CO-ORDINATION NETWORK

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ON DECOMMISSIONING

Dismantling Techniques, Decontamination Techniques, Dissemination of Best Practice, Experience and Know-how

Final Report
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1. Introduction

This report has been prepared under Work Package 7 (WP7) of the Co-ordination Network on Decommissioning of Nuclear Installations (CND) under the contract no. 0508855 (FI60) from the European Commission's Research and Technological Development (RTD) Division to a consortium of European nuclear organisations. This work was carried out by AF-Colenco AG (Switzerland) supported by Wilhelm Gottfried Leibniz Universität Hannover (Germany) and DECOM a.s. (Slovakia).

The main aim of Work Package 7 was to promote the use of the completely implemented database on technical and cost aspects of decommissioning (EC-DB-NET2) and to ensure that the collected information was made available to all interested parties involved in decommissioning activities. In addition, the educative situation within the EC Member States and the need for training related to dismantling and decontamination were investigated.

The implementation of the database on technical and cost aspects of decommissioning (EC-DB-NET2) has been reported under a specific document of the Co-ordination Network on Decommissioning of Nuclear Installations (CND): 'An integrated online Internet platform for the *Database on Technical and Cost Aspects on Decommissioning*, providing an information database relating to former and existing technical decommissioning projects".

In the area 'Dissemination of Knowledge, Need for Training', a questionnaire was developed and transmitted to selectively approached parties. In general, the responses to the questionnaire were rather negative, indicating that internal knowledge management structures will not be externalised. Public dissemination of know-how and best practices is predominantly done by public institutions.

The scope of the EUNDETRAF project was specifically the development and provision of comprehensive and concentrated training courses regarding the decommissioning of nuclear facilities in the form of theoretical and practical lessons. The text book that had been derived during the courses as a reference book summarises regulatory, organisational and technical aspects of decommissioning in an educational form.

The last segment of the European funded EUNDETRAF project was due to end in December 2006. The preparation of the part of the text book dealing with dismantling techniques was implemented at the University of Hannover, one of the partners of the CND, to facilitate easy and seamless integration of it into the CND webpage.

The third objective of the activities within Work Package 7 of the CND had been to make the EC-DB-NET2 database within the CND web site available to all interested parties in the CND network, to promote its use, to facilitate the input of new data sets and to establish a snapshot of the current state-of-the-art of dismantling and decontamination techniques.

Although a number of companies and institutions had been directly approached on conferences, fairs and meetings, no or very few inputs had been acquired from external parties. The scope and structure of the CND network have been presented, and the benefits of a partnership have been demonstrated, focusing on the technical aspects of decommissioning that were the main issue of Work Package 7.

The EC-DB-NET2 database was obviously not so attractive, however. From the beginning of 2005 until the end of March 2006 only 61 accesses had been notified, excluding accesses of administrators and Members of the Steering Group. The main arguments of companies to express their lack of interest was the structure being too complex, and their internal knowledge management systems not being compatible with the database, so that too much manpower would have to be invested to put data in the database.

In general, the attitude of most of the companies has been markedly sceptical. The background of their concerns was commonly the fact that companies forming the designated target group of Work Package 7 are competitors on the quite restrained market of dismantling activities. The addressed enterprises therefore were only willing to provide general information (i.e., a description of the *task itself*, not of the instruments that have been used to address the task, and not at all detailed technical data), which was not considered to be useful for the CND project. Even the added value situation of being able to access the whole CND database together with the Work Package 7 specific database on tools and costs, has not led to a substantial interest among the industrial contacts.

A new approach had therefore been proposed relating to data collection about dismantling and decontamination techniques. The EC-DB-NET2 database as a snapshot of the current state-of-the-art of dismantling and decontamination techniques had proved not to be very successful. To improve the added value of the webpage section of Work Package 7, it was proposed that the Work Package Manager should derive a benchmark exercise from various sources and bring the relevant data file on the CND website. Furthermore, companies and institutions would be invited to comment on the benchmark, and provide additional documents relating to dismantling and decontamination techniques in the way they felt comfortable with. As such, they would no longer be obliged to transform the data to suit the structure of the EC-DB-NET2 database. The benchmark exercise and its resonance could form the main content of the final report relating to this section of Work Package 7.

The DOE's former Office of Environmental Restoration (EM-40) conducted a benchmarking study of its decommissioning programme to analyze physical activities in facility decommissioning and to determine approaches to improve the decommissioning process. The study focused on quantifying productivity of decommissioning physical activities and identifying how productivity is affected by specific working conditions. The results of this study were included in the ‘DOE Decommissioning Benchmarking Study. Final report. January 15, 1997’ that was made available on the CND website under the work area ‘Dismantling Techniques’ and the heading ‘CND – Decommissioning benchmark studies’, and could be an example for similar benchmarking studies that could be started within the CND.

Specific information relating to dismantling, decontamination and monitoring techniques had been collected in three annexes to the IAEA document ‘Methods for the minimisation of radioactive waste from decontamination and decommissioning of nuclear facilities’, Technical Report Series No. 401, IAEA, Vienna (2001).

Despite all efforts, the activities within Work Package 7 continued to suffer from a lack of interest from companies and institutions to provide data relating to dismantling and decontamination activities whether within or without the structure of the EC-DB-NET2 database on costs and tools.

The issue has been discussed intensively within the members of the ‘Kerntechnische Gesellschaft’ (KTG), the most influential group working on dismantling and decontamination in Germany - mainly for getting any kind of support - but the common and very distinct opinion on both contractors’ and operators’ sides was that this benchmark exercise would not be of much use except for a mere informative listing of techniques, as all technical data are obsolete if they are not directly connected to a certain machine of a certain manufacturer operated at a specific set of parameters (and these data are mostly not available).

The issue has also been discussed with representatives of VAK Kahl, AKW Stade and various contractors in the field of concrete cutting, and all refrained from supporting the initiative.

It was therefore decided to prepare a final report based on information that could be made available from a co-operative work of the Work Package 7 Manager and other active members of the CND with the EUNDETRAF project. Additional dedicated information could be collected from the activities developed in the area of decommissioning costs.

As a result, this report provides a list with basic review of dismantling and decontamination techniques, including some typical characteristics if available, as well as aspects of implementation, parameters and safety aspects of dismantling and decontamination techniques in decommissioning costing. In addition, the organisation of dismantling and decontamination techniques in databases, implementation of dismantling and decontamination techniques in the structure of the 'Proposed Standardised List of Items for Costing Purposes' (PSL) and the selection of dismantling and decontamination techniques for calculation in decommissioning costing is discussed.

In general, the document represents an overview of the state-of-the-art in the area based on different documents to which participants of the Co-ordination Network on Decommissioning of Nuclear Installations (CND) have contributed in a substantial way.

2. Decontamination techniques

2.1 Introduction

Contamination of materials and components may be the result of various physical and physico-chemical processes. Contamination of metals may be found in a very thin surface layer (of the order of µm in thickness) while in concrete building structures contamination may have penetrated deeper over a few centimetres or even more.

The amount of deposition of contaminants on a surface depends on a number of factors, such as the type of the base material, the surface roughness, the degree of corrosion, the surface or material porosity, as well as on the physico-chemical properties of the contaminating fluid such as pressure, temperature, pH, etc.

There are two types of radioactive contamination, smearable (removable) and fixed [1]. Smearable contamination is typically removed by wiping the surface with a cloth rag, similar to the dust that is found in all homes. Just as dust is removed from a surface by wiping with a cloth sprayed with a chemical to help 'hold' the dust, so might smearable contamination. Treating or attempting to remove fixed contamination also may generate smearable contamination. Some methods will loosen the fixed contamination, rendering it amenable to removal as smearable. Smearable wipes used to wipe the surface (typically 100 cm^2) to determine the contamination levels are based on this type of contamination.

Fixed contamination is held tightly to the surface and typically is associated with corrosion products on metal or concrete surfaces. In these cases, the contaminants have diffused into the material, or the radio-nuclides form some type of electrostatic or chemical bond with the surface materials. The removal of fixed contamination typically requires harsh removal techniques. Chemical dissolution of corrosion films or concrete scabbling is required to remove fixed contamination; these techniques will routinely result in the creation of smearable contamination.

Decontamination is defined as the removal of contamination from surfaces of structures or equipment by washing, heating, chemical or electrochemical action, mechanical cleaning, or other techniques [2]. In decommissioning programmes, the objectives of decontamination are:

- to reduce radiation exposure;
- to salvage equipment and materials;
- to reduce the volume of equipment and materials requiring storage and disposal in licensed disposal facilities;
- to restore the site and facility, or parts thereof, to an unconditional-use condition;
- to remove loose radioactive contaminants and fix the remaining contamination in place in preparation for protective storage or permanent disposal work activities; and
- to reduce the magnitude of the residual radioactive source in a protective storage mode for public health and safety reasons, to reduce the protective storage period or to minimize long-term monitoring and surveillance requirements.

Some form of decontamination is required in any decommissioning programme, regardless of the form of the end product. As a minimum, the floor, walls, and external structural surfaces within work areas should be cleaned of loose contamination, and a simple water rinsing of contaminated systems may be performed.

Decontamination is normally performed for a specific reason, and a worker should understand both the reason and the form of contamination. If unconditional release is the criterion, the leaching of radio-nuclides from crevices after the part has been surveyed and unconditionally released is of concern [1]. Many investigators have found that some contamination resides in the cracks and pores of metals and concrete. Although a survey for unconditional release may find no radioactivity, it is often found again later - the result of radio-nuclides leaching from the interior of the surface. It is believed that the radio-nuclides are not found during the final survey because they are imbedded deeply enough to be shielded from detection. Decontamination techniques are also performed to reduce the exposure of workers or avoid the spread of contaminants. In these cases, the survey requirements are somewhat less restrictive.

A decontamination programme may also require a facility capable of treating secondary wastes from decontamination (e.g., processing chemical solutions, aerosols, debris, etc). The concentrated wastes, representing a more significant radiation source, must be solidified and shipped for disposal in licensed disposal facilities unless properly treated in the waste reduction/recycling/reclamation processing alternative. The optimal waste reduction configuration must be defined after an economic assessment of treatment versus transportation/disposal costs has been completed. Each of these additional activities may increase:

- occupational exposure rates;
- the potential for release of activity into the environment;
- the uptake of radioactive material.

These could conceivably result in even higher doses than those received from removing, packaging and shipping the contaminated system without extensive decontamination. Resolution of this question depends on specific facts, such as the exposure rate of the gamma-emitting contamination, the contamination level, and the effectiveness of the shielding component and piping (wall thickness) in reducing radiation fields in the work area.

Depending on all these factors, the processes to decontaminate contaminated materials or components can be different or can have different results. The decision to decontaminate should be weighed against the total dose and the costs of the primary operation itself. Indeed, the decontamination operation will also generate secondary wastes, involve costs for implementation and may also lead to exposure to radiation or internal contamination, which must be balanced against the potential or expected results and advantages of the primary operation.

2.2 Selection of a decontamination process

2.2.1 General considerations

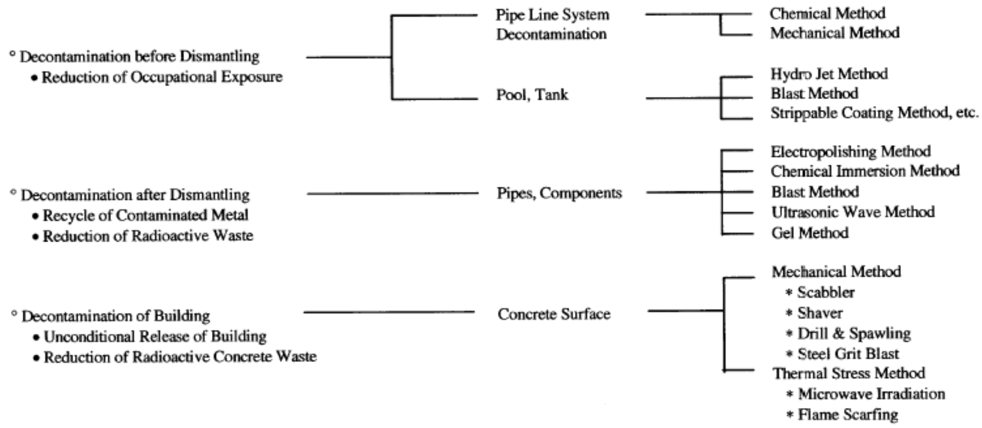
Several decontamination techniques have been developed to support maintenance work in nuclear installations, and have been applied with relative success to decommissioning. Nevertheless, with more decommissioning operations being carried out throughout the world, specific processes have been developed for decommissioning purposes. The different types of decontamination processes are summarized in Table 2.1 [2] for the most common aspects of decommissioning.

When selecting a suitable decontamination process, several criteria need to be considered in a detailed analysis based on site specific conditions, such as:

- The location of the contamination (e.g., inner versus outer surfaces of closed fluid systems);
- The material (e.g., steel, concrete…);
- The history of operation (to determine contamination profile);
- The nature of the contamination (e.g., oxide, crud, sludge…);

- The effectiveness of previously used chemical decontamination processes;
- The distribution of contamination (e.g., surface, cracks, homogeneous distribution in bulk material);
- Exposure to human health and the environment;
- Safety, environmental, and social issues;
- Exposure level reduction requirements (e.g., recycling versus disposal);
- Quantities and types of secondary wastes from decontamination and conditioning;
- The ultimate placement of decontaminated materials;
- Time and costs.

Table 2.1 Decontamination for decommissioning



2.2.2 Planning and operational considerations

Prior to the decontamination of any removable component or part, the management should consider the available options and the economics of the process [1]. An engineering evaluation should include the following questions:

- Why is the component being decontaminated?
- Can it be unconditionally released?
- Can it go straight to disposal?
- Which disposal site is required?
- What are the acceptable radiation and contamination levels at the disposal site?
- Is decontamination cost-effective?
- What decontamination method should be applied?
- Has the site decontaminated this type of part or component previously?
- What is the secondary waste generated?
- Is the secondary waste hazardous, radioactive, both?

All decontamination efforts have a common objective: the removal of radioactive contamination from its present undesirable location. A variety of decontamination methods are available, regardless of the nature or extent of the contamination. An evaluation of several considerations will determine which specific methods should be applied. The weight given each will vary greatly with the situation, with some requiring no consideration. These considerations may be generalized as follows:

- The radio-nuclides present and their physical state;
- The type of surface and substrate material bearing contamination;
- The size, configuration, location of the contaminated surface and its relationship to other surfaces;
- Accessibility of the contaminated area;
- Desired condition of the contaminated surface upon completion;
- Desired degree of decontamination to be achieved;
- Functional nature that must be retained following decontamination of the surface;
- Equipment and materials available for use in decontamination, including those present at the site and available from other sources;
- Worker safety and radiation dose minimization;
- Cost-effectiveness of various alternatives, including the relative costs of disposal and replacement versus decontamination and reuse;
- Quantity and nature of waste that will be generated (including secondary waste from decontamination solvents, etc.) and its disposal cost;
- Human resource and training requirements.

The weight given these individual considerations will vary greatly with the situation, with some requiring no consideration in many circumstances.

Experience has shown the desirability and benefits of providing hands-on training for decontamination workers and their supervisors and foremen. This training may include the use of mock-up facilities, simulating as closely as possible the thing to be decontaminated and the methods and equipment to be used during decontamination. Such training should be performed with the personnel dressed in the actual anti-contamination clothing they will wear during performance of the work.

This training with mock-ups is generally at least as useful to the people charged with planning and scheduling the work, and with staging the equipment and material to the work area, as it is for the workers and their supervisors and foremen who will perform the decontamination activities. Such training activities are the best way to ensure that the safest, and most effective and cost-beneficial results will be obtained from the work. They also provide assurances for complying with the regulatory requirement for accomplishing the required work with resultant worker radiation exposures maintained as low as reasonably achievable (ALARA).

The decontamination operation must be based on a detailed action plan. Key elements of an action program include:

- Preplanning all work, including specific activities to minimize the release of contamination, such as the use of catch basins, tenting and venting through HEPA filters, and glove box construction, the strict observation of step-off pads and other controls, and adherence to tag out, drain down, flushing, and other maintenance prerequisites.
- Minimizing the generation of contaminated items that must be transported through the site for cleaning or disposal, with the inherent potential for contaminating otherwise clean areas or items. Examples of this are the removal of all packaging materials prior to entry to a contaminated area, use of a ‘runner’ to reduce the times for dressing and undressing are required for maintenance and operation personnel, and careful selection of tools and equipment prior to the start of work so that items are not exposed to contamination unnecessarily

- Emphasis at all times on the necessity for each individual to observe and deal with any discrepancy in system function or procedural operation. This should include the immediate reporting to maintenance of any leakage or other equipment problems, the willingness of any individual to point out to another an error in procedure, open post-job debriefing, or any other activity that will correct or preclude errors in function of equipment or personnel.

The cost-effectiveness of such a program is easily realized in the reduction of labour and supplies used for decontamination, reduction in waste disposal costs, and reduction in total exposure expended per year.

2.3 Decontamination of metals

The decontamination of closed systems and the decontamination of metallic pieces and equipment relate to stainless steel (SS) or carbon steel (CS). Other materials like aluminium (Al) or even less used metals like inconel, copper, lead, or other alloys are somewhat less generic and require specific attention for the selection of the necessary decontamination process.

Table 2.2 Overview of processes for metal decontamination

METAL DECONTAMINATION	Closed systems	Open systems
Chemical processes		
• Oxidation processes		
– ODP/SODP	×	
– Cerium/Sulphuric acid		×
– Cerium/Nitric acid		×
• Oxidation-reduction processes		
– APCE/NPOX	×	×
– TURCO	×	×
– CORD	×	×
– CANDEREM, CANDECON		×
– CONAP		×
– AP/NP + LOMI for PWR	×	
– EMMA	×	
• LOMI for BWR	×	
• Phosphoric-acid-based processes		×
• Foams	×	
• Various reagents		
– HNO_3		×
– HNO_3 + HF	×	×
– HNO_3/NaF	×	×
– HCl	×	×
– DECOHA		×
Electrochemical processes		
• Phosphoric acid		×
• Nitric acid		×
• Nitric acid - Electrodeplating		×
• Sodium sulphate - ELDECON Proc.		×
• Oxalic acid		×
• Citric acid		×
• Sulphuric acid		×
• Other electrolytes		×

METAL DECONTAMINATION	Closed systems	Open systems
Physical processes		
• Ultrasonic cleaning		×
• High pressure water		×
• CO_2 ice blasting		×
• Ice water		×
• Freon substitutes		×
• Abrasives wet	×	×
• Abrasives dry		×
• Grinding/Planing		×
Combined mechanical/Chemical processes		
• Pastes + HP cleaning		×
• Foams/Gels/HP cleaning		×
• Vacuum cleaning (Dry/Wet)		×

× : decontamination technique applied for open or closed systems.

In [2], a list of processes has been identified as being of interest for the decontamination of metals (see Table 2.2). The processes are divided into chemical, electrochemical and physical processes. Moreover, a distinction has been made between the processes used in closed systems (e.g., full-system decontamination of the primary circuit of a reactor or the partial decontamination of closed loops), and the processes used in open tanks (e.g., decontamination of dismantled pieces).

