roles and stakeholder engagement

The interest of stakeholders, that is to say societal interest, in repository monitoring has been acknowledged throughout this reference framework report. Thus far, however, relatively few countries have engaged with public stakeholders on the specific subject of monitoring. A range of initiatives to engage with public stakeholders on broader issues of radioactive waste management in different MoDeRn Partner countries have nevertheless identified views and expectations on the role of monitoring that may influence decisions on repository monitoring programmes. Investigation of this issue within the MoDeRn project began by reviewing key international documents on the role of monitoring and by eliciting implementers' views through a series of interviews (MoDeRn 2013j). This identified expectations that monitoring would be used:

- To provide assurance: i.e. to demonstrate good practice and to verify the adequacy of the basis for the long-term safety case;
- To aid decision making in a stepwise process;

- To provide greater transparency; and, as a consequence of these functions,
- To support societal confidence in the disposal process.

This was consistent with feedback obtained at an expert stakeholder workshop (MoDeRn, 2011c) which identified the benefits of independent scrutiny of monitoring programmes, and monitoring results in particular, in order to build public trust. Participants also recommended the development, from the outset, of a clear strategy for implementing a monitoring programme, including when and how to communicate with public stakeholders about monitoring.

Prior to addressing what might need to be done so that monitoring can indeed contribute to stakeholder confidence, it is necessary to ascertain stakeholder expectations with respect to monitoring. In order to better understand the views of local stakeholders and what they may expect from monitoring a series of exploratory engagement activities was carried out in Belgium, Sweden and the United Kingdom as part of the MoDeRn project. The detailed results of this exercise are reported in MoDeRn Deliverable D1.4.1 (MoDeRn, 2013k) but from it a number of insights can be drawn.

It is well recognised that public acceptance is a challenging aspect of radioactive waste disposal. In the European context the public has been defined as "one or more natural or legal persons and, in accordance with national legislation or practice, their associations, organisations or groups" (Council of the European Communities, 1985). This makes it clear that 'the public' is not homogeneous but consists of a broad spectrum of potential stakeholder groupings as well as individual citizens. Therefore, it is important to distinguish between different categories of stakeholder with respect to their specific interests or responsibilities in relation to geological disposal and to the implementing organisations. These include: regulatory agencies; (other) oversight bodies or organisations; political decision makers; concerned and actively involved local stakeholders in affected communities (e.g. local information committees); local interest groups in affected communities (e.g. local economic interest groups); national or community-based environmental organisations; waste producers financing the disposal process; and other concerned but possibly less involved citizens from what is often described as the general public. While the implementers and regulators tend respectively to provide and to formalise the substance of monitoring objectives, the others all have either an explicit or an implicit stake in these decisions. These other categories of stakeholder may, however, have different understandings of what constitutes an acceptable repository or an acceptable monitoring programme, so it is important to listen to and engage with the views of different groups from the earliest stages of development.

Confidence may be based on different institutional mechanisms or arrangements and the confidence of different stakeholders may therefore be achieved by different aspects of the monitoring programme. For instance, the confidence of regulators would be maintained by a monitoring approach that meets regulatory requirements and by monitoring data that are consistent with prior expectations of key features and process evolutions therefore support the licence basis. Verification of the basis for long-term safety will also be a fundamental requirement for decision makers to have the confidence at each decision point of a staged disposal process to proceed to the next step. Other stakeholders may put greater emphasis on and draw greater confidence from the process followed to develop and implement a monitoring programme. For example, regardless of how confident expert stakeholders are in the performance confirmation provided by monitoring, current understanding of the dynamics of social trust indicate that process transparency will be essential to public confidence. In this respect, monitoring may be seen as making visible, to some extent, what is happening below the surface, thus rendering the 'black box' of the repository system more open to scrutiny.

This increases the potential for information sharing and, as is likely to be required by society, for the operation of independent oversight and expert review, as a mechanism for enhancing societal confidence in the safety of the project. Similarly, feedback from the MoDeRn engagement activities indicated that, for some stakeholders, a clearly specified process for responding to unexpected monitoring results may also be a requirement for confidence (MoDeRn, 2013k).