Table 2.3 Processes for closed systems decontamination

Process name	General Description
LOMI	LOMI is an acronym for Low Oxidation State Metal Ion and was developed by the scientists at the erstwhile Central Electricity Generating Board (CEGB) in England in the late 1970s and early 1980s. The process incorporates vanadium (II) as a reducing agent and picolonic acid as the complexing or chelating agent. LOMI has been the most successful process for the removal of deposits where zinc and hydrogen water chemistry (HWC) has been employed during reactor operations. It is also the only process approved by the Electrical Power Research Institute (EPRI) and General Electric (GE) for use on GE designed reactor systems including the reactor pressure vessel and fuel.
LOMI-2	Similar to the properties outlined above for LOMI, but adjusted to be applied in a regenerative mode. The process, developed by EPRI in the late 1990s, reduces the secondary waste produced from decontamination.
CANDEREM	A regenerative process comprised of citric acid and EDTA was developed by the Atomic Energy of Canada (AECL) in the mid-1980s. The CANDEREM process was used for the full system chemical decontamination performed by PN services at Indiana Point 2 in the mid-1990s. The process is now approved by Westinghouse for full system decontaminations, with fuel in place for Westinghouse PWRs.
CITROX	A dilute regenerative process to be applied to both PWR and BWR reactor piping and system components developed in the 1980s. The CITROX process comprises citric acid and oxalid acid.
NITROX	A proprietary chemistry of PN services was developed in the mid-1990s for the chemical decontamination of reactor coolant pumps (RCPs). The cyclic process containing nitric acid, oxalic acid and potassium permanganate was modeled on the CITROX process and was developed to minimize secondary waste. The NITROX process was qualified by Westinghouse specifically for chemical decontamination of Westinghouse RCPs.
NITROX-E	Similar to the properties outlined above for the NITROX process but adjusted to destroy the chelating species during the process. The NITROX-E chemistry has been applied very successfully to both reactor coolant pumps and contaminated systems since its inception in the late 1990s.
REMCON	Is a family of chemical reactions employed by PN services for very specific customer applications.
AP and NP	Alkaline permanganate (AP) and Nitric acid permanganate (NP) are oxidation processes applied when radioactive deposits contain high levels of chromium. These processes were developed in the early 1980s and are used when the presence of chromium in the deposit renders the deposit insoluble by simple acidic dissolution. Remnant testing prior to chemical decontamination, or samples taken during the process, can determine when these substances need to be applied.
DfD	Decontamination for Decommissioning (DfD) was developed by EPRI primarily for the decontamination of reactor systems and components for unconditional release. The process was developed in the late 1990s and used by PN services for the full system decontamination for decommissioning at Big Rock Point in Michigan and at Maine Yankee.
CORD	The CORD process (Chemical Oxidizing Reducing Decontamination) developed by Siemens KWU is a three steps chemical process. It is applied in several cycles. Each cycle comprised the following steps: an oxidation step, using permanganic acid; a decontamination step using oxalic acid; a purification step by addition of permanganic acid or hydrogen peroxide.
EMMAC	Decontamination operations for following SG replacement were performed by Framatome-ANP in association with its affiliated company STMI using a dilute chemical process developed and patented by EdF (French Utility), called EMMAC. The same process is also used for the decontamination of chemical and volume control system heat exchangers. Today, this process is used at the SOMANU (Framatome-ANP subsidiary) hot repair and maintenance workshop at Maubeuge in France. This facility consisting of four 1m³ tanks and two parallelepiped tanks, 4.2 metres long, is used to decontaminate equipment and components for disassembly/assembly and machining operations. Approximately 10 primary cooling pumps per year, which arrive for repairs and may have an initial activity level of 100 GBq, are decontaminated by up to a factor of 50 using the EMMAC process.

2.3.1 Full system and closed system decontamination

The most important objectives for the decontamination of a whole or a closed system are:

- To reduce the dose rates around the concerned system;
- To minimize the radiation dose related to the primary operation;
- To concentrate the removed activity with the least amount of secondary waste;
- To use the installation and its loops by creating a minimum number of modifications.

Most of the used or known processes for full system decontamination are summarized in Table 2.3 with their principal characteristics [3], [4], [5].

Two large types of processes may be distinguished: the so-called ‘hard’ processes with a strong concentration of reagents and the ‘soft’ processes with low reagent concentrations. Hard processes are practically no longer used as they lead to the production of a higher volume of secondary wastes. A few are only cited: TURCO, MOPAC and CITROX.

2.3.2 Decontamination of subsystems, equipment, pieces after dismantling

The aim of these processes is to allow a decategorization (i.e., change of the waste category towards a lower category or class, which is cheaper to dispose of) of the waste and even a potential unconditional release, in order to allow a drastic reduction of the total volume of produced metallic waste.

Most of these processes are used in the form of a discontinuous process, working either in a bath with immersion of individual pieces in the bath or batchwise.

Table 2.2 gives an overview of the most common processes used nowadays for this purpose. Some of these will be analysed more in detail in the subsequent sections. They are classified following their working principle (i.e., chemical, electro-chemical, mechanical, etc).

2.3.3 Chemical processes

2.3.3.1 Processes in several steps

The layer of corrosion products forming the typical crud of PWR reactors is very insoluble and is characterized by a strong content of chromium oxides. These processes always use an oxidation step followed by a dissolving step of the oxides and a complexing of the dissolved metals. Many processes exist but the nature of the used reagents and/or the concentrations of the reagents differ.

Like for closed systems decontamination, two large types of processes may be considered: the so-called ‘hard’ processes with a strong concentration of reagents, and the ‘soft’ processes with low reagent concentrations. Hard processes are practically no longer used as they lead to the production of a higher volume of secondary wastes. Soft processes are used for the decontamination of loops, entirely or partially. The most frequently used processes are given in Table 2.4 with their most important characteristics.

These processes are mainly used for the decontamination aiming at a dose rate reduction. In general they are carried out in several steps. The CORD process, used for decontamination of the primary loop was also tested for the decontamination of dismantled pieces. When these processes are used in a bath on cut pieces, their efficiency can be improved by a combination of chemistry with ultrasounds.

In general, these processes are especially well adapted for decontamination in the framework of reactor operation, in view of reusing the equipment. As a result of their weak aggressivity, they do not have an influence on the integrity of complex systems (no problems with gaskets, seals, valves or critical parts).

On the contrary, however, for the decontamination of cut pieces in a bath with a view to their dismantling and thus their possible release as non-radioactive waste, it is recommended to use more aggressive methods attacking also the base metal, as this gives a better assurance regarding the final level of contamination reached. A supplementary drawback of these techniques in several steps is the fact that, in general, they demand the application of several decontamination cycles and, consecutively, more decontamination baths placed in series. The pieces are passing from one bath to another and then a new cycle is started until the expected residual levels are reached.

Table 2.4 Most frequently used processes

	CANDEREM/CANDECOM	LOMI	CORD
Oxydation	AP NP 95°C	AP NP 90°C	$HMnO_4$ 100°C
Reduction	$H_2C_2O_4$	$H_2C_2O_4$ HNO_3	$H_2C_2O_4$ 80-90°C
Decontamination	Oxalic acid Citric acid EDTA	LOMI reagent Vanadous picolinate formate	$H_2C_2O_4$
Purification	Ion exchange resins	Ion exchange resins	Ion exchange resins

AP = Alkaline permanganate
NP = Nitric acid potassium permanganate

2.3.3.2 Processes in one single step

This section comprises a synthesis of the chemical processes applied in one single step and using sufficiently aggressive reagents in order to reach the residual levels allowing the unconditional release of the treated pieces.

Process with Cerium4+

The Cerium4+ process uses the potential of raised oxidation of the Cerium4+ (+1.61 V/ENH) to assure at the same time the oxidation of the oxides present in the crud layer (chromium of valence 3 to valence 6 and the oxide of ferrous iron into ferric iron), as well as to oxidize and to put in solution a base metal layer of some microns. This double attack guarantees the complete decontamination of the piece as far as the reagents can reach all contaminated surfaces. The Cerium IV process was mainly developed at Studsvik in Sweden where the SODP process (Strong Ozone Decontamination Process) was defined, at JAERI and JPDR in Japan where the REDOX process was developed, and at SCK•CEN in Belgium where the MEDOC process was developed.

The SODP process

This process is a one step decontamination process in view of dismantling PWR type reactors. The process works at ambient temperature and is based on the use of a nitric acid environment with a pH of approximately 0.6. The oxidant used is Cerium4+ regenerated by the addition of ozone. The Cerium reduced to valence 3 is re-oxidized by ozone at valence 4. The process was used in Sweden to decontaminate heat exchangers and steam generators, and was tested in France on a steam generator of Dampierre.

The treatment of the solutions after decontamination consists of a reduction of the overrun Ce4+ to Ce3+ by using hydrogen peroxide followed by a precipitation of the hydroxides in a basic environment. Due to the working temperature of 20°C, this process is relatively slow. It is well adapted for the decontamination of dismantled steam generators from power reactors, for which the application of processes with higher temperatures may cause some problems.

The REDOX and SC (Sulfuric Acid Cerium) processes

These two processes, developed in Japan, are based on the same chemistry, i.e., the use of the oxidizing power of Cerium4 and a decontamination temperature of 60 to 80°C, thus accelerating the reaction compared to an application at ambient temperature as the SODP process. The two processes use an electrochemical regeneration of Cerium3 reduced by the reaction. The electrochemical reactor is separated from the decontamination reactor; the decontamination solution is continuously regenerated.

These processes have mainly been used for the in-bath decontamination of complex pieces.

After decontamination, the pieces are taken out of the decontamination bath and rinsed in an ultrasound bath. The decontamination solution is used till the concentration of dissolved salts exceeds approximately 10 kg/m^3. Indeed, the dissolution of salts reduces at one hand the electrochemical performance of the regeneration and, on the other hand, it has to stay beneath the solubility limit of the dissolved salts. Moreover, also the activity of the solution increases.

The MEDOC process

The SCK•CEN has improved the existing processes and has developed a process called MEDOC (MEtal Decontamination by Oxidation with Cerium). This process distinguishes itself essentially by the continuous regeneration of the solution at the same temperature as the decontamination temperature, and it is realized with ozone in a gas-fluid contactor.

The process combines the advantages of the two existing processes: an accelerated attack rate by working at an increased temperature and a simple regeneration technique using ozone.

The secondary waste volume is low. It is estimated at 11.5 l of bituminized waste per ton of treated material for 20 m^2/ton and 10 µm dissolved. This volume could be further reduced by recycling the sulfuric acid. It can be done for instance by electro-dialysis of the solutions.

The regeneration by electrochemical means was not chosen because it presents some disadvantages compared to the ozone process:

- Hydrogen production;
- Problems regarding the maintenance of the electrolyzer module;
- Long term resistance of the electrodes.

The process is used for the in-bath decontamination of stainless steel pieces.

The installation comprises mainly:

- A decontamination tank with a basket filled with pieces to be decontaminated;
- A buffer tank and a gas-fluid contactor for the ozone regeneration; the ozone is produced by an ozonizer supplied with oxygen;
- A rinsing tank with ultrasounds.

The results give decontamination factors larger than 10,000.

The MEDOC process has been used either in batch treatment for the decontamination of cutting pieces or in closed loop for the decontamination of large components like steam generators, pressurizers or various tanks.

The HNO3/HF process

The sulfonitric mixture is commonly used for the etching of stainless steel. In this case, it is applied either in a bath, by pulverization using a pressure jet, or by application of an etching paste. In the case of stainless steel covered with an oxide layer, the attack mechanism is a combination of an oxides reducing attack followed by dissolution of the metal underneath, thanks to the penetration of the liquid through the oxide layer.

By the attack of the base metal, the oxides come off and stay in the solution. The solution is thus progressively loaded with insoluble oxides in the form of particles, and with dissolved salts coming from the partial dissolution of the oxides and the transformation of the base metal into solution.

In bath process or solutions pulverization

This process has been tested for the thorough decontamination of dismantled metallic pieces. Table 2.5 gives the typical operational conditions mentioned in literature.

Table 2.5 Fluoronitric processes

Process parameters	ENEL (Italy)	CEA (France)	Belgoprocess (Belgium)	SCK•CEN (Belgium)
Temperature °C	40	25	40	
HF M	0,5 to 0.75	0,5	2.5	
HNO_3 M	0.4 to 0.8	2	4.5	
Duration h	4 to 6	2 to 8	1	
Temperature °C	80	85		60 - 95
HF M	0.15 to 0.25	0.05		0.25 - 0.5
HNO_3 M	0.4 to 0.8	2		0.5
Duration h	5	1		1 to 3

After treatment, the piece is rinsed with a pressure jet or in a rinsing bath with ultrasounds.

The speed and the efficiency of the reaction increase with temperature, the concentration of HF and the reaction time. The process is generally used at low temperature and with a strong concentration in pulverization on large pieces (i.e., inner surface of tanks etc.), and at higher temperature and lower concentration on pieces put in a bath.

The process allows complete decontamination of pieces even if strongly contaminated. The removal of an oxide layer and a metal thickness of 10 to 20 µm allows indeed removing the contamination completely. The specific activity may reduce from a value of 100 - 5000 Bq/g to less than 0.3 Bq/g of ^{60}Co. The global efficiency of the process is improved when, after treatment, the piece is rinsed in an ultrasound bath. Part of the oxides remains insoluble and can be eliminated by filtration.

The efficiency of the treatment decreases progressively with increasing concentration of dissolved salts in the solution. The aggressivity of the fluoric ions decreases by chelation of the fluoric ions to the dissolved metal. Therefore, new HF has to be added to the solution or the bath has to be renewed.

The treatment of the fluoronitric solutions is generally a neutralizing and chelating treatment of the remaining free fluorides. Table 2.6 gives an overview of the applied treatment methods.

The in-bath technique is not very advantageous. It needs the use of special construction materials (mainly plastic materials) and presents important problems regarding the safety of the workers. Moreover, the efficiency of the bath decreases rather quickly and leads to an important consumption of reagents.

On the contrary, the pulverization of a film on the walls of an equipment to be decontaminated can be very advantageous. The quantity of used reagents is very limited, the application at low temperature gives less security problems and the volume of produced effluents is smaller.

Table 2.6 Treatment techniques for the fluoronitric solutions

ENEL (Italy)	CEA (France)	Belgoprocess (Belgium)	SCK•CEN (Belgium)
Neutralization NaOH Precipitation of the hydroxides	Neutralization NaOH, $Ca(OH)_2$ $CaCL_2$, ferrocyanide Chelation of F Precipitation of the hydroxides	Chelation of F by $Al(NO_3)_3$ Neutralization by NaOH, $Ca(OH)_2$ Precipitation of the hydroxides	Same method as Belgoprocess Solution sent to Belgoprocess for conditioning
Cementation of filters and sludge	Cementation of filters and sludge	Incorporation in bitumen	

Process with etching paste

The same process can be used by applying an etching paste on the surface of the object to be treated. After a few hours, the paste is dry and can be removed mechanically. The treatment finishes by rinsing with a pressure water jet. This technique is mainly used for external surfaces or for places of local contamination. It has been tested with success on laboratory scale and could be applied, for instance, for the decontamination of pieces coming from dismantled equipment. This technique will allow to get the equipment out, or to carry out an etching-passivation after it has been used for a long time in pool water.

The DECOHA process

The DECOHA process is based on the use of fluoroboric acid.

The metals react as: $n\ HBF_4 + Me \Rightarrow Me(BF_4)n + n/2\ H_2$

The oxides react as: $n\ HBF_4 + \text{metal oxide} \Rightarrow Me(BF_4)n + H_2O$

The process is applied by pulverization of a solution at low temperature, or by immersion in a bath at higher temperature, up to approximately 90°C. The used solution can be regenerated electrochemically. The cations are then reduced at the cathode and deposited as metal:

$$Me(n+) + n\ e \Rightarrow Me(0)$$

At the anode, HBF_4-acid is reformed. The ^{60}Co co-precipitates with the metals at the anode. The regeneration does not allow a 100 % elimination of the cations; it is generally stopped when 98 % of the cations are deposited. ^{137}Cs is not deposited at the cathode and stays in the solution. In order to treat the remaining 2 % several techniques are possible:

- Precipitation of insoluble phosphates by addition of phosphoric acid;
- Precipitation of insoluble oxalates or insoluble silicates;
- Neutralization of the solutions with $Ca(OH)_2$ giving rise to the formation of insoluble CaF_2.

The concept of the DECOHA process was illustrated by applying it at industrial scale (5 t/day) for the treatment of contaminated metallic pieces from the Chernobyl nuclear power plant. The steps of the process are the following:

- Metallic pieces are placed in the tank.
- The non-fixed activity is removed by sprinkling with a volume of approximately 500 l of HBF_4 solution at 10 %.

- The tank is then filled with 15 m³ HBF_4 at 20 % and 90°C and the decontamination reaction starts; the reaction speed is about 0.2 or1 µm/h. The reaction lasts from 3 to 18 hours.
- The solution is drained and the pieces are rinsed with 500 l of cold water.
- The pieces are rinsed with 15 m³ of water; the rinsing water is regenerated by distillation.
- The regeneration is started when the concentration of dissolved metal reaches about 70 g/l. From this moment on, the work is done under stationary conditions; this means with a constant concentration of dissolved metals.

This decontamination process can be used for the decontamination of stainless steel (rate of 0.02 to 0.5 mg/cm².h), carbon steel (rate of 0.05 to 1000 mg/cm².h) and also for the decontamination of aluminium (rate of 6 mg/cm².h or 22 µm/h). Compared with other processes like the Cerium or the sulphonitric one, this process is less aggressive (lower rate). However, being less aggressive, it shows fewer security problems than HF. Regeneration by cathodic precipitation allows to recycle the HBF_4 and to deposit the major part of the cations at the cathode. The construction material recommended for this kind of product is essentially polypropylene. The liberation of hydrogen during the reaction requires the use of a ventilation and dilution of the gaseous effluents in order to stay beneath the lowest explosion limit of the H_2-air mixture.

2.3.4 Electrochemical processes

2.3.4.1 Electrolytic polishing

Electrolytic polishing is an anodic dissolution technique. The material to decontaminate is the anode, the cathode being either an electrode in stainless steel or copper (helping electrode) in an adapted form, or the decontamination tank itself. During decontamination, a controlled quantity of surface metal dissolves taking with it the contamination fixed in the surface layers. This technique is nowadays often used in fabrication, for surface treatment of pieces in stainless steel in order to obtain a very good finish by decreasing the roughness. This improves the resistance to corrosion and also allows better and easier future decontamination.

The process is also applied for decontamination either in order to reduce the dose rate (typical case of the water boxes of steam generators), or to decategorize pieces to be dismantled. If the technique is applied on pieces to be reused, surface finish is an important parameter to reduce the possibility of new contamination of the pieces. For pieces destined as scrap, surface finish is not as important as the efficiency of the decontamination and the volume of secondary wastes produced. The different used processes distinguish themselves by the used electrolyte and the operational conditions.

2.3.4.2 The phosphoric acid process

The representative parameter values for decontamination using phosphoric acid are:

- H_3PO_4 concentration: 40 to 80 % volume;
- Working temperature: 40 to 80°C;
- Potential difference: 8 to 12 Vdc;
- Current density: 60 to 500 mA/cm².

The process can be applied to carbon steel and stainless steel.

An application at industrial scale has been conducted at the KRB plant of Gundremmingen (BWR of 250 MWe). Several hundreds of tons of ferritic steel have been completely decontaminated by using this process. A thickness of 100 to 500 µm had to be removed in order to obtain a metal without any contamination.

The installation comprises two tanks of 3 m^3 and a rectifier of 6000 A maximum. The current used was approx. 2000 A corresponding to a current density of 100 to 400 mA/cm^2 following the geometry of the pieces. The time of the treatment was about 2 hours.

When the iron concentration in the solution exceeds 100 g/l, iron oxalate precipitates, carrying along a part of the ^{60}Co activity. In this way, a ^{60}Co enriched sludge is obtained compared to the solution.

The treatment of the phosphoric acid solution comprises the following steps:

- Precipitation of the ferrous oxalate by addition of oxalic acid with entrainment of the ^{60}Co activity (^{137}Cs is not being precipitated);
- Separation by sedimentation of the residual phosphoric acid; the diluted acid is re-concentrated by evaporation to be reused;
- The iron oxalate is destroyed by pyrolysis at 250°C in iron oxide that can be conditioned for final storage.

The treatment of 1 t (5 m^2/t) of metallic waste produces 32 kg of iron oxalate and finally, after pyrolysis, 15 kg of iron oxide.

The process is very efficient for ferritic steel but presents a certain complexity for the treatment of secondary effluents, in order to avoid the presence of oxalates in the conditioned waste. From a technical point-of-view and in the case of painted carbon steel, also a pre-treatment has to be considered in order to remove the paint layer. This pre-treatment could be chemical (NaOH) or mechanical. The process releases also H_2; so the gases have to be strongly diluted in order to avoid explosion risks.

2.3.4.3 The nitric acid process

This process was developed at Harwell and commercialized by AEA for the decontamination of stainless steel. Two systems were developed: on one hand, an immersion system for cut pieces and, on the other hand, a system with a small chamber for tele-operated decontamination. The latter one is particularly indicated for decontaminating hot spots in a high ambient dose rate and is not discussed in this document.

The recommended operating conditions for decontamination are the following ones:

- The use of $HN0_3$, 1M at ambient temperature;
- A low current density, from 2 to 3 mA/cm^2;
- The use of Ti electrodes to minimize the formation of H_2 and NO_x.

The process has a high penetrating capacity; the decontamination is still effective in a closed tube at a depth of 5 times the diameter. The distribution of the current is easy: the pieces are put in a titanium basket. In 2 hours a decontamination factor of 10,000 is obtained, corresponding with putting a thickness of 5 µm in the solution. AEA announces a waste production of 0.6 dm^3 for each m^2 treated. The chosen environment, $HN0_3$, is compatible with the waste treatment installations of AEA.

2.3.4.4 Anodic dissolution process in drum, in an HNO_3 environment

The CEA developed an anodic dissolution process in drum in an HNO_3 environment for the treatment of plutonium contaminated metallic waste. The waste in bulk is placed in a titanium perforated reactor, polarized in anode and put in motion. The stainless steel cathodes are put in parallel in the drum. Nitric acid is chosen for its compatibility with the treatment of the decontamination effluents and its reprocessing in case presence of PuO_2.

The experimental conditions for stainless steel pieces are:

- HNO_3 concentration of 2M;
- Current density of 10 to 30 mA/cm²;
- Duration of the treatment: 1 to 3 hours.

The erosion rate in these conditions is about 16 µm/h and the alpha waste could be de-categorized beneath the limit of 3.7 MBq/kg in order to authorize surface storage. This process is also applicable to unpainted ferritic steel; the erosion rate is then very high, about 500 µm/h. It is also applicable to aluminium alloy; the erosion rate amounts then up to 20 µm/h.

The process is easily applicable for pieces of small dimensions presenting no 'hidden' contaminated surfaces (internal sides of tubes, blind holes...). Putting into service of a process of such a capacity or larger gives raise to some technological problems.

2.3.4.5 The sulfuric acid process

This process was developed by Toshiba in Japan for the decontamination of stainless steel pieces in the framework of the dismantling of the Japanese reactors. The characteristics of the process are:

- H_2SO_4 concentration of 5 %;
- Temperature of 60°C;
- Current density of 300 to 1000 mA/cm².

At the beginning of the treatment, an erosion rate of 240 µm/h can be reached. When the dissolved salts concentration increases and the acidity decreases due to the consumption of H^+, the erosion speed decreases to 60 µm/h. The current efficiency reduces also with the concentration of dissolved ions, going from 40 to 20 %. The acidity has to be kept at a certain level, sufficient to maintain the rate and the efficiency to an optimal value.

Exploratory tests have been carried out on strongly contaminated pieces of the BR3 reactor in Belgium. They showed that it is indeed possible to reach a high erosion rate till about 50 mg/cm². In order to obtain a very low residual contamination level, a quite large quantity of the material has to be removed. The contamination present in the crud does not dissolve completely and an important fraction remains as crud particles which were removed from the surface by the underneath erosion of the metal. To accelerate this phenomenon, it is better to change regularly the polarity of the electrodes.

Compared to the Cerium process, a thicker layer has to be removed in order to obtain the same residual contamination level. The treatment of the solutions comprises the neutralization of the solution and the precipitation of the hydroxides. If ^{137}Cs is present, a treatment with ferrocyanide in combination with the precipitation of the hydroxides has to be applied.

2.3.4.6 The sodium sulfate process

Toshiba also developed a process based on the use of sodium sulfate as electrolyte and alternating the polarization of the electrodes. It is called the Alternative Electrolytic Decontamination with Sodium Sulfate (AEDSS) process. In anodic electrolysis, the metal is oxidized and dissolves, but oxides like ferric iron oxide remain intact. The attack of the metal situated underneath the oxide layer is only realized when the electrolyte penetrates through the film. With cathodic electrolysis, the oxide film at the surface is reduced, the ferric iron is reduced to ferrous iron and the base metal remains intact. A combination of the two techniques, this means a regular modification of the polarization of the electrodes, will accelerate significantly the global erosion rate.

The process is particularly interesting for pieces in ferritic steel covered by a thick layer of iron oxides. The operational conditions are:

- Na_2SO_4 concentration of 20 wt %;
- Voltage 20 V.

The iron in the solution precipitates in the form of iron hydroxides carrying along the ^{60}Co.

The current efficiency is relatively weak of the order of 6 % leading to a large energy consumption of about 4000 kWh/ton (200 kWh/m² for an erosion of 50 µm). On the contrary, however, following Toshiba, the secondary waste is very low, about 10 kg/ton waste in the same conditions.

2.3.4.7 The ELDECON process

This process, based on the use of sodium sulfate as electrolyte, is commercialized by ABB Atom (Sweden) for the decontamination of reactor pieces. The characteristics are:

- Na_2SO_4 concentration of 5 wt %;
- Current density from 100 to 600 mA/cm²;
- pH = 7;
- Potential difference of max 24 V;
- Duration of the treatment: from 15 minutes to one hour depending on the pieces; the erosion rate is approximately 60 µm/h at a current density of 400 mA/cm².

ABB is commercializing an installation with a bath of 1060 x 660 x 500 mm meant to accept a charge of 600 kg. The rectifier delivers maximum 1000 A at 24 V. During decontamination the dissolved iron precipitates in hydroxide form carrying with it the ^{60}Co activity.

2.3.5 Other chemical processes

2.3.5.1 Foam decontamination

Cleaning agents use foam such as produced by detergents and wetting agents as a carrier of chemical decontamination agents. They can be applied in a thin layer to a surface in any orientation, even to overhead surfaces. The foam decontamination method can effectively decontaminate metallic pieces and parts of complex components. By increasing dwell time, the foam better exploits the capability of the decontamination agent. Surfactants in the foaming agent enhance the effect by increasing contact with the surface.

The advantages of this process are that it is effective in large components with complex shapes. It is a good process for internal in-situ decontamination to eliminate smearable contamination before dismantlement, and it produces a low final waste volume. In addition, the process is readily applied using remote operation. It is a well-developed and widely used process. It can be operated by recirculation to improve its effectiveness, and it reduces operator exposure to and potential uptake of the acid.

The disadvantages are that it is difficult to obtain a good decontamination factor using a one-time application (batch process). It is difficult to recirculate when it is used to fill large cavities, and it is not appropriate for use on cracked surfaces or where there are deep or convoluted crevices.

The process is well developed and widely used in the nuclear industry. It has been developed at DOE sites (Savannah River-SRS) as a waste minimization tool. Previous experience with foam and gel decontaminants has shown a significant waste reduction of up to 70 %, which is higher than achieved with current decontamination methods. The process has been tested to decontaminate a series of large valves and heat exchangers with complex internal configurations. In this instance, results indicated that decontamination foams achieve better decontamination factors on stainless steel surfaces than on carbon steel or painted concrete.

When using the technique with a closed system for preparing the foam, extreme caution should be taken. The closed system is pressurized to force a mixture of organic foam makers and decontaminating agent through a chamber where air is added to prepare the foam and to shoot the foam through the nozzle. One of this hazards occurred at SRS when a large amount of organic foam maker was added. This resulted in a chemical reaction between the chemical foam maker and the nitric acid (i.e., decontamination agent) that had a constantly accelerating reaction rate. The volume of gas that was produced was more than the pressure relief set point. The system was over-pressurized and ruptured. It is worth noting that the equipment was not supplied with a pressure-relief valve and that one was added by the plant before equipment installation and operation.

2.3.5.2 Chemical gels

Chemical gels are used as a carrier of chemical decontamination agents. Gels are sprayed onto a component, allowed to work, and then scrubbed, wiped, rinsed or peeled off. An airless compressor can be used for spraying the gel, and with a change in heads, for rinsing. Typical reagent combinations are a nitric-hydrofluoridric-oxalic acid mixture and a non-ionic detergent mixed with a carboxy-methy-cellulose gelling agent, with aluminium nitrate used as a fluoride chelating agent. Steps include scraping and vacuuming solid waste material, using a hot water rinse as pre-treatment, and gel spraying throughout the cell.

The advantages of this process are that it is effective for removing smearable contamination from large components in-situ. It generates small volumes of secondary wastes. It can be readily applied using remote applications and it can achieve decontamination factors as high as 100. The disadvantages are that it is a chemical complex that generally requires at least two applications and rinsing, and it requires further treatment before the optimum compound composition and operating conditions are fit to site specific needs.

Chemical gels have been used to decontaminate cooling carbon dioxide pipes and pipes of ordinary ferritic steel. The following procedure has been used:

- Soda gel spraying (3 M NaOH);
- 30 minutes contact time;
- Rinsing;
- Acid gel spraying (3 M H3PO4, 3 M H2SO4, and 16% silica); and
- Rinsing for 30 - 60 minutes.

The results indicated that gel spraying is an effective process for beta gamma emitters on ferritic iron steel pipes with simple geometry. It generated a low volume of secondary wastes. The waste generated from the chemical gel can be collected, neutralized and treated using precipitation.

2.3.5.3 Decontamination in molten salt reactors

A new method developed in Brazil for the decontamination of dismantled segments from the decommissioning of nuclear fuel cycle facilities is reported in [6]. It is based on burning of organic liquid waste containing uranium and plutonium in a molten salt (sodium carbonate) reactor at temperatures up to 900^{o}C. The technique proved to be effective for thin wall parts like small diameter tubes or painted construction parts.

The treatment of radioactive wastes in the form of painted structures made of perforated carbon steel, and presenting superficial contamination were investigated. The superficial radioactive contamination is located mainly in the corroded regions and mixed with rust.

This contamination is frequently difficult to remove due to the layers of paint applied on the contaminated area. The paint over the contamination impedes the action of the usual acid or alkaline pickling methods. The process selected for paint stripping was the immersion of pieces in molten salt mixtures at different temperatures and different residence times.

Molten salt stripping uses simple and straightforward processing steps. The items to be stripped can be loaded into baskets or supported on hooks. The process allows rapid and complete paint removal with a minimum of handling. The method can be applied for parts with complex shapes. The internal superficial contamination of tubes, which are not reached by blasting or abrasive methods, can be successfully treated by immersion in molten salts.

2.3.5.4 Decontamination by pastes

Pastes are widely used for treating metal surfaces, particularly stainless steel [7]. They consist of a filler, a carrier, and an acid or a mixture of acids as the active agent. A variation on this method is widely used in the Commonwealth of Independent States. It involves the inclusion of an abrasive within the paste. Mechanical action with the abrasive assists in breaking down surface films, increasing the effectiveness of the chemical reagents.

2.3.5.5 Decontamination by chemical fog

Decontamination by chemical fog has being developed under EC sponsorship and the technique uses a chemical agent dispersed as a fog [7]. It was used in a laboratory at the KRB plant in Gundremmingen, Germany, where an experimental set-up for the ultrasonic generation and electrostatic deposition of the chemical on a target was constructed and tested.

Water and/or acidic fogs are used in the Russian Federation for the decontamination of equipment removed from liquid metal cooled reactors. Verification tests on spray methods for large component decontamination techniques are being conducted in Japan.

2.3.5.6 Gas phase decontamination

Gas phase decontamination is a long term, low temperature technique which uses a mixture of treatment gases which are injected into a cell containing diffusion cascade equipment at low pressure and are allowed to react with uranium deposits [7].

2.3.5.7 Other (proprietary) technologies

Some examples of other (proprietary) technologies are [7]:

- The CORPEXTM chemical process, a non-destructive cleaning method that only removes the contaminant and a matrix that fixes the contaminant to the surface;
- TechXtractTM, which is based on the application of a mixture of chemical agents to decontaminate porous surfaces such as concrete and metals such as lead;
- The multiphase treatment process CANDECON (Canada);
- The EMMA process (France);
- The metal decontamination process DECOFOR based on formic acid;
- The DECOPAINT process based on alkalis;
- The concrete decontamination process DECONCRETE, based on phosphoric acid.

It should be noted that other proprietary technologies may exist and their omission here does not reflect adversely on the capabilities of any of these processes.

2.3.6 Physical processes

Besides chemical and electrochemical processes used for thorough decontamination, physical processes are available that are often a bit simpler to use, but are generally less aggressive than their (electro-) chemical counterparts. Physical processes, as their name indicates, use a physical mean to remove a contamination layer from the base material.

2.3.6.1 Cleaning in an ultrasound bath

Cleaning in an ultrasound bath is a classical technique for the decontamination of pieces presenting an unstable not strongly fixed contamination. It is generally used with addition of a detergent (like e.g., DECON90). The energy losses in the bath increase the bath temperature in a natural way, thus favouring the decontamination effect.

The technique is only applicable for slightly fixed contamination.

For pieces strongly contaminated like stainless steel pieces having stayed for a long time in storage pools, this technique does not allow to remove the contamination fixed on the piece. The decontamination factors are smaller than 2.

Cleaning in an ultrasound bath is very often used for the rinsing of pieces that underwent a chemical decontamination in order to eliminate completely the liquid film as well as the liquid micro-droplets fixed at the surface of the material. This treatment is even more important as the roughness after chemical treatment is high.

Ultrasounds can also be used immediately in combination with a chemical treatment process. Generally, in this case a synergy is observed between the effect of the ultrasounds and the chemical effect. This synergy increases the efficiency of the reaction and allows shortening the treatment time. Moreover, the mechanical effect allows to loosen crud particles and thus to liberate the attack surfaces.

2.3.6.2 Blasting of CO_2 ice

This decontamination process uses the principle of projecting CO_2 ice pellets at high speed against the surface to decontaminate. The pellets are accelerated in an injector by means of compressed air at 18 bar and with a rate of about 21.5 m^3/min. The contamination is pulled out of the surface and carried away by the excess of air. The CO_2 pellets evaporate and the removed contamination is settled, or taken away by the air filtration system. Finally, the contamination will be located on the floor of the enclosure and/or in the filters.

The ventilation of the enclosure has to be sufficiently high in order to avoid accumulation of CO_2 and to eliminate air contamination. The operators are working in ventilated suits. The noise level can be from 75 dB to 125 dB. Different results are reported, and it is strongly recommended to make some decontamination tests before selecting this process for a particular operation.

2.3.6.3 Ice blasting

This technique is completely similar to CO_2 ice blasting. Ice crystals are projected by means of compressed air against the surface to be treated. The water, formed by melting of the ice, takes the removed contamination away; the contamination is then in suspension or dissolved.

Putting into service this technique is somewhat easier than the CO_2 blasting technique. The contamination is trapped in the water and requires a system to treat liquid effluents. The efficiency is comparable to the efficiency of CO_2 ice blasting. The process is insufficiently aggressive to carry out a thorough decontamination of fixed contamination.

2.3.6.4 Blasting of other materials

Other blasting decontamination techniques include [7]:

- *Sponge blasting*. Sponges made of water based urethane, when blasted onto a surface, create a scrubbing effect by expanding and contracting. An 'aggressive' grade of sponge, impregnated with abrasives, can be used to erode material such as paints, protective coatings and rust.
- *High pressure liquid nitrogen blasting*. This technique is a variation of grit blasting whereby abrasive is injected into a liquid nitrogen jet, the jet propelling the grit onto the surface to be decontaminated. The contamination is removed by the embrittlement induced by the liquid nitrogen and the abrasive action of the grit.
- *Freon jetting*. Decontamination by freon jetting is effected by directing a high pressure jet of a freon cleaning solvent onto the surface to be cleaned. It is usually used on discrete components inside a glovebox, but experimental units have been developed for in-situ cleaning. However, regulatory restrictions on the use of freon limit the application of this technique.

2.3.6.5 Pressurized water jet

Water/vapour jet decontamination uses the kinetic energy of water flow for the removal of contamination, and high temperature for the acceleration of chemical reactions between decontamination solutions and contaminated surface. The joint action of the kinetic energy of the jet and the high temperature is more effective than solutions of chemicals or detergents. Amounts of secondary radioactive waste considerably decrease. The temperature of the jet stream at 200 mm from the nozzle is 50 - 100^{o}C.

Low pressure water jet - 50 to 150 bar

This technique is frequently used as a pre-decontamination technique for pieces strongly contaminated. It is used for cleaning pool walls, for pieces or tools having stayed a long time in the pool, and for the decontamination of dismantled pieces.

More particularly, the technique allows to reduce the dose rate of dismantled activated pieces beneath the limit of 2 mSv/h by removing an unstable residual layer of crud.

This technique is regularly used to decontaminate dismantling tools that are contaminated, for instance with activated metal swarfs or with crud deposition.

Medium pressure water jet - 150 to 700 bar

This technique allows the decontamination of surfaces presenting a cold fixed contamination. The water flow rate is from 60 to 6000 l/h depending on the apparatus. Additives can be added and can be used with warm water up to a temperature of 60°C. The efficiency increases with the working pressure. The water consumption can vary from 10 to 600 l/m^2. The work output for a large surface, for instance pool walls, is approximately 10 to 20 m^2/h. This technique is usually used in nuclear plants for the decontamination of equipment in order to reduce the dose rate and the transferable contamination. In some cases, it allows thorough decontamination.

Drawbacks of this technique are the formation of contaminated aerosols and the large water consumption. This technique can, however, be considered if working with recirculation after filtration, or in an open loop in case it is used for specific decontamination operations like for instance removing contaminated equipment out of the dismantling pool.

High pressure water jet > 700 bar

This technique is identical to the one used for cutting metals. Water is pressurized at a pressure able to reach 3000 to 4000 bar. The water at the outlet of the injector reaches a speed of about 900 m/s. The efficiency can be increased by adding abrasives.

The water rate is about 120 to 240 l/h. The power of the compressor is about 20 to 40 kW. The investment for such a technique is rather high. Moreover, when using abrasives, the consumption of those is considerable as this system is not foreseen to recycle the abrasives.

The technique allows a thorough decontamination as it is possible to remove a layer of the surface material. The formation of liquid aerosols is relatively important as a result of the very high speed of the ejected water.

Hydro-jet with chemicals

A hydro-jet with chemicals is applied for the removal of heavy contamination with deep penetration of radio-nuclides into the stainless steel or alloys [6]. A hydro-jet with abrasives is very effective for the decontamination of external surfaces of buildings and constructions with deep penetration of contaminants into concrete or other constructions. Hot alkali solutions of surfactants are useful for the removal of grease that traps contamination. There is a variety of steam mixtures for jetting. The choice depends on many factors, especially if there is a need for minimal corrosion of structural materials. The main advantage is reducing secondary liquid radioactive wastes; the main disadvantage of the water/vapour jet decontamination method is the intensive formation of radioactive aerosols.

2.3.6.6 Decontamination with abrasives

This technique uses the power of the abrasives of different types projected at high speed against the surface to be treated.

Imperative for this technique is to assure the recycling of the abrasives in order to limit the secondary waste production. So, dry or wet abrasive blasting units without recycling are a priori excluded.

Two techniques seem to be more appropriate: decontamination by wet abrasive blasting with recycling of the abrasives, and decontamination by dry abrasive blasting with recycling of the abrasives.

Abrasives in a wet environment

In this case, the fluid transporter is water and compressed air under pressure. The installation for decontamination by wet abrasive blasting comprises:

- A ventilated working enclosure connected to the general ventilation system through HEPA filters;
- A system to collect the mixture water-abrasives-contamination;
- An abrasive blasting pistol with water jet/compressed air and addition of abrasives;
- A recycling unit for abrasives with a circulation pump;
- A filtration unit for the fine abrasives and removed contaminants;
- A preconditioning unit for the filtration sludge.

Such systems are in use in various decommissioning projects and showed good results for large contaminated pieces, painted metals and localized (but reachable) contamination patches.

Dry abrasives

In the case of dry abrasive blasting the fluid transporter is compressed air. An installation for dry abrasive blasting comprises:

- A working enclosure put under depression and filtration by pre-filters, type filter bags, and connected to the general ventilation system through HEPA filters;
- Abrasive blasting pistols or injectors with compressed air;
- A system to collect the abrasives and the contaminants;
- A system to separate the abrasives and the contaminants; generally it is a cyclone system. The abrasives are collected in the cyclone and recycled. The contaminants and the fine abrasive particles are evacuated to the filtration system where they are collected and filtered.

Such systems are also in use in different decommissioning project with relative good results. The automated system used at Belgoprocess (Belgium) can be mentioned where the metallic pieces are automatically loaded, decontaminated and unloaded, while the abrasives are recycled.

Comparison of the wet and dry abrasive blasting techniques

For the two techniques, it is important to choose an abrasive with a long lifetime and a high decontamination power. The following abrasives have a decreasing hardness:

- Shot of stainless steel;
- Ceramic micro-balls or angular ceramics;
- Angular garnet;
- Glass micro-balls.

The purchase price of the abrasives follows the same order. In spite of the higher price of the abrasives, it is important to choose an abrasive that deteriorates very slowly as this will reduce the secondary waste production. More generally and depending on the application, a variety of materials may be used as abrasive media:

- minerals (e.g., magnetite or sand);
- Steel pellets, aluminium oxide;
- Glass beads/glass frit, silicon carbide, ceramics;
- Plastic pellets;
- Natural products (e.g., rice hulls or ground nut shells).

Silica has also been used as an abrasive; however, its use is not recommended since it is moderately toxic as a highly irritating dust and is the chief cause of pulmonary disease. Prolonged inhalation of dusts containing free silica may result in the development of a disabling pulmonary fibrosis known as silicosis.