In addition to requiring transparency, stakeholders may have a strong desire to be involved in the major steps of repository implementation. There are several critical points in a repository development programme that are likely to demand input from a broader range of societal groups than the repository operators and regulators alone. It is conceivable, for example, that society, having endorsed the solution of geological disposal at a political level, would want to be involved in some of the more important decisions concerning a repository such as site selection and approval for its backfilling, sealing and closure.

On a more technical level, it is less clear whether those stakeholders not having a direct responsibility for developing or controlling the repository may have an interest and/or should have an opportunity to be involved in setting technical monitoring objectives. If that were the case and if specific expectations were to be elicited from stakeholders, these might be taken up by the regulator, translated into a guideline or licensing requirement and, thus transmitted to the implementer, be incorporated into a specific monitoring activity designed to address their concerns and to provide the required information. Public stakeholder expectations of monitoring have to date been expressed indirectly or at quite a general level, so the existing understanding of public stakeholder views was not sufficiently detailed to inform the consideration of specific monitoring parameters within the MoDeRn project. Entertaining the possibility of stakeholder input influencing the design of the monitoring programme raises the questions of whether or not the implementer would be able to establish a strong link between a specific monitoring activity requested by stakeholders and the basis for the safety case. This is an important consideration when designing a monitoring programme, the implications of which, should this issue arise, would need to be communicated to and debated with the stakeholders, regulators and decision makers concerned. Whatever the answer to that question, however, it is clear that being seen to address seriously and where possible to respond to specific monitoring expectations is likely to contribute to public confidence.

The nature, form and extent of engagement with stakeholders will be dependent to a large degree on the national context. Engagement with stakeholders about monitoring of a geological repository will be carried out within the context of arrangements established for engagement relating to the repository process as a whole. A variety of approaches, models and methods exist, documented both in the research literature on public participation and in reports of practice in the field of radioactive waste management, which can provide further insight and resources for implementers and stakeholders seeking ways to engage more effectively with these issues. Petts & Leach (2000) identify four levels of participation which can be considered for public involvement with monitoring programmes:

- Education and information provision: this involves the production and dissemination through different media of materials that inform people about what is going to happen, is happening, or has happened, and create awareness of activities and issues but offer no specific mechanism for response.
- Information provision and feedback: where stakeholder groups and the wider public are invited by the decision maker to comment on information, pre-formed proposals and/or related questions.

- Involvement and consultation: Processes may involve face-to-face interaction within and between professional stakeholders, local stakeholder groups, and citizens' issues of concern.
- Extended involvement: Deliberative processes that occur over an extended period where the public and stakeholders may play an active role in influencing decisions.

Each of these types of activity serves a different purpose and therefore all may have a role in stakeholder engagement about geological disposal and, in particular, about repository monitoring. Experience with geological disposal programmes in several countries indicates a growing adoption of extended dialogue processes, either in response to or to avoid conflict with stakeholders. Some of the most widely used methods for public and stakeholder participation are described and evaluated in Renn et al (1995) and an analytical typology of such methods is offered by Rowe & Frewer (2005). Within the field of radioactive waste management the review carried out in the MoDeRn project identified examples of a variety of locally implemented arrangements and practices, many of them documented in the reports of the NEA's Forum for Stakeholder Confidence, where stakeholders and local citizens engaged in some way with facility monitoring (MoDeRn, 2013k).

7.8 Accessibility of monitoring information

Throughout the MoDeRn Project there has been a strong awareness of the need to ensure that monitoring information can be made accessible to all stakeholder groups. The MoDeRn partners recognise some of the challenges in ensuring that monitoring programmes are both transparent and accessible. The MoDeRn Expert Stakeholder Workshop (MoDeRn, 2011) further advised that there should be a clear monitoring strategy, from the outset of implementing a monitoring programme, based on independent scrutiny and on when and how to communicate with public stakeholders on monitoring. These points were also discussed during the programme of engagement with public stakeholders (MoDeRn, 2013k). These engagement activities identified several challenges to making information accessible and transparent, which will need to be addressed in dialogue with public stakeholders in order to arrive at arrangements that are practicable and that meet effectively stakeholders' information requirements. The issues identified include:

- It is necessary to ensure that stakeholders have the capacity to understand and respond appropriately to results from monitoring;
- Some raw information from monitoring requires processing to make it meaningful and it is necessary to ensure that such processing is viewed as both clear and transparent;
- There is a risk of stakeholders being overwhelmed with large volumes of data, which therefore need to be presented in such a way that the key information can be valued.