The two techniques (wet and dry abrasive blasting) allow recycling of the abrasives by separating the abrasives from the contamination. For wet abrasive blasting, the contamination is trapped on filters. For dry abrasive blasting, the contamination is filtered on declogging filters and collected in a drum.

The two techniques have to be used in a ventilated enclosure. However, air contamination is much more important using dry abrasive blasting than when using wet abrasive blasting. The risk to contaminate the walls of the enclosure is greater, and cross contamination can be provoked when changing from strongly contaminated pieces to slightly contaminated pieces. The system can be automated.

2.3.6.7 Vibration abrasive techniques

Vibratory finishing can be used to decontaminate pieces which are able to be removed from the system [8]. However, the maximum size is limited by the size of the machine. Large components can be cut into smaller pieces for processing. Vibratory finishing has proven to be effective for simultaneously decontaminating metal, hard and soft plastics and rubber pieces. Usually vibratory decontamination is carried out by immersion of the item in a basket containing small pieces of metal or ceramic. When the basket is vibrated, the small pieces rub against the surface to be cleaned and act as an abrasive, rubbing away the material which adheres to the surface of the item. Generally a liquid flows through the scrubbing medium and flushes away the material removed by the rubbing action.

Vibration abrasive techniques for decontamination were developed and tested in Argentina [6]. Abrasion processes in vibratory tumblers are widely used in the manufacture of metals, ceramics, and plastics to smooth, clean, and polish the materials. The system is based on a mechanical action. Samples to be treated, solid abrasive media and liquid media are set up into a metallic vessel. This vessel is mounted on springs and lined with a suitable polymeric material. A special heavy duty vibratory motor provided with adjustable counterweights is attached to the vessel. Vibration is transmitted from the motor to the vessel putting the entire load in motion at the same time so that the abrasive media acts against the parts throughout the complete mass.

Before working with contaminated material, cold tests were performed with different materials. Contamination was simulated by controlled oxidation at high temperatures. Samples of carbon steel, stainless steel, titanium, Zircaloy-4 and aluminium were used. Hot tests were performed with three aluminium tubes and one sample of stainless steel bar. Decontamination factors up to 15 were achieved on inner surfaces of dismantled segments with complex shapes.

2.3.6.8 Flushing with water

As a decontaminant, water acts by dissolving chemical species or by eroding and flushing loose debris from the surface [7]. Flushing with water, which can be used for areas that are too large for wiping or scrubbing, involves flooding a surface with hot or cold water, followed by water collection.

2.3.6.9 Dusting/vacuuming/wiping/scrubbing

Dusting, vacuuming, wiping and scrubbing involve the physical removal of dust, aerosols and particles from building and equipment surfaces using common cleaning techniques [7]. Suction cleaning is most useful as a pre-treatment for removing large quantities of loose contaminants. For example, the concrete hot cells at Risø in Denmark were remotely vacuumed before further decontamination took place. Specially designed vacuum cleaners incorporating air filtration systems are widely used at the Chernobyl nuclear power plant. A dustless decontamination system, followed by a manually controlled scabbler and a manually controlled needle gun, were used to remove contamination from concrete surfaces at Rocky Flats environmental technology site in the USA.

2.3.6.10 Strippable coatings

The strippable coating technique consists of a two stage process, (1) the application of a polymer and decontaminant mixture to a contaminated surface, and (2) the removal of the stabilized polymer layer after setting [7]. It is applicable to a wide range of contaminants and materials, with the best results achieved on large non-porous surfaces that are easily accessible.

Decontamination by strippable coatings consists of the application of a coating over the surface to be decontaminated [8]. This coating is then left on the surface for a set period (from a few hours to a few days) and then removed/stripped resulting in the removal of the contamination. Strippable coating formulations usually consist of high molecular weight, film forming, synthetic polymers such as polyethylene, polyvinylacetate, polyvinylchloride, acrylics, etc., dispersed as an emulsion in an aqueous base. These coatings usually contain an active agent, e.g., an acid or mixture of acids, which attack the contaminants on the surface to which the coatings are applied.

The coatings may be applied with a brush, spray system, roller or other similar method. In some cases, it may be necessary to apply two or more coats to ensure that the coating has sufficient strength to be readily removed from the surface without tearing. The coatings are applied in varying thicknesses from 0.5 to 2 mm. Usually, the coating is then manually stripped off the surface in sheets, compacted and placed in waste containers. The strippable decontamination technique generates no liquid wastes because no rinsing or washing procedures are used. The wastes are contained within the stripped coating and this simplifies its handling. The stripped film can be disposed of in standard dry waste storage containers.

The effectiveness of strippable coatings has been demonstrated in the decontamination of a variety of surfaces and components. In particular, strippable coatings can be very effective for the removal of fine layers of the contaminated surface. Decontamination factors obtained with this method are quite good, usually in the range of 20 to 50, but under the same conditions can be as high as 1000. The procedure can be repeated if necessary to obtain a complete decontamination.

2.3.6.11 Steam cleaning

Steam cleaning combines the solvent action of hot water with the kinetic energy effect of blasting. It is recommended for removing contamination from complex shapes and large surfaces, even if grease or similar substances are present, and for removing contaminated soil particles from earth moving and drilling equipment. Secondary waste volumes produced by the process are relatively low as the steam can be collected by vacuum extraction, or similar means, and condensed. Decontamination by superheated steam has been successfully applied to Russian KT-50 transport casks.

2.3.6.12 Decontamination by grinding, polishing, brushing

These techniques are mostly used for the decontamination of building surfaces (see Section 2.3.8) and are also applicable for the decontamination of metal surfaces. Generally, the same device can be used for different functions and for different types of surfaces. A large range of abrasive belts or rollers are available. Due to the production of dust, this type of decontamination has to be carried out in a ventilated enclosure, and the operator has to wear protection clothing (mask or ventilated suit).

2.3.7 Techniques based on the use of the melting of metals

The melting technique can also be considered to be a decontamination technique. Indeed, certain elements are found in fumes and dust (i.e., ^{137}Cs), others in slag and are eliminated as waste (i.e., heavy weight elements that form oxides like uranium and plutonium). Elements like ^{60}Co or ^{63}Ni follow the metal in the ingots.

The melting of metallic waste can be considered for:

- The recycling by melting of metallic materials with reuse of the recycled materials in the nuclear field, for instance containers for radioactive waste.
- To allow by melting a precise radiological estimation of the residual activity of the decontaminated pieces and also to allow their clearance.

Table 2.7 gives a summary of the most important melting facilities in Europe and in the U.S., with their principal characteristics [2]. Two other melting facilities exist, but only little information could be obtained: the Capenhurst Melting Facility, United Kingdom (start 1994), and the Manufacturing Sciences Corporation (MSC) facility in Oak Ridge, USA (start 1996).

Melting tests at the Korean Atomic Energy Research Institute [6] for aluminium showed that 40 – 70 % of ^{60}Co and up to 99 % of ^{137}Cs can be removed from the ingot phase. As for stainless and carbon steel, most of the ^{60}Co remained in the ingot phase.

^{137}Cs was completely eliminated and distributed to the dust phase. The portion remaining in the slag phase depended considerably on the slag basicity.

Table 2.7 Characteristics of operating melting facilities

Facility	Furnace type	Types of metal treated	Charge size	Products	Radiological limitations
STUDSVIK Sweden	Induction for steel, small electric arc for aluminium	Carbon steel, stainless steel, aluminium	3 t	Ingots for direct clearance or after a decay period of 20 years	Max. 15 Bq/g for Co-60.
CARLA Siempelkamp Germany	Induction	Carbon steel, stainless steel, aluminium, copper, lead (R&D)	3.2 t	Ingots, shield blocks, waste containers	Max. 200 Bq/g for beta-gamma nuclides. Max 100 Bq/g for alpha nuclides, separate limits for uranium
CENTRACO France	Induction	Carbon steel, stainless steel, aluminium	3 t	Ingots, shield blocks, waste containers	Max. 20 000 Bq/g for beta-gamma nuclides. Max 50 Bq/g for alpha nuclides, separate limits for uranium
SEG Duratek USA	Induction	Carbon steel, stainless steel, aluminium, (planning to melt copper and titianium)	20 t	Ingots and shield blocks, waste containers and reinforcing steel	Normally <2mSv/h, greater dose rates with prior review and approval

2.3.8 Selection of decontamination techniques for metals

To summarize the topic of decontamination of metal components, a range of decontamination techniques can be used with a view:

- To reduce the dose rate of equipment to be dismantled or dismantling tools;
- To de-categorize, this means to change the category of radioactive waste;
- To reach residual contamination levels enabling to send the metal material to a nuclear foundry for recycling of the material in the nuclear industry or for unconditional release after fusion;
- To reach residual contamination levels authorizing immediate unconditional release.

Table 2.8 gives a simplified overview of the techniques and their field of application. Several possibilities may exist for each piece. The criteria used to choose a technique are mainly:

- The geometry and size of the pieces;
- The nature and the level of the contamination;
- The state of the surface and the type of material;
- The availability of the process;
- The treatment of the secondary wastes.

The aim should be to minimize the decontamination costs by choosing the best adapted technique. The goal is to carry out the decontamination in one single step.

Table 2.8 Choice of a decontamination technique

Treatment	Contamination	Geometry	Material	State of the surface	Example pieces
Polishing, grinding	External	Simple surface, rough, rusted	CS; SS	Painted/non-painted	Covers, flanges
Manual cleaning	External	Simple to complex	CS; SS	Painted/non-painted	Beams, plates, cable runs, electrical cables, pneumatic part of valves
High pressure jet	External	Simple to complex	CS; SS	Painted/non-painted	Tanks, radiators
Wet abrasive blasting	External	Simple, large pieces	CS; SS	Painted/non-painted	Beams, plates, tanks (after cutting)
Dry abrasive blasting	External	Simple, small pieces	CS; SS	Painted/non-painted	Beams, plates, cable runs
Chemical decontamination	Internal	Simple to complex	CS; SS	Non-painted	Tubes, valves, bends, tanks (after cutting)

Note: CS = carbon steel, mild steel
SS = stainless steel

2.4 Decontamination of buildings and concrete

For the decontamination of buildings in general and of surfaces susceptible to be contaminated in particular, a first technique that can be used is the washing technique. This technique is very efficient for painted and slightly contaminated surfaces. Washing can be done manually for small surfaces, or by using an industrial washing machine. For strongly contaminated surfaces and in particular for floors of which the coating is damaged, this technique is not aggressive enough. The contaminated layer has to be removed.

Simple processes, such as brushing, washing and scrubbing, and vacuum cleaning have been widely used, since the need for decontamination/cleaning was first noted in the nuclear industry, and each nuclear facility has to some extent a certain practical experience of these kind of decontamination processes. These processes are generally labour-intensive, but they have the advantage of being versatile. They are often used as a first step (e.g., to vacuum dust and remove loose contamination) before or during dismantling, to prepare items for more aggressive decontamination using stronger processes.

Other, more aggressive techniques are grinding, spalling and drilling, high-pressure water jetting, foam decontamination, the use of strippable coatings, high-frequency microwaves, laser and induction heating. The use of most of these techniques is limited to specific applications in specific cases. Some of these have disadvantages such as spreading of contamination, or produce a lot of undesirable secondary waste. Some of these are also less suitable for industrial applications.

When decontaminating concrete surfaces, mainly mechanical scarifying techniques such as needle scaling, scabbling, or shaving are used, although other ‘innovative’ techniques are currently under development, like the laser ablation technique, micro-explosive decontamination, abrasive blasting, …. Nevertheless, these techniques are either not yet completely industrialized or do not comply with all the requirements of a nuclear decontamination, and some of their parameters are still under analysis or under development. Therefore, this section will concentrate on the three major techniques, mostly used in various decommissioning projects worldwide:

- Scabbling;
- Milling/Shaving;
- Rock breaker/Jackhammer.

2.4.1 Decontamination by scabbling

Scabbling is a pure mechanical process. The upper layer of a concrete surface is pulverized by means of tungsten carbide heads that are moving up and down at high speed or rotating. The pulverized concrete is sucked by a filtration unit and collected in suitable packaging. The equipment available on the market is characterized by the number of heads, varying from 1 to 7. For places difficult to reach, angle scabbling systems can be used.

Both electrically and pneumatically-driven machines are available.

The technique is a dry decontamination method - no water, chemicals or abrasives are required. The waste stream produced is limited to the removed debris. Work rates are not easy to predict due to the variety of concrete composition and characteristics as well as to the different types of bits that may be used. Scabblers are best suited for removing thin layers (up to 15 or 25 mm thick) of contaminated concrete (including concrete blocks) and cement. It is recommended for instances where:

- airborne contamination should be limited or avoided;
- the concrete surface is to be reused after decontamination;
- waste minimization is envisaged;
- the demolished material is to be cleaned before disposal.

The scabbled surface is generally flat, although coarsely finished, depending on the bit used. This technique is suitable for both large open areas and small areas.

2.4.2 Decontamination by milling/shaving

Milling is also a pure mechanical process. It concerns a tool composed of a series of diamond disks placed one next to the other, the rotation of these disks in contact with a concrete surface provoking erosion of the concrete up to a depth of a few millimetres. This machine is similar to a normal floor scabbling unit. It has a quick-change diamond-tipped rotary cutting head designed to give smooth-surface finish, easier to measure and ready for painting. It is capable of cutting through bolts and metal objects, which would have damaged the scabbling head of a traditional scabbler.

Based on the positive experience with the floor shaver a remote-controlled diamond wall-shaving system has been developed as a solution for concrete decontamination of larger surfaces [2]. The machine consists of:

- a remote-controlled hydro-electric power pack for the remote-controlled shaving unit;
- vacuum systems to fix temporarily vacuum pads holding the horizontal and vertical rails of the shaving unit;
- a simple xy-frame system containing a guide rail, a vertical rail and a carriage for the shaving head;
- a quick-change diamond-tipped rotary shaving head with dust-control cover for connection to existing dust-extraction systems.

The entire system is built up in sections which are portable by one operator. It removes a concrete layer in a controlled and vibration-free manner with the removal depth being controllable between 1 and 15 mm per pass, and producing a smooth-surface finish. The cutting head is designed to follow the contours of the surface being removed, and depth adjustments may be set manually in increments of 1 mm to minimize waste production. With 300 and 150 mm wide shaving heads, both large areas and awkward corners may be accessed. When the vertical rail is fitted to the wall with the cutting head shaving, the horizontal rail may be disconnected and moved forward, thus ensuring continuous operation.

Production rates vary depending on the structure and the hardness of the concrete, the depth setting, the cutting speed and the type of diamond used. Heads can be used for shaving up to 2 000 m².

2.4.3 Decontamination with a rock breaker or hydraulic/pneumatic hammering

In nuclear facilities, floors are generally more deeply contaminated than walls and ceilings. Contamination depths up to a few tens of centimetres are commonly reported. For such contamination depths, the scabbling and milling techniques are often too slow and labour intensive. Therefore, using machines like a rock breaker or a jack hammer, forerunner of a chisel, may be considered to decontaminate floors and potentially walls when contamination (or activation) reaches an important depth.

Cutting and decontamination of concrete structures may be carried out with hydraulic or pneumatic hammers, either hands-on or using an electrically-powered, hydraulically-controlled support arm. The latter may be equipped with a hydraulic hammer, an excavator bracket, or other tools, and is well suited for decontaminating floors and walls. A mini electro-hydraulic hammering unit (weighting only 350 kg) is commonly used in areas where contamination has penetrated deeply into the concrete surface, increasing the decontamination possibilities and reducing significantly the workload for the operators.

2.4.4 Comparison of the various techniques and production rates

In order to compare the various techniques presented, the production rate can be used as an indicator. Nevertheless, like for the selection of decontamination processes for metals, other elements can influence the choice of a technique. Table 2.9 gives some typical work rates obtained with the different kinds of scarifying techniques mentioned above [4].

Table 2.9 Typical work rates obtained with different kinds of scarifying techniques

Scarifying technique	Layer thickness removed (mm)	Removal speed (m²/h) (machine working time)
Needle scaler	2	0.1
Hand scabbler (1 head)	2	0.6
Floor scabbler (7 heads)	3	4.6
Wall scabbler (3 heads)	3	4.6
Wall scabbler (7 heads)	4	8.4
Floor shaver	1.5	13.6
Wall shaver	1.5	21

When selecting an appropriate decontamination technique for building surfaces, some general considerations should be taken into account. In any case, the use of techniques that would make contamination penetrate further into the substrate should be avoided. In addition, as general rules:

- For decontaminating painted floors and walls, where it may be proved that contamination has not penetrated into the substrate, simple processes as brushing, washing, scrubbing and vacuum cleaning may be used.
- For decontaminating concrete surfaces which are not painted and in which the contamination has slightly or more deeply penetrated into the substrate, more aggressive techniques (e.g., scabbling, shaving, jack hammering or drilling) must be considered.

One could also be surprised not to find abrasive blasting or water jetting as primary techniques to be used. This is intentional, as it has been frequently reported that these techniques, although sometimes efficient, present the risk of enforcing the penetration of contamination into the concrete, and spreading the contamination along the surface.

2.5 Soil decontamination techniques

The soil is a structure that is stratified. The upper layer is the unsaturated zone (or infiltrating zone), below which there is the saturated zone. There are many characteristics of soil that influence the transport of contaminants, such as: density, porosity, humidity and permeability. This phenomenon is also influenced by some properties of the contaminants, such as vapour pressure and chemical nature. After identifying the type of soil and the nature of the contaminants, a suitable remediation technique must be chosen, and the effectiveness of the decontamination process evaluated. The existing methods for soil decontamination may be divided in 'in-situ' techniques, 'ex-situ' techniques, and the confining/isolation of the contaminated area, which is a temporary solution. These methods can be further divided in biological and non-biological methods. Non-biological methods may be subdivided in physical-chemical methods, thermal methods and others methods (e.g., supercritical extraction and electro-kinetic). In Tables 2.10 and 2.11 some of the existing decontamination techniques are summarized, including some of their advantages and disadvantages.

Table 2.10 Biological technologies used in soil remediation

Technique	Advantages	Disadvantages
Land-farming	- Relative simple design and implementation. - Short treatment times (six months to two years under optimal conditions).	- Reductions of concentration greater than 95 % and concentrations lower than 0.1 ppm are difficult to achieve. - The required area is high. - Dust and vapour generation during land-farming aeration may cause some air quality problems.
Bio-venting	- Uses readily available equipment, easy to install. - Creates minimal disturbance to the treatment site. - May not require costly off gas treatment. - Easily combinable with other technologies (e.g., air sparging, groundwater extraction).	- The high concentrations may be toxic for micro-organisms. - Not applicable for certain site conditions (e.g., low soil permeability). - Sometimes requires nutrients and air injection wells. - Only treats unsaturated zones of soils, and needs other methods to treat saturated zones of soils and groundwater.
Natural attenuation	- The generation of less remediation waste, and less impact on the environment. - Ease to use when combined with other technologies. - No equipment down time.	- The public may not perceive the effectiveness of the process correctly. - Site characterization can be more costly and complex. - Due to monitoring, active remediation may be more economical. - The potential exists for continued migration.
Phyto-remediation	- Is much less expensive than conventional options.	- Is a technology that is seasonal. - Only applicable to low profundity.
Bio-sparging	- Readily available equipment. - Cost competitive. - Requires no removal, treatment, storage or discharge of groundwater.	- Some interactions among complex chemical, and physical and biological processes are not well understood. - Potential for inducing migration of constituents.
Bio-rehabilitation in-situ	- Degradation of material dissolved in infiltrated and saturated zone. - Equipment easily available.	- The hole can be obstructed by biomass or precipitation. - Continuous monitoring and maintenance.