With some repository processes evolving very slowly and showing no discernible change during the monitoring period, there is a need to focus on processes that will actually show something.

The MoDeRn project recognises the importance of monitoring to all stakeholders and that there is a need for monitoring programmes to be discussed at an early stage in the process.

7.9 Monitoring and governance of the disposal process

Confronting objectives and possible technological implementation enables the presentation of a realistic picture of how much added value monitoring can contribute by informing the governance of the disposal process – i.e. by informing the decision making involving the WMO, Safety Authority, Elected Representatives, Designated Advisory Boards, as well as other concerned stakeholders likely to have a role to play in such governance.

For a programme where a staged process of authorisation is required by the regulators, monitoring data could be used to refine the understanding of system behaviour as the disposal programme progresses. Monitoring is not merely undertaken to confirm expected behaviour, but also to help reduce uncertainties by measuring parameters *in situ*.

Although monitoring information to support decision-making may be focused on evaluation of performance against the safety case, additional monitoring (e.g. of structural integrity) would be required to protect those options, which should be available to decision-makers if, for example, as a result of an evaluation, there was a need for a delay in the disposal process.

Differences in national contexts may affect:

- The extent to which possible alternative routes, including potential waste retrieval, have to be considered from the outset;
- The extent to which provisions for such alternatives have to be included in the original design, and possibly
- The formal procedures that may be developed for decision making.

Notwithstanding these potential differences, the general principle of stepwise decisions (NEA, 2011) is to obtain broad agreement and it is expected that monitoring would provide useful information regarding the options, conditions and flexibility available to support pre-closure management decisions.

Although the initial plans for a repository will include assumptions about many aspects that are part of the design basis, it is probable that decades of operational experience will allow early decisions to be adjusted and modified to take advantage of what is learned from concurrent monitoring information (IAEA, 2001). During monitoring, large quantities of new information will become available each day and not all of this information will be required to demonstrate safety, but will still be useful to help develop an understanding of the disposal system.

Increased understanding of the disposal system through monitoring will assist implementers, regulators and other involved bodies as it will support decisions on whether there is sufficient/insufficient information to progress to the next stage or to take alternate action.

The decision for final closure of a repository – at least from today's perspective – would generally be preceded by a century of experience of disposing of waste, managing a repository and obtaining confirmatory information from *in situ* monitoring and from a parallel long-term science and technology programme. Based on these operations and this monitoring information, as well as on other associated activities and indeed general progress of technology and of scientific understanding, confirmation and re-evaluation of the safety case prior to closure should have been performed and evaluated to the satisfaction of the stakeholders involved at that time. Should residual questions remain concerning the long term safety of the repository, it might then be argued that the decision to close the repository should be postponed. If, on the other hand, all stakeholders at that time have confidence in the long term safety of the repository, further monitoring may be considered unnecessary.

7.10 Flexibility of monitoring programmes

Monitoring activities should be flexible and adaptable to respond to the needs of operators, regulators and other stakeholders and to be used to support decisions that need to be taken throughout the disposal process. The recognition that implementing organisations are prepared to listen to and adapt, where appropriate, may also contribute to the confidence these stakeholders need to have in the disposal process. It is acknowledged that taking decisions to move through the different phases of the implementation of a repository will require different levels of confidence and that the roles of stakeholders may vary both in the route to confidence building and during the subsequent decision steps.

The progressive approach from construction to closure provides an opportunity to verify the knowledge basis over extended periods of time (i.e. several decades up to a century), as well as an opportunity to further adapt the repository to its natural environment. This has been formalised using various approaches in different countries including provisions for waste retrievability, e.g. the French context includes an explicit requirement for a reversible management approach that calls for flexibility in management options to respond to future demands set within a structured decision-making process (Loi, 2006).