Table 2.11 Non-biological technologies used in soil remediation

Technique	Advantages	Disadvantages
Vitrification (Thermal)	- Ex-situ vitrification is a well developed technology. - The mobility of contaminants is reduced/eliminated. - The vitrified mass resists leaching for geologic periods of time.	- The process requires intensive energy and high temperatures up to near 2000 K. - Water in soil affects operation and increases the total costs of the process. - Off-gases must be collected and treated before release. - In-situ vitrification is in a pilot scale development.
Incineration (Thermal)	- Contaminant toxicity, as well as volume reduction is addressed by this technology. This is specially true for organic contaminants. - Widely used and available commercially.	- Metals are not destroyed and end up in the flue gases or in the ashes. - Community resistance to incineration is often present. - Certain types of soils such as clay soils or soils containing rocks may need screening.
Soil washing (Physical-Chemical)	- Reduces the volume of contaminant, therefore, further treatment or disposal is less problematic. - Commercially available.	- Contaminant toxicity is unchanged, although volume is reduced. - Less effective when soil contains a high percentage of silt and clay. - Costs associated with the disposal of the subsequent waste streams must be considered.
Soil vapour extraction (Physical-chemical)	- Proven performance, readily available equipment, easy to install. - Minimal disturbance to site operations. - Short treatment times (6 - 48 months).	- Concentration reductions greater than 90 % are difficult to achieve. - Effectiveness decreases when applied to sites with low permeability. - Only treats the unsaturated zone. - May require costly treatment for atmospheric discharge of the extracted vapour.
Electro-kinetic (Others)	- In-situ technology that has small impact on environment (soil removal is not required). - Metals are actually removed from soil unlike stabilization that leaves the metals in the soil.	- Alkaline soils reduce the effectiveness of the process. - Requires soil moisture.

2.6 General lessons learned from the implementation of decontamination techniques

Lessons learned from the implementation of decontamination techniques refer to the following aspects [7]:

- Often a combination of decontamination technologies is needed rather than just one particular technology.
- An evaluation must be made in order to optimize the decontamination needs of a project. Issues such as dose uptake, secondary waste generation and waste disposal can have an impact.
- On-site decontamination is to be preferred if it is not inconsistent with optimization of dose uptake, costs and waste disposal routes.
- Current technologies for chemical decontamination are still case specific. Efforts should be made to enlarge the direct applicability of existing processes.
- Most of the processes used for decontamination are proprietary. In this case, special attention must be given to the analysis of specific chemical decontamination solution capabilities and resulting waste prior to selection for a given application.
- For closed systems, one-stage decontamination and treatment processes generally produce the smallest volumes of secondary waste.

3. Dismantling techniques

3.1 Introduction

Dismantling involves decontamination, removal of components and structures, packaging of wastes, transport of packages, and disposal in a controlled burial facility. The planning should be performed in reverse order, however. Once characterization has identified the waste streams, the next step is to contact the waste disposal facility to learn and understand the waste acceptance criteria, including permissible package/container radioactive inventory (Becquerel and doses), package size and weight requirements, and documentation. If the facility will not accept the waste form or content, alternative measures must be taken. When the package sizes, weights, and radioactivity limits are selected, the mode of transport and number of shipments may be determined -- truck, rail, or barge.

The planner may then select the most cost-effective technology to segment piping, equipment, and structures to fit into the selected packages. The segmentation/removal production rates (tons/day) for each potential technique evaluated will determine the number of shipments per day or week and thereby set the overall schedule. Adjustments might be made as experience demonstrates improved productivity with other technologies.

This section will help the decommissioning planner choose appropriate technology for specific applications. Current dismantling, removal, and size reduction technologies include mechanical saws, circular cutters, abrasive cutters, diamond wire, explosive cutting, plasma arc torch, oxyacetylene torch, arc saw, abrasive water jet, and hydraulic shears. Backhoe hydraulic rams, conventional wrecking techniques, and explosives are used to dismantle large, thick concrete structures. The use of explosives requires a certified blasting expert for safety.

Many of these techniques are available as hands-on or remotely operated equipment. The selection of any of these technologies requires an evaluation of:

- *Cutting speed* - potential exposure of workers to radiation;
- *Maintenance frequency* - limited accessibility in congested areas;
- *Dust emissions* - spread of contamination;
- *Generation of secondary waste* - fire hazards;
- *Stringent rigging requirements* – noise;
- *Industrial safety issues* associated with working at heights.

Years of experience working with these technologies have yielded methods to effectively deal with these issues, and lessons learned have been shared among projects to improve performance.

New technologies often entail changes to old processes and accepted equipment. This has been the case with remote operations, where increased use is closely linked to safety and the diminished risk of working with hazardous materials. Opportunity to use remote technologies is not limited to waste removal but is also advantageous in other areas of mechanical operations.

Nuclear facilities are generally substantial structures built to withstand external and internal hazards. And the structures are often unique, so that no single method of dismantling and demolition can be all-encompassing. But there are principles that may help. Maneuverability and ease of transport play large roles since the dismantling tool or equipment often must fit within a confined space. Reach is also important, as some buildings may only require equipment with a two-story reach, while others are so large that other techniques are necessary, such as controlled blasting, which has been shown to be effective in bringing down structures quickly to permit the use of conventional size reduction methods.

Dismantling methods are of two types: disassembly and segmentation. Disassembly generally means removing fasteners and components in an orderly, non-destructive manner (the reverse of assembly). Segmentation includes flame cutting, abrasive cutting, and cold cutting. Flame cutting technologies include oxyacetylene and other gas torches, carbon-arc torches, air or oxy-arc torches, plasma arc torches, and cutting electrodes. Most torches can be operated either remotely or by hand.

Abrasive cutting technologies include grinders, abrasive saw blades, and drilling machines. Cold cutting technologies include nibblers, shears, and cutters for bolts, pipes, and tubing. The best method depends on the application. The following sections present dismantling activities for the two primary materials, concrete and metal. A final section discusses the use of robotics in dismantling operations.

3.2 Thermal dismantling techniques for metals

Thermal segmentation of metals refers to the general technique of cutting without making direct contact. In direct contrast to mechanical cutting, thermal cutting uses a medium other than a cutting edge to sever the metal. Such medium may be a focused beam of high-powered light (laser) or a high-temperature flame (plasma arc). Some of the more important benefits of most thermal cutting technologies are that they can be:

- Performed under water or in air;
- Operated remotely; their use on highly radioactive materials reduces worker exposure;
- Used for extended durations of time and reduce overall costs (although set-up and take-down times are generally longer).

There are basically two essential thermal cutting techniques: one chemical based on incineration in oxygen (oxygen cutting), and the other electrical (plasma arc cutting).

Thermal dismantling techniques bear a common feature; they make use of a heat source to melt, sublimate, combust or weaken a material to enable the separation of large structures to manageable formats. Often it is combined with a mechanical means to transport slug or molten substances.

Furthermore, these processes can be subdivided according to the kind of energy source they make use of for generating the heat. These energy sources include:

- chemical means (oxy-fuel cutting, metal powder assisted oxy-fuel cutting, oxygen lance)
- based on electric current (plasma cutting, oxy-arc cutting, electric arc water jet cutting, electric discharge machining, contact arc metal cutting, contact arc metal grinding, contact arc metal drilling)
- laser beams (laser beam cutting, oxygen assisted laser beam cutting, laser sublimation cutting).

A common disadvantage of all thermal techniques is the generation of solid or gaseous waste products including aerosols and suspensions that require potentially extensive filtering and conditioning.

In the following sections, a range of thermal cutting techniques is described and correspondent performance data are given.

3.2.1 Chemical energy sources

3.2.1.1 Oxy-fuel cutting

Oxy-fuel cutting makes use of the exothermic chemical reaction between oxygen and the material to be cut. Thus, this material has to have a number of specific characteristics:

- It has to be combustible in a pure oxygen environment;
- Ignition point < melting point;
- Combustion temperature > slug melting point (sufficient combustion heat generation);
- Low slug viscosity.
- Limited heat conductivity.

Mainly, these preconditions are fulfilled by low alloyed ferritic steel qualities. In this case, the cutting process is self-preservative; activation energy is normally supplied by an acetylene flame. The produced oxides (slug) is removed from the kerf by the mechanical energy of the oxygen stream.

Due to the transportation of the process heat by the slug, it is also possible to cut through ferritic sheet metals that are plated with austenitic steels, a combination often to be found for example in reactor pressure vessels. Oxy-fuel cutting is a well introduced procedure and is widely used for dismantling, for example during the deconstruction of the nuclear power plant Gundremmingen Block A in Germany.

Some performance parameters of oxy-fuel cutting are given in Table 3.1.

Table 3.1 Performance parameters of oxy-fuel cutting

Environment	Atmospheric and submerged conditions
Water depth	Up to 10 m with acetylene based activation, above 10 m alternative fuels
Automation / Remote operation	Possible
Cutting speed	350 to 700 mm/min (10 mm sheet metal)
Depth of cut	25 mm to 800 mm (standard tools); feasibility studies of up to 3200 mm
Contour cutting	Possible
Secondary waste	Ferritic oxides (slug)
Consumables	Oxygen and combustible substance (acetylene, petrol, butane, etc.)
Characteristics	Only for a limited range of materials usable

3.2.1.2 Metal powder assisted oxy-fuel cutting

Oxy-fuel cutting has the above mentioned limitations. In order to be able to cut for example austenitic materials, cast iron, non-steel alloys and even concrete, a process was developed that is deploying a combustible metal powder (normally fine grain iron particles, or even magnesium or aluminium) that is introduced into the oxygen stream in order to deliver enough energy to melt the work piece which is then removed from the kerf by the mechanical energy of the oxygen stream.

The technique is not widely used as it is generating excessive amounts of aerosols and secondary waste (oxides of the used additional metal powder); however, it is quite versatile. Performance data are currently not available.

3.2.1.3 Oxygen lance

The oxygen lance consists of a pipe filled with iron wire or similar structures. Oxygen is led through the pipe and supports a continuous combustion of the lance’s iron filling on one end of the tool that generates a temperate of about 2500 °C to 3000 °C. The thermal energy is transferred to the work piece by the hot process gases as well as the liquefied iron oxides.

The generated heat is sufficient to melt most technical materials including steel, cast iron, concrete, glass, non-metal alloys, organics and most ceramics. The slug is removed from the kerf by a manual movement of the lance as well as the gas flow. The tool is only suitable for drilling; however, by neighbouring the drilled holes, a cutting process analogue is achievable. Currently there are no efforts to automate or remote control the process; therefore, the application in the context of the decommissioning of nuclear installations is limited to areas with a low radiation exposition. It is extensively used for conventional dismantling of thick and/or large structures.

Some performance parameters of oxy-fuel cutting are given in Table 3.2.

Table 3.2 Performance parameters of oxygen lance

Environment	Atmospheric and submerged conditions
Water depth	Not limited
Automation / Remote operation	No; currently only handheld operation
Cutting speed	Approx. 200 mm rod progress rate in mild steel
Depth of cut	Limited by length of rod (1500 to 2000 mm)
Contour cutting	Possible, at a low precision
Secondary waste	Ferritic oxides (slug)
Consumables	Lance, oxygen
Characteristics	Only hole punching possible, low precision, very versatile

3.2.2 Electric current based cutting techniques

3.2.2.1 Plasma cutting

Plasma cutting makes use of a high-velocity high-temperature plasma (ionised gas) stream to melt the work piece and to transport the molten kerf material. Plasma can not only be manipulated pneumatically, but due to its inherent load also with electric and/or magnetic fields, so that very elaborate cutting tools are available. The plasma is generated by an electric current flowing from the plasma torch to the work piece, heating up the process gases until the plasma state is achieved. Ignition is done by a high voltage spark that delivers enough ions (and thus a conductive path) to enable the high current low voltage electric source to overtake.

Currently, plasma cutting is state-of-the-art in the field of sheet metal processing as it is combining high cutting velocities with a high precision and processible material thicknesses up to 150 mm. Consequently, it can also be used for various cutting tasks in the decommissioning field; it can be easily adapted to remote handling.

Some performance parameters of plasma cutting are given in Table 3.3.

Table 3.3 Performance parameters of plasma cutting

Environment	Atmospheric and submerged conditions
Water depth	Currently up to 100 m
Automation / Remote operation	Yes
Cutting speed	100 to 500 mm/min (10 mm sheet metal)
Depth of cut	Approx. 150 mm, resp. ∞ for a plasma immersion torch
Contour cutting	Yes
Secondary waste	Solids: none; process gases (N2, noble gases)
Consumables	Process gas
Characteristics	Precise, fast, conductive material required, limited depth of cut

3.2.2.2 Oxy-arc cutting

Similar to oxy-fuel cutting, a self-consuming hollow electrode is used. A plasma arc is ignited between the electrode and the work piece delivering heat to the material to be cut; additionally, oxygen is led through the electrode, both combusting the electrode and (if the material is suitable) the work piece. The oxygen enhances the cutting process by introducing reaction heat from the oxidation, and also contributes to the transportation of slugs. Similar to oxy-fuel cutting, only a drilling operation mode is possible.

Oxy-arc cutting is mainly used hand-held for smaller cutting tasks (limited length, limited depth of cut), and preferably submerged; it is widely applied in the docking industry. Application in the decommissioning field is currently limited.

Some performance parameters of oxy-arc cutting are given in Table 3.4.

Table 3.4 Performance parameters of plasma cutting

Environment	Preferably submerged
Water depth	Physically not limited
Automation /Remote operation	No
Cutting speed	100 to 500 mm/min (10 mm sheet metal)
Depth of cut	Rod length, for hand-held devices approx 400 mm
Contour cutting	Yes
Secondary waste	Solids: electrode slug (metal oxides); process gases
Consumables	Lance, oxygen
Characteristics	Manual operation, low precision, versatile, conductive work piece required, only drilling, discontinuous process

3.2.2.3 Electric arc water jet cutting

The electric arc water jet cutting torch is in terms of design and construction similar to a MIG/MAG torch; a self-consuming wire electrode delivers electric energy to melt the work piece’s material, and the water nozzle (corresponding to the inert resp. active gas nozzle) provides the removal of the molten metal. Up to now, it has only been qualified and used for dismantling tasks in Cadarache (France).

Some performance parameters of electric arc water jet cutting are given in Table 3.5.

Table 3.5 Performance parameters of electric arc water jet cutting

Environment	Atmospheric and submerged
Water depth	Physically not limited
Automation / Remote operation	Yes
Cutting speed	2700 mm/min @ 2400 A
Depth of cut	No sources available
Contour cutting	Yes
Secondary waste	Solids: electrode slug (metal oxides)
Consumables	Wire electrode, process water
Characteristics	Suitable for medium thickness work pieces, conductive material required, continuous process

3.2.2.4 Electric discharge machining

Electric discharge machining (EDM) is an impulse based process delivering high voltage low current sparks from a (usually copper) electrode to the work piece. The sparks melt or sublimate the work piece’s material and also cause a gas bubble that immediately implodes after the spark’s ignition generating a shock wave in the surrounding medium. This shock wave then provides the removal of the processed kerf material. Electrode designs include wires (wire-cut EDM) or fixed electrodes (sinking EDM machining).

Currently EDM based cutting is very much limited in terms of cutting speed and is only widely used in the tooling industry. However, it is the functional base for the next techniques that are described in this document.

3.2.2.5 Contact arc metal cutting (CAMC)

CAMC is based on the principle of EDM as it features a graphite electrode to deliver the electric current necessary to support the cutting process. However, the energy is not transported by high voltage sparks but by low voltage plasma arcs. The necessary ions to start the arc are generated by establishing a short circuit when directly contacting the electrode with the work piece. At the contact point, high temperatures are generated producing enough ions to enabling the cutting arc ignition.

The electrode is covered by a parallel high velocity water stream to transport the slug resp. molten metals, to manipulate the arc's position and to remove excess heat from the electrode material. Electrode design is commonly sword-like; electrode materials include graphite and carbon fibre reinforced graphite. The technique has been deployed successfully to dismantle the thermal shield at the MZFR (multi purpose research reactor) at the research centre Karsruhe (Germany).

Some performance parameters of contact arc metal cutting are given in Table 3.6.

Table 3.6 Performance parameters of contact arc metal cutting

Environment	Only submerged
Water depth	Physically not limited
Automation / Remote operation	Yes
Cutting speed	Approx. 1500 mm/min (10 mm mild steel sheet)
Depth of cut	Approx. 270 mm (depending on sword length)
Contour cutting	No; only straight cuts feasible
Secondary waste	Solids: electrode slug (graphite); gaseous: CO_2
Consumables	Electrode, water
Characteristics	Suitable for complex hollow structures; only conductive materials; easy cut-through controlling

3.2.2.6 Contact arc metal grinding (CAMG)

Similar to CAMC, an electrode is used to transport the necessary electric energy to perform the cut. The CAMG electrode (mostly Cu/W alloys) is discoid and rotates at approximately 500 to 1500 min^{-1}, the necessary fluid stream to remove the molten resp. slug material is generated by this rotation. Arc ignition is again done by a short-circuit contact between electrode and work piece. The cutting speed is extremely high.

Some performance parameters of contact arc metal grinding are given in Table 3.7.

Table 3.7 Performance parameters of contact arc metal grinding

Environment	Only submerged
Water depth	Physically not limited
Automation / Remote operation	Yes
Cutting speed	Approx. 4000 mm/min (10 mm mild steel sheet)
Depth of cut	Approx. 1/3 of disc diameter
Contour cutting	No; only straight cuts feasible
Secondary waste	Solids: electrode slug
Consumables	Electrode
Characteristics	Suitable for complex hollow structures; only conductive materials; easy cut-through controlling; highest cutting speed of all thermal submerged techniques

3.2.2.7 Contact arc metal drilling (CAMD)

CAMD tools feature a hollow cylindrical electrode (not necessarily with a circular footprint); the contact area to the work piece is the end face. The necessary process water is led through the electrode to the end face and there facilitates the slug and molten material removal.

Some performance parameters of contact arc metal grinding are given in Table 3.8.

Table 3.8 Performance parameters of contact arc metal drilling

Environment	Only submerged
Water depth	Physically not limited
Automation / Remote operation	Yes
Cutting speed	Approx. 1000 mm/min intrusion speed in mild steel
Depth of cut	Limited by electrode design
Contour cutting	n/a
Secondary waste	Solids: electrode slug
Consumables	Electrode, water
Characteristics	Suitable for complex hollow structures; only conductive materials; easy drill-through controlling

3.2.2.8 References to thermal cutting techniques

References to thermal cutting techniques can be found in [9], [10], [11], [12] and [13].

3.2.3 Basics of laser beam cutting for the dismantling of nuclear power plants

3.2.3.1 Introduction

Laser beam cutting offers the possibility to cut steels with thicknesses up to 20 mm economically by using lamp-pumped Nd:YAG lasers with average output powers up to 4 kW. Recently, average laser output powers up to 6 kW could be made available for industrial applications. To introduce the necessary process energy for the laser beam services, use is made of the following means.

3.2.3.2 Laser cutting processes

There are three basic cutting processes: laser flame cutting, laser fusion cutting and laser sublimation cutting. The application of the different processes is dependent on the material and the given demands.

With laser flame cutting, the additional exothermal reaction energy of the burning process is exploited. Thus, high cutting speeds are available as the release of energy during the burning process can be as high as the energy input of the laser beam. As process gas oxygen is applied, that starts the exothermal reaction. The material burns to a fluid slag, which drains off easily. Therefore, the gas pressure is set to lower values compared to laser fusion cutting. Besides, the exothermal energy has to be limited in order to guarantee a controlled cutting process. At the cut edge, an oxide layer is formed by the burning reaction. This layer has only a weak connection to the work piece.

Laser fusion cutting is characterised by the use of an inert process gas, i.e., nitrogen or argon. An additional exothermal reaction is prevented by the atmosphere of the shielding gas. Accordingly, the process works only with the input of laser power and, therefore, the cutting speed is substantially lower than it is with laser flame cutting. In return, the cut edge is not oxidised after the processing. Further treatment of the work piece is thus not necessary. However, the fusion resulting during the treatment is viscous. For that reason, the gas pressure has to be very high in order to expel the melt from the kerf and to realise a clean and burr free cut.

High power densities are required for the laser sublimation cutting in order to transform the material directly from the solid to the vapour phase. In addition, for this treatment an inert process gas is applied to protect the material from burning. The gas pressure used is dependent on the material which has to be processed. Because of the high vaporisation temperature of metallic materials and the limitations of available power densities, only organic or plastic materials are treated using laser sublimation cutting, while metals are mainly processed by the other two cutting methods described before [14], [15]. However, the sublimation process can be used very effectively for decontamination purposes, e.g., to remove thin surface layers.

3.2.3.3 Laser cutting processes

Comparison of thermal cutting technologies

Laser cutting is characterised by small cutting kerfs and precise cutting contours, small heat affected zones, small tolerances, limited distortion of the work piece, stress-free treatment and high reproducibility. On the other hand, a high investment is necessary, and the low efficiency of lasers is coupled to high energy consumption. However, compared to other thermal cutting techniques, the laser produces the smallest cut [16].

A considerably reduced amount of particle-shaped process emissions are released. The comparison of the laser process with the plasma process relating to the Nominal Hygienic Air Requirement Limit Value (short: NHL) shows that less fresh air is needed to meet the tolerable limit values with the laser processing than with plasma processing. The NHL-value characterises the amount of fresh air which is theoretically necessary with a given emission mass flow not to exceed the tolerable limit value for each hazardous substance in the air [17].