Other options available to disposal management decision makers should therefore be considered, e.g. disposal design changes that could be implemented during the progressive construction; timing for backfill as part of a flexible closure strategy; etc. These options may lead to the development of additional monitoring activities. For instance, to maintain infrastructure and access could require additional operational monitoring and inspection to ensure that ongoing monitoring of disposal facilities (or retrieval) could be carried out safely and effectively. This could include monitoring of:

- The state and durability of the infrastructure (accesses, plant and equipment) and the need for maintenance to maintain access, re-open, close or retrieve;
- The evolution of repository components and its near-field;
- The condition of waste and waste packages

Indeed monitoring programmes will be necessary for all of those areas/services etc. required to maintain flexibility to continue operation, modify design, continue monitoring or retrieve waste. The decision-makers would consider information obtained from these monitoring activities and combine it with other information – most importantly that pertaining to the basis of the safety case and any input received from stakeholders – and take action with respect to the reference path of the disposal process.

7.11 Post-closure monitoring

Although a general consensus exists that during the implementation stage, monitoring can play an important role in the safe disposal of radioactive wastes, it is a requirement that long-term safety should not depend on monitoring after waste emplacement and closure of a repository (IAEA, 2001). Apart from existing regulations (BMU 2010), post-closure monitoring is often mentioned by stakeholders and expected in principle, even though this activity would at best be decades and more realistically over a century away and is therefore difficult to be definitive about what monitoring would be done at that time. There are significant differences between post-closure monitoring for near-surface disposal facilities for short-lived wastes and geological disposal facilities for long-lived wastes. Post-closure monitoring of a near-surface repository can provide direct evidence of a repository's overall performance through measurement of the concentrations or absence of radionuclides in the accessible environment over the comparatively short time they present a risk - this is not the case for geological disposal, where the timespan for radionuclide decay is considerably greater, the disposal is much deeper and the wastes are much more isolated and contained.

Should any consideration of post-closure monitoring include, in addition to surface-based monitoring, consideration of some form of *in situ* monitoring, then the technological challenges and limitations should be understood. Post-closure monitoring would deliver only limited additional data to further support the basis for evaluating long-term safety. Indeed, more information might be obtained during intermediate closure steps in the main facility or the closure of a pilot facility when these would more closely reflect the early transient evolutions of the repository. Other monitoring after complete closure, such as downstream radiological monitoring e.g. through boreholes, would not be expected, over the timescales envisaged, to provide additional information as to the basis for long term safety, and would thus be of limited value for further performance confirmation. Any proposals for *in situ* monitoring post-closure would need to be planned, designed and installed before repository closure. If near-field monitoring is viewed as an option, monitoring equipment would need to be installed from the outset in parallel with disposal operations. Knowing that there would be no more access to the monitoring equipment, this early installation would be the only way of providing future decision makers with the flexibility to decide whether to monitor or not after closure. If monitoring equipment is not installed in already closed areas it would not be feasible to monitor these areas. This needs to be considered with the clear understanding that the lifetime and durability of monitoring systems would be limited.

An exception may be the case when repository closure would result in a near- or far-field response that can be monitored over reasonable timescales, and that was not already seen subsequent to partial closure of, say, disposal drifts. For instance, the hydrogeological response to closure in crystalline rock might deserve special attention. In that case, monitoring from distant boreholes may provide useful information over a time span beginning prior to construction, continuing throughout operation and the early post-closure phase.

It is, however, difficult to know at this stage whether additional confirmatory post-closure monitoring may be called for by society and its representative institutions a century or more in the future, when the decision on final closure of a repository would be taken, and it would be presumptuous to guess at what specific requests for further monitoring, if any, might be expressed at that time. A clearer picture needs to be developed of what can and cannot be done in relation to post-closure monitoring, always recognising the need to assure that post-closure monitoring activities do not compromise the primary intent, which is safety of disposal. There is a need for implementing organisations, responsible for delivering safe disposal, to consider these issues and provide clear information to discuss with stakeholder groups.

While this issue may not be developed in full detail for several generations, - except for countries who have national regulations which require a post-closure monitoring concept as a condition for granting a licence - it is nonetheless considered an important issue, particularly for those stakeholder groups who remain concerned about geological disposal as a permanent solution for radioactive waste.

8. Conclusions

The MoDeRn Project was initiated by the MoDeRn partners to further develop the understanding of the role of monitoring in the staged implementation of geological disposal with the aim of providing examples, guidance and recommendations that may be useful, particularly to waste management organisations (WMOs) for their development of monitoring programmes and the understanding of how these could be implemented and used as part of the overall disposal process. The suite of monitoring reports which address *Process* (this report), *Technology* (MoDeRn, 2013h), and *Case Studies* (MoDeRn, 2013g) provide detailed accounts of work carried out within the project on these aspects.

The MoDeRn Project focuses particularly on monitoring repository system behaviour, as from a technical point of view disposal cell monitoring remains the biggest challenge today, one that is relatively unique to geological disposal. Other types of monitoring activity that will be called for in any geological disposal programme, such as *operational safety*, *environmental* and *safeguards* monitoring, while recognised as very important, are likely to be similar to those already in use at other nuclear installations and their implementation can be planned and further developed based on prior experience. They have not therefore been considered in detail within MoDeRn.

The MoDeRn project has drawn on previous work (IAEA, 2001, IAEA, 2006, EC 2004, RWMC and Nirex, 2007) and has developed the thinking contained in that work on the approach to monitoring to produce this *Reference Framework Report*.

This Reference Framework Report presents a *MoDeRn Monitoring Workflow* which provides a systematic approach to developing monitoring objectives into processes and parameters to be monitored. The workflow should aid implementing organisations in developing monitoring programmes and should also provide a basis for discussing monitoring programmes with key stakeholders.

The emphasis for this report has been monitoring of the disposal and in particular to monitor for long-term safety, which requires analysis of the safety case to identify appropriate parameters to monitor. The report provides examples of what might typically be considered in such a monitoring programme and the *Case Studies* (MoDeRn, 2013g) provide more comprehensive examples of such monitoring programmes for three host rock types (evaporite, clay and crystalline).

The *Monitoring Reference Framework* does not claim, nor aim to describe a reference monitoring programme. Any examples provided only serve to illustrate specific aspects of the *process* presented in the *Reference Framework*. Indeed, the project clearly recognises the diversity of national contexts and the diversity of monitoring solutions that are thus likely to be developed.

The MoDeRn Project also conducted a substantial amount of research into applicable monitoring techniques, producing a report on the current *state-of-the-art* for monitoring (MoDeRn, 2013a) and has also conducted five programme of development and demonstration of state-of-the-art monitoring techniques (MoDeRn, 2013b to f) in underground research laboratories (URLs). This research and development provides important insight into the technical feasibility and limitations of monitoring of geological disposal and helps identify those areas of RD&D that merit further investment.

One of the significant benefits provided by having URLs available is that these can be used to conduct testing and development of monitoring systems in advance of a disposal programme. These URLs and pilot facilities also provide opportunities to commence longer-term evaluation of monitoring systems (e.g. durability) and of monitoring evolutions related to the design and safety case. They also provide opportunities for WMOs to develop and evaluate disposal concepts as well as to develop and test monitoring techniques.

Many of the implementing organisations recognise both the significance and the challenge in developing a well-founded and flexible monitoring programme that remains realistic and of value to all involved parties. For this reason, the value of progressing monitoring studies at an early stage of development of geological disposal plans is recognised.

The results of the MoDeRn Project should help WMOs and stakeholders to understand the progress to date on monitoring for geological disposal, but also to recognise that monitoring is very much a developing subject, which will benefit from continuing research and development.

Monitoring is a likely focus of public stakeholder interest in relation to geological disposal programmes and therefore early planning and consultation should assist WMOs in communicating a complex topic. Using the *MoDeRn Monitoring Workflow* should assist all parties in developing properly focused and justified monitoring programmes.

Monitoring represents a significant investment of time, financial resources and effort for all parties but has the potential to provide significant added value in the form of enriched information provision, of better-informed decision making and of enhanced public confidence.

9. References

ANDRA (2005): Synthesis Argile – Evaluation of the feasibility of a geological repository in an argillaceous formation.

ANDRA (2009): Options de réversibilité du stockage en formation géologique profonde. - Andra report n°C.NT.AHVL.09.0005.

ASN (2008): Guide de sûreté relatif au stockage définitif des déchets radioactifs en formation géologique profonde. - Fontenay-aux-Roses, 27 Fev 2008.

BGR, DBETEC & GRS (2012): Szenarienentwicklung – Methodik und Anwendung. - Bericht zum AP8, Vorläufige Sicherheitsanalyse Gorleben, GRS – 284.