Use in nuclear facilities

Laser technology can be used in many areas of dismantling nuclear power plants. Experimental investigations on laser processing under water were carried out, for example. First, the process gas is switched on, in order to protect the optical components and to keep water from getting into the processing head. Afterwards, the processing head is dipped into the water where the cutting process is carried out. The water does not hinder the laser beam, as the gas beam displaces the water and guarantees the free propagation of the laser beam.

Also, in the area of asbestos cutting, the laser offers process specific advantages. The release of cancerous fibrous aerosols can be significantly reduced using the laser, as the asbestos is vaporised and condenses to harmless spherical particles in the air. At the same time, the cut edge of the asbestos material is glazed during the treatment. Thus, a durable sealing of the cut edge is guaranteed, and the release of remaining fibers from the asbestos material is prevented [18], [19].

Emission-minimised cutting using special process parameters offers the possibility to attach the molten material on the underside of the work piece in form of a burr. This reduces the release of emission products and contaminations. Also, the cutting of tubes is possible by laser material processing. Only the material and its thickness are decisive for the process. The production of a burr is also possible in this case [20].

For the dismantling of tanks or storage basins consisting of concrete walls which are lined with steel plates, cutting of the steel material is difficult, for example. The metal sheets lie directly on the concrete, and it is very difficult to cut them mechanically. Thermal cutting methods producing very deep fusion penetration in the subjacent concrete can lead to contamination of the concrete. In that case, a further treatment of the concrete would be necessary. Laser cutting offers specific advantages here. The energy input is very precise and can be controlled in depth so that the process can be adjusted exactly to the thickness of the work piece. Fusion penetration in concrete can therefore be minimised. Moreover, there is the problem of the treatment of coated sheets. The sheets can be processed nearly without burning the coating. An additional advantage of this method is the separation of gas and laser beam. A special nozzle technique can be used to expel the molten material to the top surface of the sheet. A specific removal by suction of the released process emissions is also possible [21].

The mobility and flexibility of the laser is an important reason for its application in nuclear facilities. A condition for the realisation of these applications is the availability of hand-held laser processing heads. For this reason, a device was developed at the Laser Zentrum Hannover (LZH) which allows guidance by hand. The feed rate is given by the system, to guarantee a stable cutting process. With this device, which was specially constructed for the demands of the dismantling of nuclear facilities, programming and teach-in procedures are not necessary, as for example with the use of robots, which leads to significantly lower costs and saving of time. For low contaminated areas, this system offers a useful alternative to other thermal cutting techniques providing all advantages of the laser technology [22], [23], [24].

Some performance parameters of laser beam cutting are given in Table 3.9.

Table 3.9 Performance parameters of laser beam cutting

Environment	Atmospheric and submerged
Water depth	Physically not limited
Automation / Remote operation	Yes
Cutting speed	Approx. 1000 mm (10 mm mild steel sheet)
Depth of cut	Approx. 20 mm with single focus setups
Contour cutting	Yes
Secondary waste	Process gas
Consumables	Process gas
Characteristics	Fast and precise; limited depth of cut; usable for a wide range of materials

3.3 Mechanical dismantling methods for metals

3.3.1 Shearing

According to its definition shearing is a mechanical separation without developing shapeless materials [25]. It is differentiated between the following kinds of cuttings, which are assigned to shearing:

- Shear cutting;
- Blade cutting;
- Tearing;

- Breaking.

For the dismantling hydraulic shears were among other places used in the nuclear power plant in Würgassen (Germany).

One application of this technique in the field dismantling is the fractionalization of graphitic reactor components. Some 900 t of graphitic reactor components (moderators, reflectors and thermal columns fabricated from graphite or carbon stone) in Germany will sooner or later be subject to decommissioning and/or dismantling.

Fractionalizing graphitic components will reduce the volume to be stored, minimize disposal costs and reach a separation of activated/contaminated and non-radioactive parts. For example, the amount of MOSAIK type II containers needed for graphitic parts of the AVR-reactor was estimated to a number of 2,511 and might be reduced down to some 50 % [26].

Under radiological load, each material is subject to change of its mechanical properties, and these changes in graphitic parts are substantial to this project. As the best known radiological effect on graphite, the Wigner-Energy, can easily be released through a relatively short heat treatment, it is not considered to be an issue of scientific interest. This to an even greater intent, as lots of information from theoretical and practical experience is available.

It is well known that mechanical treatment of any kind of graphite results in dust emission from the working place. For reasons of safety, this dust has to be collected during cutting operations applied to nuclear parts. Thus, another scientific goal was reached by the development of a matching filter technique to collect graphite dust emitted by the cutting process. It was applied during evaluation works on irradiated graphite.

Technique of choice in this case is the mechanical breaking of graphitic components by means of a straddling tool as it is widely in use by fire brigades. Two arms of the tool are inserted into a hole of the graphitic part and then, by means of an electro-hydraulic pump, opened.

3.3.2 Sawing

According to its definition sawing is cutting with a multi tooth tool of small kerf width.

With all sawing types, the tool is moved and supported by a feed motion. Differences exist in performance data, in the wear of tools and in the accumulation of secondary wastes:

- <u>Fret saw:</u>
  - Cutting depths up to 100 mm;
  - Wear of tool rises with the cutting depth super-proportionally;
  - Tool works without coolants and lubricants in most applications.
- <u>Bow saw:</u>
  - Also for thin-walled components suitable;
  - High tool life circles lives by characteristic movement;
  - Coolants and lubricants increase tool life circles;
  - Handling of components with dimensions to 1 m cut lengths usually.
- <u>Band saw:</u>
  - Handling of larger diameters;
  - High tool service lives by few load of the individual tooth;
  - Coolants and lubricants increase tool life circles;

  - Small kerf widths and a low amount of secondary waste can be obtained by narrow dimensions of the tool;
  - Very good results obtained in various decommissioning projects (as well for cutting in air as under water).
- Circular saw:
  - Cutting depths in metals up to 200 mm;
  - Cutting depths in concrete up to 550 mm;
  - Coolants and lubricants recommendable;
  - The use of remotely operated underwater circular sawing is currently common in decommissioning projects.
- Core saw/wire saw:
  - Separation process is a mixture of sawing and grinding;
  - Wire-cable with cutting elements of boric nitride or diamond;
  - Coolants and lubricants are needed;
  - Secondary waste is predominantly powder or slurry;
  - Cutting depths in metals up to 300 mm;
  - Cutting depths in concrete up to 1000 mm.

In general, one can say that sawing is a proved industrial technique which produces few secondary wastes (chips) easily collectable. It has been used successfully in different decommissioning projects worldwide.

3.3.3 Grinding

With abrasive cuttings beside the work piece also the tool material is removed away. The tool material used is: aluminium oxide, silicon carbide, boric nitride or diamond merged in resin and partially strengthened by fibre glass.

A cutting depth in metal up to 30 mm with mobile devices has been achieved. During cutting a good heat dissipation and a stable tool guidance are necessary.

3.3.4 Explosive cutting

Explosive cutting is a method of segmenting metal or other materials with an explosive formed in a geometric shape especially designed and sized to produce the desired separation of the work piece [1]. The explosive cutter consists of an explosive core surrounded by a casing of lead, aluminium, copper, or silver. The cutting is accomplished by the high explosive jet, detonation products, and deformed casing metal, which form a directed shock wave to cut the target material.

Usable on virtually any material, explosive cutting has segmented materials up to 6 inches thick in air and under water. The technique is limited only by the effect of the blast on the mechanical integrity of the surrounding structures and the ability to control the spread of contaminants. Explosive cutting is expensive if used extensively, mainly due to the need to hire qualified explosive contractors. Explosive cutting of contaminated components and systems may be used for the following unique applications:

- Where simultaneous cuts must be made;
- Where other cutting techniques do not have sufficient access;

- In high radiation zones where long-handled tools are used to position the explosive cutters.

3.3.5 Orbital cutters

Orbital cutters can be manually actuated devices or self-propelled units that cut as they move around the outside or inside circumference of a pipe or vessel and they are an effective means of segmenting pipes and circular vessels [7]. Three different types of tool are used for orbital cutting:

- *Swaging cutter*. This tool uses a hardened wheel which compresses and shears the metal. The technique is able to cut thin walled metal pipes.
- *Lathe tool*. Typically two lathe tools are placed diametrically opposite one another and rotate around the pipe to be cut; a ratchet system feeds the tool into the metal after each rotation, thus performing a cutting operation similar to that of a lathe. Such a tool can be used on small pipes as well as on large cylindrical vessels. The tool can be arranged to rotate either outside the pipe, as at the Hanford C reactor, or inside as at the Japan Power Demonstration Reactor (JPDR).
- *Milling tool*. In place of hardened wheels on the rotating head, a small milling cutter (e.g., slit cutter) is used to cut a slit in the pipe while rotating around or inside it. The tool can be fed by a ratchet after each rotation of the head, or fed continuously by a dedicated system.

Orbital cutters can be controlled remotely, allowing the operators to work at a distance from the radiation area, but they often require manual positioning in the first instance.

3.3.6 Milling

Milling is a procedure for the processing of work pieces at a high rate of material removal. It is not used as a separation process in the original sense. The material is processed with high expenditure of time and tools.

This procedure is not particularly suitable for dismantling of nuclear power plants and is used only in special cases (for example for the conditioning of components).

Milling tools are applied in most cases as stationary units. Additionally, mobile devices are used, for example in the conventional area for milling railway switches.

3.3.7 Hydraulic cutting techniques

The wide potential of jets is caused by their wide range of resulting loading regimes, from static loading to dynamic loading resulting from jet disintegration, cavitation, electrical or ultrasonic modulation. The jet technology is involved in a wide range of applications and processes besides cleaning and cutting. Examples are milling, turning, drilling, fragmentation, surface modification, etc. This results in a lot of different industrial applications like manufacturing, surface preparation, medicine, electronics, automotive industry, military, and nuclear application, for example.

The improvement of the reliability of jet cutting systems as well as the increasing implementation of automation and recycling systems of water and abrasive will rise the number of applications and accelerate the spreading into different fields of application in the future.

The increasing pressure levels of the plunger pumps, which are normally connected with higher flow rates compared to intensifier pumps, opened a wider field of effective application like shipyard cleaning, removal of concrete, nuclear application, etc.

3.3.7.1 Cutting and de-coating with pure water jets

The plain water jet is generated by pressurising the water with an intensifier or plunger pump. The pressure energy is transferred with a small nozzle into kinetic energy. The water is accelerated up to several 100 m/s depending on pressure and flow rate. Today intensifiers deliver typically pressures of 400 MPa and flow rates of 4 l/min. Plunger pumps, with a higher efficiency, reach 350 MPa and a flow rate of 20 l/min and are used for cleaning purposes.

The pressure used for surface cleaning is related to the material properties. In the case of decontamination of concrete structures, typically pressures are in the range of 100-150 MPa.

A water jet of a pressure up to 400 MPa is allowed to cut many materials like plastics, wood and other comparatively soft materials. However, the range of materials, which could be cut, is remained limited. Metals, ceramics and other technical materials, are not machinable by pure water jets. Only the addition of abrasive particles to the water jet makes an effective cutting of technical materials possible.

3.3.7.2 Cutting with abrasive water jets

By adding abrasives to the plain water jet the efficiency of the tool is increased. Two kinds of abrasive water jets are currently in use: The 'Abrasive Water Entrainment Jet' or 'Abrasive Water Injection Jet' (AWIJ) and the 'Abrasive Water Suspension Jet' (AWSJ), which are generated by different pumping principles.

'Abrasive Water Injection Jet' (AWIJ)

The idea to generate an '*Abrasive Water Injection Jet'* was developed in the lately seventies. The main component is a mixing head, with an assembly of a water nozzle and a focusing or mixing tube. The water nozzle has a diameter of 0.2 - 0.5 mm and generates a plain water jet. This jet runs through the mixing chamber and generates a vacuum pressure. Through an opening, the abrasive particles are sucked into the chamber pneumatically. In the mixing tube the abrasive and the water are mixed, accelerated and focused.

'Abrasive Water Suspension Jet' (AWSJ)

A second variation to generate an abrasive water jet is the '*Abrasive Water Suspension Jet'* and was developed in 1984 by the BHR-Group in Cranfield, United Kingdom. A high-concentrated suspension is stored in a vessel under system pressure in the pressure circuit.

The main difference to the '*Abrasive Water Injection Jet'* is the absence of air in the jet. One part of the pressurised water is used to feed the high concentrated suspension into the main water stream. The suspension can be transported with long high pressure hoses to the cutting location.

Due to the fact there is no air in the jet the efficiency of this jet is much higher than the efficiency of an '*Abrasive Water Injection Jet'*. '*Abrasive Water Suspension Jets'* are well known in the dismantling industry and only a few applications for manufacturing purposes are known today. State-of-the-art for '*Abrasive Water Suspension Jets'* is pressures up to 200 MPa. 400 MPa-'*Abrasive Water Suspension Jets'* are developed and running under laboratory conditions.

Characteristics of 'Abrasive Water Injection Jets' and 'Abrasive Water Suspension Jets'

The characteristics of the different abrasive water jets are based on their generation. The *'Abrasive Water Injection Jet'* consists of three phases (for example ≈ 95 % vol. air, ≈ 4 % vol. water, ≈ 1 % vol. abrasives), the *'Abrasive Water Suspension Jet'*, however, only consists of two phases (80 - 90 % vol. water, 10 - 20 % vol. abrasives). This leads to a better acceleration of the abrasive particles in an *'Abrasive Water Suspension Jet'*. Therefore its cutting efficiency is at least twice as high as of an *'Abrasive Water Injection Jet'* of the same hydraulic power and abrasive flow rate (see Figure 3.1). However, the *'Abrasive Water Injection Jet'* is commonly used with pressure as high as 400 MPa, which leads to similar performances as the *'Abrasive Water Injection Jet'* in terms of the depth of cut.

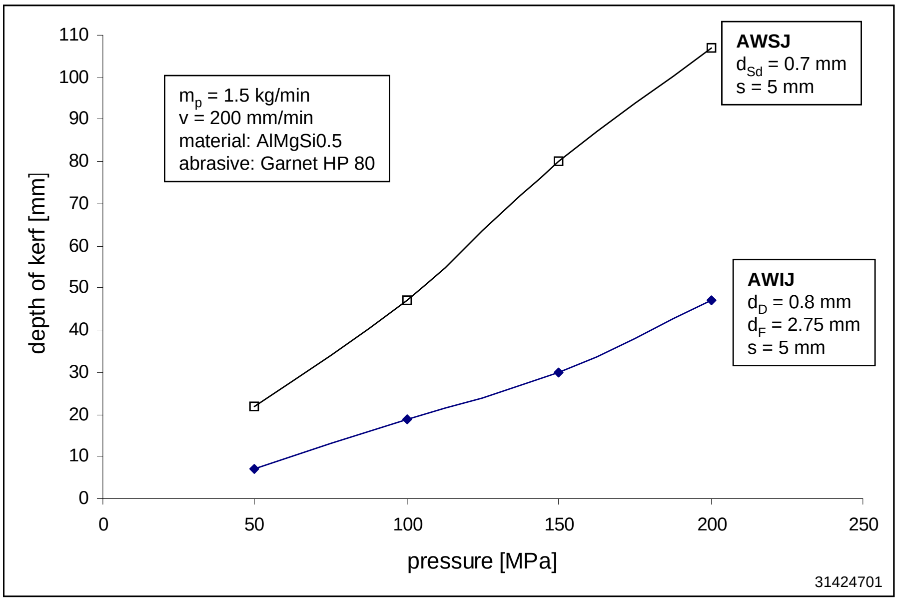
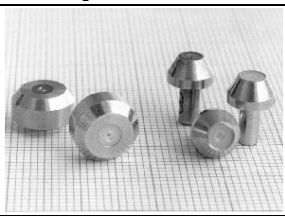
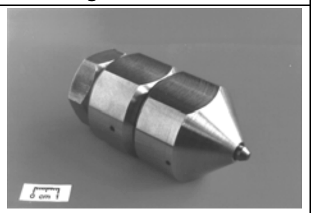


Figure 3.1 Characteristics of '*Abrasive Water Injection Jets*' and '*Abrasive Water Suspension Jets*'

Table 3.10 Advantages of the water jet technology

Principles	Water jet	Abrasive Water Injection Jet	Abrasive Water Suspension Jet
Multifunctional tool	Cutting, drilling, turning, de-coating, cleaning		
Non-thermal process	No toxically reaction products		
Omni-directional	Sharpness of the jet from every side		
Almost all materials can be cut	'Soft' materials	Metallic and ceramic materials	
	homogeneous- and inhomogeneous material, composite materials		
Small width of cut	> 0,1 mm	> 0,4 mm	> 0,3 mm
Achievable depth of cut	e.g. PVC 20 mm	e.g. steel 120 mm	e.g. steel 300 mm
Small and flexible tool			
Application in different environment	In air, under water, in explosive environment		
Low reaction forces	15 N – 250 N		
Low stand-off distance sensitivity	No focussing necessary		
Natural resources	Water	Water and abrasive	

Comparison of cutting efficiency of 'Abrasive Water Injection Jets' and 'Abrasive Water Suspension Jets'

Due to the fact that *'Abrasive Water Suspension Jets'* only consist of water and abrasive material, the particles are guided in a better way than in *'Abrasive Water Injection Jets'*. This leads to a higher jet stability and finally to an improved cutting quality and cutting efficiency.

'Abrasive Water Injection Jets' generating a water jet leaves the water nozzle, passes the mixing chamber and then enters the focussing tube. This leads to the demand, that the focussing tube diameter is at least twice (normally 3 - 4 times) as large as the water nozzle diameter. Therefore, *'Abrasive Water Suspension Jets'* of the same nozzle diameter - and consequently the same hydraulic power - produce lower cutting widths and higher cutting depths.

The advantages of the water jet technology in relation to thermal and conventional procedures are summarized in Table 3.10.

3.3.7.3 Abrasive water jets for the dismantling of nuclear power plants

One first example of dismantling by *'Abrasive Water Injection Jets'* is the biological shield of the Japan Power Demonstration Reactor (JPDR) in Japan [27]. Beside water jets, diamond saw and drill, and explosive techniques was used to dismantle the biological shield, consisting of reinforced concrete.

The advantages of the abrasive water jet cutting technique, combined with newly reached developments in combination with other advantages, generated the idea to qualify this technique as an alternative decommissioning technique in the nuclear power plant (VAK) in Kahl [28], [29], [30], [31]. Two research projects, the generation of higher working pressure as well as the application at VAK, Kahl, were sponsored by the Federal Ministry of Education, Science Research and Technology (BMBF). Within the project at VAK, Kahl the cutting of the lower core shroud - activated material to be cut under water - and the development of a strategy to cut the reactor pressure vessel with *'Abrasive Water Suspension Jet'* were planned.

Cutting strategies for dismantling are:

- Cutting through:
  - For total material separation, a setting angle for cutting of 15° has to be taken.
  - If other parts of the object are closed to be cut and should be affected minimal, the cutting angle can be increased up to 45° to minimize the effect of the gap.
- Kerfing:
  - Kerfing a definite percentage of the material thickness (for example 95 %) to prevent the surroundings by impurities. The used abrasives and the machined (radioactive) material are collected inside of the pressure vessel. Only when cutting the remaining wall thickness a small percentage of abrasive and machined material are ejected to the surroundings.

First application of an *'Abrasive Water Suspension Jet'* was at the nuclear power plant VAK, Kahl. At the beginning a 140 MPa cutting unit was used to cut the lower core shroud and the thermal shield. The reactor pressure vessel itself was cut by a 200 MPa unit. The data of application are given in Table 3.11.

An advantage of abrasive water jet cutting compared to thermal cutting is the small amount of aerosols, the disadvantages the secondary waste. Both are quantified and analysed for kerfing and cutting through for application in air as well as under water. Only a very small amount of waste is spread into the air as aerosols, most of the wastes are sediment particles.

To manage the waste, a catcher and a special filtering device is to be installed. At the VAK, Kahl most of the abrasive material (97 %) was directly filled into a special container. Small particles were held back by a special filter system, the water could be reused [32].

An optimized cutting process and the right cutting strategy are necessary to minimize the flow rates of abrasives.