BOLLINGERFEHR, W., FILBERT, W., LERCH, CH., & THOLEN, M. (2012): Vorläufige Sicherheitsanalyse Gorleben (VSG), Endlagerkonzepte (AP5) - Abschlussbericht, GRS-272, DBE Technology, Peine.

BMU (2010): Safety Requirements Governing the Final Disposal of Heat Generating Radioactive Waste. - Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Berlin, Germany.

COUNCIL OF THE EUROPEAN COMMUNITIES (1985): Council Directive of 27 June 1985 on the Assessment of the Effects of Certain Public and Private Projects on the Environment. - Directive 85/337/EEC.

DOE (1996): WIPP Compliance Certification Application - Carlsbad, NM - U.S. Department of Energy, DOE.

DOE (2007): Compliance Monitoring Implementation Plan for 40 CFR §191.14(b), Assurance Requirement - Carlsbad, NM, U.S. Department of Energy, Revision 5, December 2007, DOE/WIPP 99-3119

EC (2004): Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste. - European Commission Project Report EUR 21025 EN. EC, Luxembourg.

ENSI (2009): Spezifische Auslegungsgrundsätze für geologische Tiefenlager und Anforderungen an den Sicherheitsnachweis. Richtlinie für die schweizerischen Kernanlagen ENSI-G03. - Eidgenössisches Nuklearsicherheitsinspektorat (ENSI), Villigen, Switzerland.

GSL (2004): An Illustrative Post-Closure Monitoring Programme for the Nirex Phased Disposal Concept. - Galson Sciences Report 0435-1, Version 1.

GSL & GOLDER (2004): Techniques for Post Closure Monitoring. – Galson Sciences Limited and Golder Associates (UK) Ltd, Galson Sciences Report, 0358-1, Version 1.1, 18. June 2004.

GSL (2008): Summary Report of RWMC/Nirex Monitoring Workshop. Geneva, 21-22 February 2007. - GSL Report 0759-1, Version 1.

HANSEN, F. D. (2011): Repository Performance Confirmation. - Sandia Report SAND2011-6277, Sandia National Laboratories.

HANSEN, F. D. & WAGNER, S.W. (2013): Confirmation Monitoring of Repositories in the United States. - SAND2012-10498C., Monitoring in Geological Disposal of Radioactive Waste – Conference and Workshop, Luxembourg.

ICRP (2013): Radiological protection in geological disposal of long-lived solid radioactive waste. - ICRP Publication 122. Ann. ICRP 42(3).

IAEA (2001): Monitoring of Geological Repositories for High Level Radioactive Waste. - IAEA-TECDOC-1208, IAEA Vienna.

IAEA (2006): Safety Requirements for the Geological Disposal of Radioactive Waste. - IAEA Safety Standards Report No. WS-R-4, IAEA Vienna.

IAEA (2010): Technological Implications of International Safeguards for Geological Disposal of Spent Fuel and Radioactive Waste. - Nuclear Energy Series, No. NW-T-1.21, IAEA Vienna, October 2010

IAEA (2012): IAEA Safety Guide Standards - SSG-23: The Safety Case and Safety – IAEA, Vienna.

LOI (2006): Loi N° 2006-739 du 28 juin 2006 - Loi de programme relative à la gestion durable des matières et déchets radioactifs. - Publiée au Journal Officiel du 29 juin 2006.

MoDeRn (2010a): Technical Requirements Report. - MoDeRn project report, *www.modern-fp7.eu*.

MoDeRn (2010b): Monitoring Technologies Workshop Report 7-8 June 2010 – Troyes (France). - MoDeRn project report, *www.modern-fp7.eu*.

MoDeRn (2011a): National Monitoring Contexts Summary Report. - Deliverable D1.1, *www.modern-fp7.eu*.

MoDeRn (2011b): National Monitoring Contexts Country Annexes. - *www.modern-fp7.eu*.

MoDeRn (2011c): Expert Stakeholders Workshop. - Deliverable D5.3.1, www.modern-fp7.eu.

MoDeRn (2012): Monitoring the Safe Disposal of Radioactive Waste: a Combined Technical and Socio-Political Activity. - Deliverable D1.3.1, *www.modern-fp7.eu*.

MoDeRn (2013a): MoDeRn State-of-the-art Report on Monitoring Technologies. - Deliverable D2.2.2, *www.modern-fp7.eu*.

MoDeRn (2013b): MoDeRn Seismic Tomography at Grimsel - Deliverable D3.2.1, *www.modern-fp7.eu*.

MoDeRn (2113c): MoDeRn High Frequency Wireless Sensor Networks at Grimsel. - Deliverable D3.3.1, *www.modern-fp7.eu*.

MoDeRn (2113d): MoDeRn Fibre Optic Sensing at HADES URL - Deliverable D3.4.1, *www.modern-fp7.eu*.

MoDeRn (2113e): Wireless Data Transmission Demonstrator: from the HADES to the surface. - Deliverable D3.4.2, *www.modern-fp7.eu*.

MoDeRn (2113f): MoDeRn Fibre Testing of Disposal Cell Monitoring Systems at Bure URL. - Deliverable D3.5.1, *www.modern-fp7.eu*.

MoDeRn (2113g): MoDeRn Case Studies Report. - Deliverable D4.1, *www.modern-fp7.eu*.

MoDeRn (2113h): MoDeRn Technology Summary Report. - *www.modern-fp7.eu*.

MoDeRn (2013i): MoDeRn, Failure detection methods for repository monitoring. - Internal report, *www.modern-fp7.eu*.

MoDeRn (2013j): MoDeRn, Basis for Stakeholder Engagement. - Deliverable D1.3.1, www.modern-fp7.eu.

MoDeRn (2013k): Monitoring and the Risk Governance of Repository Development and Staged Closure: an Exploratory Investigation of Stakeholder Views in Three European Countries. - Project Deliverable D1.4.1., www.modern-fp7.eu.

NEA (2011): Reversibility and Retrievability (R&R) for the Deep Disposal of High-Level Radioactive Waste and Spent Fuel – Final Report of the NEA R&R Project (2007-2011). - Report No. NEA/RWM/R(2011)4.

NRC (2003): One step at a time – The staged development of geologic repositories for high-level radioactive waste. - The National Academies Press, Washington, D.C.

OPG (2003): An Approach to Long-term Monitoring for a Nuclear Fuel Waste Repository. - OPG Report No. 06819-REP-01200-10106-R00.

PETTS, J. & LEACH, B. (2000): Evaluating Methods for Public Participation: Literature Review. - Environment Agency R&D Technical Report , Environment Agency Bristol.

POSIVA (2003): Programme of Monitoring at Olkiluoto During Construction and Operation of the ONKALO. - Posiva Report 2003-05.

RENN, O., WEBLER, T. & WIEDEMANN, P. (1995): Fairness and Competence in Citizen Participation: Evaluating Models for Environmental Discourse. - Kluwer, Dordrecht.

ROWE, G. & FREWER, L.J. (2005): A Typology of Public Engagement Mechanisms. - Science, Technology & Human Values 30(2): 251-290.

RWMC (2005): Monitoring of Geological Disposal – Current Status and Technical Possibilities. - RWMC Technical Report RWMC-TRE-04004.

RWMC & NIREX (2007): International Workshop on Repository Monitoring Strategies in Geneva, 21-23 February 2007. - CD of Workshop Proceedings, Final Version.

SAM, NNC, NAGRA & CSEC (2002): Options for Monitoring During the Phased Development of a Repository for Radioactive Waste. - Safety Assessment Management Report SAM-J078-R1.

SANDIA (2008): Performance Confirmation Plan. - TDR-PCS-SE-000001 REV 05 AD 01. Las Vegas, Nevada: Sandia National Laboratories. Reference: SNL 2008, ACC: DOC.20080227.0003; DOC.20080324.0002.

SKB (2004): Monitoring during the Stepwise Implementation of the Swedish Deep Repository for Spent Fuel. - SKB Report R-04-13.

SKB (2011): Long-term safety for the final repository for spent nuclear fuel at Forsmark. - Main report of the SR-Site project, Volume I, TR-11-01

US NRC (2012): Disposal of High-Level Radioactive Wastes in Geologic Repositories – Performance Confirmation Program. - Code of Federal Regulations 10, Part 60, Subpart F, www.nrc.gov.

WAGNER, S.W. (2012): Performance Confirmation Strategies for the Waste Isolation Pilot Plant – A Historical Perspective from an Operating Disposal Facility. - Waste Management Conference, Phoenix, Arizona, USA.