Table 3.11 Cutting parameters of VAK Kahl

	Lower Core Shroud	Thermal Shield	Reactor Pressure Vessel
Material	X 6 Cr Al 13	X 6 Cr Al 13	Austenitic plated, ferritic steel, 19 Mn 5
Material thickness	51 mm (132 mm)	32 mm	104.5 mm (6.5 + 98)
Working pressure	140 MPa	140 MPa	200 MPa
Water flow rate	8 – 20 l/min	8 – 20 l/min	9.5 – 20 l/min
Abrasive flow rate	1.3 kg/min	1 kg/min	1 kg/min
Cutting speed	40 mm/min (13 mm/min)	65 mm/min	25 mm/min
Total length of cut	20 m	70 m	63.9 m
Total consumption of abrasive	1000 kg		2553 kg

3.4 Dismantling of concrete structures

Methods for dismantling concrete structures (walls, floors, ceilings, and foundations) are diverse in that each has particular advantages and disadvantages related to costs, personnel exposure, and overall effectiveness [1]. Some methods minimize wastes while others are designed strictly for structural demolition (with no segregation of material, clean or contaminated).

Each method has a justifiable application; what is best in a particular case depends on its unique circumstances and ultimate goal.

3.4.1 Selective cutting

Selective cutting removes sections of concrete in planned increments or quantities. The object of selective cutting is to remove the concrete in an orderly, precise fashion to enable the application of additional techniques to accomplish specific goals. Some of these techniques and goals are:

- *Removal in sections*: enables decontamination of each section to permit unconditional release of the section after contamination has been removed.
- *Removal of designated areas*: large surfaces may not be entirely contaminated; thus, it is only necessary to remove those affected areas.
- *Removal of sections restricting access to contaminated zones*: selective cutting permits an orderly removal of such structures without cross-contamination.

The main techniques for cutting of concrete are described in the following sections.

3.4.1.1 Flame cutting

Flame cutting of concrete is a thermite reaction process whereby a mixture of iron and aluminium powders is oxidized in an oxygen jet. The jet flame temperature (~ 8900°C) causes rapid decomposition of the concrete. The generated molten concrete is blown away from the kerf by the jet mass flow rate, keeping the cut clean.

Reinforcing rods (rebars) are also segmented by the flame since the iron actually augments the thermite reaction. Normally, track-mounted flame cutters are capable of cutting through 150 cm of concrete with or without rebars. The major disadvantage of flame cutting is the generation of large quantities of heat, smoke, and toxic gas.

3.4.1.2 Thermic lance

The thermic lance is an iron pipe packed with a combination of steel, aluminium, and magnesium wires through which a flow of oxygen gas is maintained. The lance cuts are achieved by a thermite reaction at the tip of the pipe, where all components are completely consumed. Temperatures at the tip will range from 2200 - 5600°C, depending on the environment (e.g.; in air or under water). Lances can only be used in the hand-held mode in cutting metals and demolishing concrete.

A single lance can burn a 5 cm diameter hole through 0.5 to 1 m thick reinforced concrete in about 6 minutes. While the lance is best used for producing holes, a rock splitter is required to complete segmentation of the concrete. The lance generates significant smoke in air and bubbles in water. Therefore, ventilation must be maintained to protect the worker and the environment.

3.4.1.3 Rock splitter

A rock splitter uses a hydraulically operated expanding wedge placed into a drilled hole to fracture the surrounding concrete. The hydraulic cylinder drives the wedge into the hole at a pressure of about 50 MPa and can develop splitting forces of up to 350 tons. Rebars in the concrete must be cut by other means. Limited access areas can be segmented easily by rock splitting since the unit is held manually. About ten minutes are required to drill and split each hole. Contamination controls required are minimal since only a small amount of dust is generated.

3.4.1.4 Sawing

A motor-driven diamond or carbide saw blade may be used to cut a kerf through concrete floors or walls. The blades are capable of cutting rebars if they are at right angles to the cut. Most concrete saws are track-mounted and operated manually, although newer technologies are evaluating remotely-operated systems. A normal thickness of cut is about 1/3 the diameter of the blade, with about 1 m of concrete being the maximum thickness. Saw cut speed can reach 1 m^2 per minute, depending on the concrete composition. Since most concrete saw blades are water-cooled to prevent warping, the water is a secondary waste concern. Another concern is airborne contamination (dust and metal particulate).

3.4.1.5 Bristar demolition compound

Bristar concrete demolition compound is a mixture of limestone, siliceous material, gypsum, and slag. When mixed with water and poured in predrilled holes in concrete, the compound hardens and expands within 20 hours, developing a force of over 30 MPa. This force causes cracks along a predetermined fracture line delineated by the drilled holes. Exposed rebars are cut by other methods. The process produces no secondary waste (except during the hole drilling) and there are no noise, gas, or airborne considerations. A hole 5 cm in diameter and 30 cm deep takes 1 kg of Bristar.

3.4.1.6 Explosive cutting

Used to segment metals as well as concrete, this method uses an explosive, normally formed in a geometric shape specially designed and sized to produce the desired segmentation. Consisting of an explosive core surrounded by a casing of lead, aluminium, copper, or silver, the cutter produces a high explosive jet of detonation products and deformed casing metal. The shock wave cuts the target material.

Explosive cutting, which must be performed by a licensed contractor, can be performed in air and under water on materials greater than 15 cm thick. But its use is limited since the blast may affect the structural integrity of surrounding structures or produce an uncontrolled spread of radioactive materials. It is therefore used in situations where other cutting methods are not practical or access is limited. Containment control is required because of the high levels of noise, smoke, and debris.

3.4.1.7 Diamond wire cutting

Diamond wire cutting is most often used to cut reinforced concrete monoliths. A cart-mounted unit drives a wire that carries diamond impregnated beads. The wire is either threaded through holes drilled in very large components or, if the component is small enough, the wire completely surrounds the component and is field-spliced. The wire size and length depends on the application (normally 1 or 1.5 cm in diameter) with a cutting speed of 2 to 3 m/hr. This technique has a ratio of 1 m^2 of concrete cut per m of diamond wire consumed.

The diamond wire must be water-cooled during cutting; the water is also used for flushing the debris from the cut. The water consumption, now a secondary waste, is normally 10 to 15 litres per minute. Airborne activity is minimal as long as the cooling water and contained dust is periodically removed.

3.4.1.8 Abrasive water jet cutting

The water jet cutting system uses abrasives (such as garnet) in a high velocity water jet to cut through large pieces of concrete. Achieving cutting speeds up to 1.5 m/hr, the system consists of an intensifier pump, a nozzle head assembly, and an abrasive supply system. The nozzle head assembly can be located away from the supply system in order to permit remote manipulation. Nozzles on this system erode after about 50 hours of use and must be replaced. The main waste stream is water-generated at the rate of 5 l/min. Airborne contamination is not a concern, but cross-contamination due to water spray and mist must be considered.

3.4.1.9 Other techniques

Inefficiencies and narrow or specialized task application are the key reasons for not using various other cutting techniques. While they may be suitable on a small scale, they are not considered viable for the scope of a decommissioning project. Examples of these slower, more narrowly focused, techniques are:

- *Paving breaker*: normally used for breaking up pavement;
- *Chipping hammer and chisel*: limited in application;
- *Core stitch drilling*: requires additional technology application, i.e., rock splitter and rebar cutter;
- *Power saws*: normally under-powered and inadequate blade technology.

3.4.2 Concrete blasting

Concrete blasting is a general term to describe indiscriminate removal of concrete, without regard for keeping the structure in workable form. Concrete blasting normally results in rubble that is not conducive to further decontamination. The decision to blast should follow the determination to dispose of an entire structure as either clean or as radioactive waste.

An acceptable method for removing a clean structure is to survey and release it in-place before demolition. This process is less time-consuming and radiologically more concise than attempting to survey rubble after demolition. The following criteria must be satisfied to dispose of an entire structure as clean material:

- The entire structure must be radiologically free of contaminants - all smearable surfaces and all internal surfaces and penetrations.
- Destruction must not subject the structure to cross-contamination from other sources (e.g., allowing a clean wall to fall into an area with a contaminated floor).
- Material from the structure must be controlled as clean until removed from the radioactive waste area.

The determination to dispose of a structure as contaminated should be reached only after it satisfies the following criteria:

- The structure is completely (not superficially) contaminated.
- All efforts have been made to decontaminate the contaminated portions of the structure.
- Other options have been evaluated and discarded (e.g., cutting out contaminated sections).
- No other viable alternative is available.

Controlled blasting is used to demolish concrete greater than 0.5 m thick, provided it is not limited by the effects of noise and shock to adjacent occupied areas. Controlled blasting produces the high degree of fragmentation needed for heavily reinforced concrete. The exposed reinforcing bars must then be cut by other methods (torch or bolt cutter). The high level of dust in the work area must be carefully controlled. Controlled blasting is used to achieve maximum demolition at a minimum cost, but it is also used to reduce occupational exposure to personnel. Personnel can ensure a minimum spread of contamination by using the following preventive techniques:

- Using explosive charge sizes that minimize rock throw and dust generation while accomplishing the intended task;
- Applying a three-element blanket.

Application of the three-element blanket means:

- Three layers of sealant (e.g., TURCO 5580-G) to the concrete seals in the contaminants;
- Layered tar paper and rubber-backed carpet to absorb the blast and limit rock-throw;
- Cover of all exposed surfaces and those beyond the perimeter with a protective material (e.g., Hypolon) to protect against contamination.

Following are details about the types of controlled blasting currently available:

- *PETN (Pentaerytritol Tetranitrate)*: This explosive is primarily used in the form of a detonating cord. It is effective for surface spalling that requires the removal of very small sections of about 20 cm from an exposed surface.
- *High- Velocity (85 %) Gelatin Dynamite*: This explosive is used in shallow holes ranging in depth from 500 into 150 cm. It may also be used as a partial loading in selected holes when a concentrated energy is needed in a particular area. While the breakage created is excellent, this explosive produces high quantities of dust and crushed stone around the bore hole.
- *Cast TNT (High Detonation Pressure Primers)*: This explosive is used to achieve a high degree of fragmentation with less of a heaving effect than with conventional dynamite.
- *Binary Energy System*: This liquid explosive is normally mixed immediately before use and is not considered an explosive until mixed. It is used as a replacement for

TNT during the spalling of surface contamination and to make shaped charges that can be used to punch holes in high-density concrete.

- *Water Gel Explosives*: Gelatin dynamite is sometimes replaced by a water gel explosive containing a large amount of aluminium. It produces good shattering characteristics and larger rubble than other explosives. It is mostly used in areas of little or no reinforcing rods, where larger sized rubble is preferred.

3.4.3 Surface erosion/removal

Surface erosion/removal is the removal of concrete structures by gradual erosive techniques, such as scarification (also known as scabbling), or massive demolition. Selecting a particular technique depends on several considerations:

- Radioactivity associated with the target area;
- Worker exposure;
- Potential for release of radioactive particulate during demolition, via fluid leaks or airborne activity;
- Porosity of the concrete (potential resistance to non-destructive cleaning methods);
- Actual volume of material to be removed;
- Reinforcement (imbedded and superficial) of the concrete;
- Accessibility of the structure to be removed.

Typically, a concrete shield surrounding a radioactive source will consist of massive sections (0.5 to 5 m thick) of standard (2200 to 2400 kg/m^3) or high-density concrete (magnetite or metal aggregate, 4000 to 5000 kg/m^3). Some concrete shields are also heavily reinforced to meet seismic design criteria. The technique selected will either remove the whole object or only the contaminated portions.

The more practical methods for complete removal reduce the concrete to rubble. These methods are described in the following sections.

3.4.3.1 Controlled blasting

Controlled blasting reduces concrete sections to rubble by controlling the actual explosion and its effect on material movement and adjacent structures. When applied to thick, massive, or heavily-reinforced concrete sections, the wave created by detonation separates the fractured boreholes and moves the material toward the structure's free face. The boreholes are pre-drilled in the concrete and are loaded with explosives. The various types of explosives and the method's operational characteristics were discussed previously.

3.4.3.2 Wrecking ball/slab

The wrecking ball is typically used for unreinforced or lightly reinforced concrete structures less than 1 m thick. This 2 to 5 ton ball or slab, suspended from a crane boom, repeatedly impacts the structure and reduces it to rubble. While it is an effective demolition technique, the wrecking ball is not recommended for use on radioactive structures for its inaccessibility to internal structures and its inability to control dust generation or rebound impact.

The wrecking ball has been used on decommissioning projects, but only after all radioactive material has been removed from a facility. The equipment and operating crew required make this technique costly and useful only in limited applications.

3.4.3.3 Backhoe-mounted ram

The backhoe-mounted ram is a backhoe arm equipped with an air or hydraulically-operated impact ram fitted with a chisel point. The chisel point impacts structural surfaces at a rate of about 600 blows per minute, at up to 3000 Joule of energy per blow, depending on the size of the ram head. This configuration normally keeps the operator away from the structure being demolished due to the reach (6 – 7.5 m) of the backhoe arm. This technique is used extensively on many decommissioning applications because of its versatility and relatively low rental costs. Generated dust and noise pollution are adverse side effects that must be considered, but the overall effectiveness on concrete structures (less than 0.5 m thick) makes this process valuable for the removal of interior walls and floors.

The removal rate of a backhoe-mounted ram will vary greatly depending on accessibility, radiological concerns, and the method used for removing rubble. More recent technology uses the same concept but allows for remote operation of the backhoe, thus reducing worker exposures. Such remotely operated units (e.g., Brokk) are available in a variety of sizes and have a number of decommissioning applications.

3.4.3.4 Wall and floor sawing

Cutting speeds for concrete saws vary, depending on the thickness of the concrete and the amount of reinforcing metal present. A thickness of up to 1 m (with a maximum of one third of the blade's diameter) can be cut at about 1 m^2/min.

Saws can be operated manually or remotely, with a corresponding increase in cost for the remote systems. The structure and thickness of the concrete determine how often the blades must be changed, thereby affecting the overall cost. The reasons for using floor and wall sawing are:

- Keeps disturbance of surrounding areas at a minimum;
- Removes only affected areas of a structure, enabling waste minimization;
- Facilitates handling of smaller sections that can be decontaminated;
- Removes structural sections to gain access to affected areas without unnecessary disruption of the area;
- Improves accessibility to limited-access areas.

Saw blades for floors and walls are usually water-cooled and that water must be treated as radioactive waste, along with the minimal dust generated by the process. The process of cutting can be slow, depending on the material being cut, but it is a useful technique. Concrete sawing is cost-effective but has limited application.

3.4.3.5 Paving Breakers / Chipping Hammers

Sometimes better known as jackhammers or pneumatic drills, paving breakers remove concrete by mechanically fracturing localized sections of the surface. A hardened tool steel bit (either a chisel or moil point) is driven into the concrete surface by a reciprocating motion at the rate of about 1600 blows per minute.

The ‘hammer’ itself is either a compressed air or hydraulic fluid pressure source that sends energy to the bit at the rate 50 to 150 Joule per blow. Paving breakers are primarily used on floors to remove small areas that are inaccessible to heavy equipment. Paving breakers are also used to scarify surface areas of concrete where contamination has penetrated several inches. Using the paving breaker generates large amounts of dust and noises, requiring environmental controls. Although a relatively slow process, paving breakers are cost-effective and have proven to be valuable equipment.

Chipping hammers are similar in concept but are lighter (7 – 15 kg), making them suitable for hand-held for use on walls and ceilings. Their rate of delivery is normally about 2,000 blows per minute, but the nail size is about half that of the paving breaker and their weight (up to 15 kg) makes them cumbersome. They are used to scarify small areas of walls where contamination may have penetrated several centimetres. Continued use renders them impractical except for instances where there are no other options. Reasonably priced, they are effective for removing surfaces in a partially contaminated structure.

Neither the paving breaker nor the chipping hammer is designed specifically for the complete removal of a structure, but rather as an aid to removing small pockets of contamination or to reach areas not otherwise accessible. Several of each type are found at decommissioning sites and they are considered essential tools for decontamination.

3.5 General lessons learned from the implementation of dismantling techniques

Lessons learned from the implementation of dismantling techniques refer to the following aspects [7]:

- Plasma arc and all other thermal cutting systems tend to spread contamination and require means to contain the contamination. Therefore, while mechanical cutting may be slow initially, it could prove to be more efficient in the longer term. All the advantages and drawbacks of the different methods (cutting speed, overall speed, secondary waste generation, dose uptake, cost, etc.) should be balanced.
- Underwater cutting (for highly irradiated pieces) is very efficient and the dose uptake does not depend significantly on the specific activity of the work piece.
- The appropriate tool should be used in its proper place. Investment costs are minimal when compared with waste and staffing costs and should not be the driving factor in tool selection.
- Maintenance, tool replacement and ease of decontamination are important factors in selecting a tool.
- The amount of planning required for power supplies, support systems and a central cable network should not be underestimated. Flexibility is essential if unplanned events are to be accommodated.

3.6 Robotic dismantling techniques

Remote controlled techniques are used in areas where the dose rate levels do not enable the full day work presence of personnel, or there are other hazards to human which exclude the presence of personnel in the working ambient of dismantling task [7].

In general, robotic wheeled/tracked vehicles are used for characterization, decontamination and dismantlement tasks. Other developments include: bridge mounted robotic platforms; power sources for mobile platforms; failure recovery equipment; automated separation technology; pre-programmed obstacle avoidance; programmed motions; teach/playback; voice control; transportable control systems; hardware (umbilical); laser based communication; force feedback; and flow, mass and volume sensors. These techniques are currently considered as mature technologies.

There are also other remote controlled techniques under development and also already in use like internal pipe/duct crawlers; light, medium and heavy duty long reach arms; arms with more than six degrees of freedom; remote/automated interchangeability; tool-arm interfaces; force limiters; multiple concurrent mobile platform controls; combined mobility/ manipulation/end-effector controls; sample management; data integration/fusion; fuzzy control; microwave communication; radio frequency based communication; 3-D vision; high definition television; directional audio; wall thickness measurement; laser range finders; and force controls.

Another area of remote controlled techniques are the compact high capacity arms, multi-fingered end effectors, single human multiple vehicle control stations, human-robot symbiosis, imaging and image processing and proximity probes and positioning.

Remote controlled techniques are used especially in decommissioning projects for nuclear power plants after an accident, for the management of damaged spent fuel or for the management of various specific historical wastes. Several groups of robotic systems can be recognised:

- *Deployment systems*. Deployment systems in this context are systems such as manipulators, xyz-frames or remotely controlled vehicles which can be used to deliver a tool to a work-site and deploy it. Deployment systems can be used to facilitate the decommissioning tasks and to reduce human exposure to radiation and contamination.
- *Viewing and detection equipment*. These are systems which allow the operator to view remotely the work-site or allow data and information on the operating environment to be collected without manual intervention.
- *Segmenting and disassembly equipment*. The presence of high radiation fields or contamination levels often requires that segmenting and disassembly equipment be controlled and monitored remotely. Progress in electronics and sensor technology has led to considerable advances in the area of remote operation in both air and water.
- *Decontamination equipment*. The decontamination equipment considered here is primarily for use as an end-effector to a remotely deployed arm or other delivery device. As with the deployment systems described earlier, this is an area of considerable research and development activity and new advances are being made almost continuously.
- *Material handling equipment*. Remote material handling equipment has been developed and used on various projects in the USA: the versatile remote handling system (LANL); the T-Rex materials system and a handling system, both being developed at ORNL; a vehicle for autonomous waste transfer (Idaho National Engineering Laboratory (INEL)) ; and a mobile work system to be used specifically for retrieving Fernald K-65 silo waste.

In the selection of remote controlled equipment the following should be considered:

- Work specification and task analysis;
- Dimensions and location of the workplace;
- Access and disposal route;
- Size and weight of the component involved;
- Type and quantity of generated waste;
- Environmental conditions;
- Available services and auxiliary systems;
- Maintainability and reliability;
- Failure recovery methods;
- Safety and regulatory requirements;
- Cost and schedule factors.

The lessons learned from the implementation of remote controlled techniques refer to the following aspects:

- The use of robotics should be considered only after a thorough analysis of other options has been made. This statement reinforces the general message, which is to keep decommissioning simple.
- Few projects require tele-manipulators or sophisticated tools. Simple tools, having only a few degrees of freedom, are often sufficient for most operations. Remote tools need to be user-friendly, readily adaptable and robust.
- To be useful for decommissioning applications, manipulators need a sufficient payload capacity and must be robust. In addition, in the selection of tools, it is good practice to allow for contingencies arising from reaction forces and other factors. Control of manipulators when operating at full payload capacity is often poor.
- Stereo viewing systems are beneficial for use with machines having several degrees of freedom.
- Umbilical and cable management is always a problem. This has been partially solved in some recent applications, but improvements are still needed.

4. Aspects of the implementation of dismantling and decontamination techniques in decommissioning costing

Costing in decommissioning is the area where the data are developed for:

- The selection of a decommissioning strategy;
- The funding of decommissioning;
- The project management data for planning of decommissioning.

Decontamination and dismantling activities represent some of the most important parts of the decommissioning costs. Therefore, this section reviews the relation of the decontamination and dismantling activities to the decommissioning costs and highlights the aspects about the decontamination and dismantling activities that should be respected in decommissioning costing. Individual aspects are further discussed in Sections 5 to 9 of this document.

The costing aspects discussed in Sections 4 to 9 are mostly related to a costing methodology implementing the cost structure as defined in the document ‘Proposed Standardised List of Items for Costing Purposes’ [33]. The details of the methodology which uses this structure are presented in the document ‘Cost Aspects of Decommissioning’ relating to the activities in Work Package 2 of the Co-ordination Network on Decommissioning of Nuclear Installations’ [34]. Principles of the discussed methodology can be applied also in other costing systems.

4.1 Relation of decontamination and dismantling techniques to decommissioning costing

Decommissioning cost estimates are generally based on a detailed decommissioning strategy and a detailed decommissioning plan, and may also be used as a basis for contracting, as a starting point for establishing a project baseline for costs and schedule management, and for cost accounting and scheduling purposes during the decommissioning operations. Reliable cost estimating is one of the most important elements of decommissioning planning.

Alternative technologies may be evaluated and compared on their efficiency and effectiveness, and measured against a baseline cost as to the feasibility and benefit derived from the technology. This principle ensures that the cost consideration is economically sound and practical for funding.

This refers especially to decontamination and dismantling techniques because the scenario of the decontamination and dismantling of systems and structures has a major impact on the subsequent waste management activities and on the final state of the facility. These two aspects belong to the most important factors of decommissioning costing. Therefore, a proper involvement of decontamination and dismantling techniques has one of the most important impacts on decommissioning costing.

The main aspects of the involvement of decontamination and dismantling techniques (further referred to as D&D) in decommissioning costing comprise:

- Aspects of the implementation of D&D techniques into costing (see this Section 4);
- Parameters of D&D techniques related to costing (see Section 5);
- Safety aspects of dismantling and decontamination techniques in decommissioning planning and costing - how to organise the involvement of D&D activities in relation to the safety of decommissioning (see Section 6);
- The organisation of data of D&D techniques in databases: structure of the datasheets (see Section 7).

- Implementation of D&D techniques into the structure of the ‘Proposed Standardised List of Items for Costing Purposes’ (further referred to as ‘PSL’ structure) [33], including a review of segments of the ‘PSL’ structure in relation to D&D techniques (see Section 8); a detailed description of the ‘PSL’ structure is presented in [34].
- Methods for the selection of D&D techniques for costing: organisation of the data for the techniques in selection matrixes (see Section 9).

4.2 Purpose of decommissioning costing and relation to D&D activities

Experience accumulated shows that a reasonable degree of reliability and accuracy can be achieved by developing cost estimates based on a case-by case site/project specific evaluation. This means that decommissioning costing should involve proper D&D activities which are most suitable for the given conditions of the decommissioning case.

In general, the main purposes of decommissioning costing are defined at various levels:

- *Governmental level*: to inform the government and guide their policy for assuring that decommissioning funding will be available when needed.
- *Facility level*: to determine the funding requirements and the financial liabilities.
- *Planning level*: as a basis for industrial strategy and planning of the decommissioning activities.

Governmental level

The results of decommissioning costing at the highest level should have such a structure and reasoning that a government/regulator can develop an appropriate understanding of the decommissioning costs as an input to policy and regulation development in order to assume that adequate funds for decommissioning are appropriately collected.

Another important issue of decommissioning costing at the highest or at the international level is the comparability of calculated costs. Without proper common understanding of individual cost items, comparability is hampered. In relation to the common understanding of costing issues, the use of a standardised cost structure is an important issue [33]. The ‘PSL’ structure is now identified as a common platform for harmonisation in decommissioning costing.

The issue also reflects the requirement of international comparability of individual cost items in relation to D&D activities. The involvement of D&D activities in decommissioning costing should therefore respect the ‘PSL’ structure of the decommissioning activities.

Facility level

At facility level, decommissioning costs are generally based on an agreed decommissioning strategy, and will focus on the amount of money necessary and the timeframe for spending the collected fund. Decommissioning cost estimates that are made for this purpose are therefore periodically updated to reflect the current decommissioning strategy as well as the actual state of the decommissioning technology.

Having this in mind, the involvement of D&D activities should be performed in a way that enables periodical updating of the decommissioning cost when the criteria and the input data have changed, i.e., the D&D activities should be organised in the decommissioning planning and the subsequent costing such that a compact calculation structure is developed which can be updated when needed, based on modifications of the input data.

Planning level

The results of cost estimates used for planning may be well more detailed than those serving the development of an overall cost envelope for the purpose of decommissioning funding.

A decommissioning cost at planning level is generally based on a detailed decommissioning strategy and a detailed decommissioning plan, and may also be used as a basis for contracting, as a starting point for establishing a project baseline for costs and schedule management, and for cost accounting and scheduling purposes during decommissioning operations.

At the level of planning of elementary D&D activities, the cost calculation should correspond with the structure of the decommissioning tasks. The relations between the elementary decommissioning activities and the decommissioning tasks should enable a detailed planning of the decommissioning project. The organisation of decontamination and dismantling activities should be structured to the level of detail that enables the development of a detailed planning for performing the activities either by a contractor or by own personnel of the license holder.

The main message at planning level is that the organisation of the calculation of costs and other decommissioning parameters should be able to produce the project management data (costs, manpower, exposure, duration, etc.) in a structure usable for contracting or for detailed planning of the decommissioning activities carried out by own personnel.

4.3 Costing principles for decontamination and dismantling activities

In general, proper evaluation of decommissioning costs is important for following issues and relevant measures for achieving the listed aspects are [35]:

- *Selection of a decommissioning strategy and activities*: several decommissioning options should be evaluated.
- *Support to a cost-benefit analysis to ensure that the principle of optimization and reasonably practicable measures are applied*: the extent of evaluated decommissioning options should cover all possible scenarios for D&D activities.
- *Estimate of required financial resources for the selected strategy*: the selected option should involve the D&D activities in a structure and extent relevant to real procedure of D&D activities.
- *Preparation of the project schedule, workforce requirements and phased funding needs*: D&D activities should be structured according to the tasks of the decommissioning schedule.
- *Definition of measures for proper management and maintenance of resources for safe and timely decommissioning*: the time distribution and safety related parameters of D&D activities should be known.
- *Establishment of financial mechanisms*: the distribution of costs and other project management parameters of D&D activities should be the result of decommissioning costing.
- *Harmonisation in costing*: implementation of the standardised cost structure ‘PSL’ into decommissioning planning and costing ensures the comparability of costs for D&D activities [33].

In order to follow the above listed issues, the decommissioning costing for D&D activities should be organised according to the following principles presented in [34]:

- The evaluation of the D&D activities should be done at the level of elementary decommissioning activities;
- The unit factor approach should be used;
- The elementary evaluated decommissioning activities should be organised according to the standardised ‘PSL’ structure.

An elementary decommissioning activity in relation to D&D decommissioning activities means a breakdown of the elementary activities to a level identical to the elementary records in the facility inventory database and a breakdown of preparatory and finishing activities to the level of individual specific activities both for system oriented and for room oriented decommissioning activities [34].

Implementation of the unit factor approach enables making the cost evaluation case specific by developing the unit factors according to the situation within the decommissioning case. This can be achieved by identification of relevant decommissioning categories and developing unit factors for the identified categories.

Organisation of cost calculations for D&D activities according to the standardised 'PSL' cost structure means that the individual D&D activities are allocated according to the segments of the 'PSL' structure.

5. Parameters of dismantling and decontamination techniques related to decommissioning costing

This section gives an overview of the principles of the unit factor approach and its implementation in costing in relation to decontamination and dismantling activities.

5.1 Principles of the unit factor approach

A method widely adopted in cost estimating is the bottom-up technique. Using this approach, a decommissioning project is divided into discrete and measurable work activities. This division provides a sufficient level of detail so that the estimate for a discrete activity can apply to all occurrences of the activity. Groups of repetitive elementary activities can be identified in decommissioning projects. Examples of elementary repetitive activities are cutting a unit length of pipe, removing a valve, a pump, or a unit quantity of concrete, etc.

The bottom-up principle means that costs are evaluated for each elementary decommissioning activity; the extent of elementary activities corresponds with the decommissioning scenario as presented in the decommissioning plan and with the level of detail of the costing case. In the case of D&D activities, their extent should be identified in relation to the accepted scenario.

Practical costing is carried out by identifying all work activities together with their associated material, equipment and service requirements. Subsequently, an estimate is made of the costs arising from each activity, which is subdivided into a series of discrete and measurable elementary work activities for which unit costs are calculated or estimated - unit cost factor approach.

The unit factors define the normalised amount of work related to the unit of input variable for typical decommissioning activities in the decommissioning plan. Unit factors should be adapted for specific conditions at the facility to be decommissioned and to overall decommissioning background related to the case. If for some work activities only limited experience is available, preparing the cost estimate includes a phase-by-phase review of the required data and adequate engineering judgement is needed in order to assess manpower requirements, work efficiencies and time schedules.

The prerequisites for this approach which uses the unit factors and bottom-up principle are:

- *A facility inventory database* [34]: the facility inventory data which have a relation to the implementation of D&D activity parameters are discussed in Section 7.1 of this document.
- *A database of unit factors involving data for all techniques/procedures relevant for the project*: the extent of data for D&D activities is discussed in Section 6 and the format of data in Section 7.1 of this document.
- *A list of all elementary decommissioning activities of the decommissioning project in accordance with the decommissioning plan*: the D&D activities may be organised in various hierarchical structures, in principle according to a work breakdown structure or according to the 'PSL' structure.

The basic classification of decommissioning activities according to the cost drivers of the activities is [34]:

- *Costs for hands-on decommissioning activities*. The main cost drivers are the workers using proper tools or equipment for doing the work and the physical quantity of input variables recorded in the facility inventory database; the human-tools-techniques/inventory driven activities.

- *Costs for period-dependent activities*. The main cost drivers are the duration of the elementary activities and the number of workers involved; the human-presence/duration driven activities.
- *Collateral costs* identified as a kind of specific cost elements which are fairly independent of hands-on activities or period-dependent activities; the cost drivers are mostly the items with fixed cost values.

D&D activities are typical examples of hands-on activities. The data needed for costing are mainly data on techniques represented by manpower unit factors, cost unit factors and data relating to the personnel.

Minor parts of the D&D activities have the character of period-dependent activities. These are mostly the auxiliary preparatory and finishing activities needed for supporting the D&D activities during their implementation. Collateral costs are used for the identification of costs for procurement of equipment for D&D techniques.

The activity-dependent costs in D&D activities are directly related to activities such as decontamination and dismantling components. Costs arise from labour, materials, energy, equipment, services and specific items related to waste management. The costs are directly related to the input variables which in general are mass, areas, volumes, number of pieces, etc., using the calculation principle of unit factors.

A direct relation to the input variables gives rise to implementation of the principle of categorisation of items involved in the inventory database. The size, construction and material composition gives rise to different unit factors for the different equipment to be dismantled. The unit factors are similar for equipment with similar size, physical and material properties and are different for equipment with different constructions. As an example, the manpower needed for the dismantling of pipes with the same weight but with small diameters and thin walls can be several times higher than for the dismantling of pipes with large diameters and thick walls. The reason is the different amount of work needed for the normalised input variable, in this case 1 tone of pipes.

Due to the fact that a large extent of types of equipment can be identified in a nuclear facility, the principle of categorisation proved to be effective in decommissioning costing. The principle is based on grouping of types of inventory items with similar properties into one group for which the unit factors are defined.

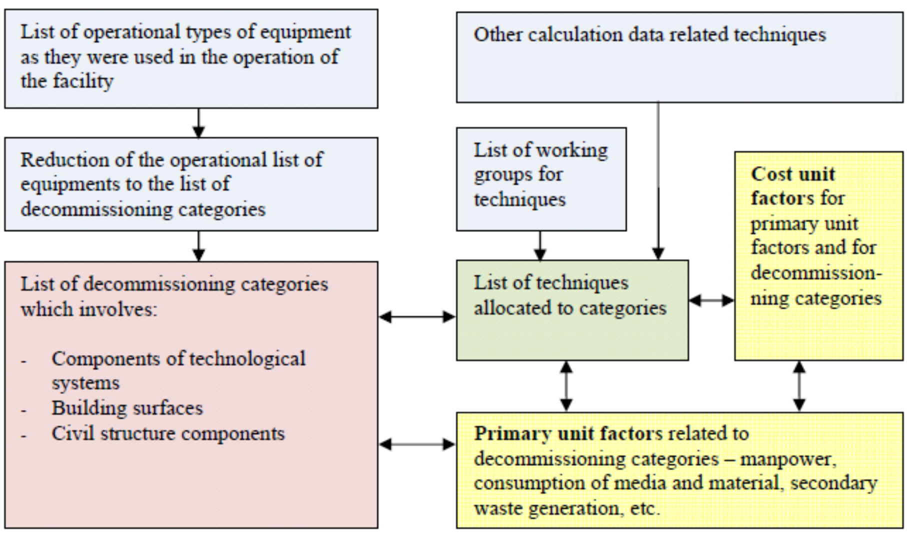


Figure 5.1 Principal scheme of relations between decommissioning categories, unit factors and techniques

The principle of categorisation is also used in the selection of relevant decommissioning techniques for the given category. The various techniques have different properties and the consequences in decommissioning costing are different unit factors for the various techniques. The selection of the optimal decommissioning technique for a given decommissioning category is an important issue in decommissioning costing and the categorisation approach enables to reduce significantly the volume of data needed for decommissioning costing.

The principle of the implementation of the unit factor approach versus categorisation and inventory of elementary decommissioning activities is presented in Figure 5.1.

5.2 Types of unit factors for D&D activities

The extent of unit factors depends on the details of the costing approach. For simple cost calculations one cost unit factor may be sufficient in relation to the decommissioning categories.

This section gives an overview of the extent of unit factors for a costing approach based on the implementation of the 'PSL' structure. In this case, the cost groups necessary for a presentation at the level of elementary D&D activities are:

- *Labour costs* related to personnel allocated in relation to the techniques used;
- *Investment costs* as the cost elements with an investment character;
- *Expenses* which represent all items of technical media, materials and other items spent during performance of the elementary activity;
- *Contingency* as the cost element for compensating unforeseen constraints within the scope of the project.

This list of cost groups defines the extent of unit factors which should be developed for D&D activities. Calculation of labour costs is based on manpower components. So, manpower unit factors are needed for the calculation of manpower as a first step. The investment costs and expenses are in general calculated in two steps. In a first step, the quantities of investment and expense items are calculated and in a second step the costs for these quantities. Remaining cost elements are calculated in direct relation to cost categories. Based on this, the unit factors are classified following:

- Manpower for performing the decommissioning activity;
- Consumption unit factors defined separately for items with investments and expenses character;
- Cost unit factors for individual items listed in the previous paragraph;
- Cost unit factors for investment costs and for expenses not listed in the previous paragraph; the costs are calculated in direct relation to the decommissioning category.

5.2.1 Manpower unit factors

Manpower is the total manpower of all members of the working group needed for performing a given decommissioning activity under pre-defined conditions. As an example, the manpower unit factor for the dismantling of pipes of the category 'Pipes 2 CS' is the manpower needed for the dismantling of 1 tone of pipes made of carbon steel, with a diameter from 100 mm to 250 mm, the cutting length being 1,5 m as the longest dimension of the largest waste transport container is 1,5 m. The manpower unit factors include all activities starting from cutting until placing the material into the transport container.

The manpower unit factor also takes into account whether the inventory item to be dismantled is located within the controlled area or outside of the controlled area. When situated within the controlled area, the sequence and structure of the decommissioning activities should also include all elements of working activities related to the safety of work with radioactively contaminated materials and to work within dose rate fields. Other reasons for differences in manpower unit factors are the conditions for performing decommissioning activities. In the case of dismantling outside of the controlled area, segmenting of materials can be done into pieces with much larger dimensions, if ever. These approaches require different amounts of work which result in different manpower unit factors.

Manpower unit factors are defined separately for decontamination and dismantling activities performed as remotely controlled techniques. The extent of the involved activities is larger, productivity factors are in principle lower due to the nature of the techniques and the number of personnel and qualification requirements are higher. These are reasons why such manpower unit factors may be 5 to 10 times higher when compared with manual techniques.

Manpower unit factors are defined for D&D activities for which the input variable can be defined in the facility inventory database. Examples of these activities are:

- The decontamination of selected systems before dismantling;
- The dismantling of main technological systems like reactors, primary and secondary piping; components which are specific for the decommissioning project;
- The dismantling of auxiliary systems with a general character;
- The dismantling of contaminated and activated structures like reactor shafts, concrete; biological shielding; embedded elements;
- The decontamination of building surfaces;
- The removal of building structures as clean structures.

For some decommissioning techniques which are repetitively performed in the same extent, under the same conditions and representing the same amount of work, the manpower unit factors are constants, for example some preparatory and finishing activities as implemented in the room-oriented dismantling approach.

5.2.2 Other unit factors

Consumption unit factors for technical media represent the amount of individual technical media needed for performing the given decommissioning activity for a normalised amount of the input variable. An example is the amount of technical gases needed for cutting 1 tone of equipment of a given decommissioning category or the amount of electricity needed for the electrochemical decontamination of 1 m^2 of a stainless steel surface. A similar approach is used for the calculation of spare parts and tools for individual techniques.

The identified consumption unit factors for technical media and for spare parts and tools cover normally part of the costs needed for using the given decommissioning technique. In order to calculate the complete costs, the rest of the costs can be expressed as cost unit factors involving all expenses other then the identified consumption items. A similar approach can be implemented for the calculation of investment costs, by defining the cost unit factors for the investment costs per individual technique or technology:

- Investment unit factors for the consumption of materials and spare parts of investment character; the involvement of items into the category of investment cost is defined in national accounting principles.
- Non-specified investment cost unit factors not related to items listed in the previous paragraph; the investment costs are calculated in direct relation to the quantity of the decommissioning category; depreciation factors or costs for hiring may be involved.

- Consumption unit factors for general expenses - general technical media spent in the process like electricity, steam, fuel oil, compressed air, technical gases, etc.
- Consumption unit factors for specific expenses - items specific for individual processes like tools and spare parts, specific media and materials.
- Non-specified expenses - the cost unit factors expressing the total cost for specific items for which the quantities are not required; the expenses are calculated in direct relation to the quantity of the decommissioning category.

Within the cost calculation system, the above listed unit factors are completed with the cost unit factors for individual consumption items, like cost unit factors for electricity, steam and other media and material items.

5.2.3 Grading aspects in the unit factor approach

The principle of a decommissioning category can be easily graded. At the initial or preliminary level of decommissioning costing, manpower unit factors can be developed for several typical categories. Other unit factors for these several categories can be defined as an overall cost unit factor covering all costs other than labour costs. This calculation approach enables to calculate the manpower uniformly at all stages. Later, at the conceptual level of decommissioning costing, the extent of unit factors can gradually be extended for a limited number of decommissioning categories. Finally, at the level of detailed decommissioning costing, the extent of unit factors and the amount of decommissioning categories can be developed to the final level of detail, depending on the size and the complexity of the facility to be decommissioned.

5.3 Other data related to D&D activities

In addition to the above listed unit factors, the following main groups of data for D&D techniques are required for decommissioning costing:

- Working group data;
- Non-productive working time components and increase factors;
- Data for the procurement of equipment and tools for D&D techniques;
- Generation of secondary wastes and radioactive aerosols.

Some of these data are organised within data sheets for individual D&D techniques and some within the general database for calculation data.

5.3.1 Working group data

Working group parameters include the assignment of working groups to individual activities. Based on the composition of a working group, the calculated manpower components for individual working groups and the labour cost unit factors for individual professions, the labour costs can be calculated. Labour costs represent one of the major components of the decommissioning costs (approx. 40 to 60 %, depending on the decommissioning case and the local conditions). Therefore, a proper definition of the working groups for D&D techniques is important for decommissioning costing.

Working groups consist of individual universal professions and for each profession are defined labour cost unit factors. Each profession in working group has assigned number of workers. It is recommended to define limited set of several representative professions in order to keep the extent of calculation in reasonable extent. As an example, following professions can be used for definition of the working groups:

- manager - average personnel on the management level;

- senior engineer - experienced graduated engineer (normally more than 10 years of experience in the field, as an example),
- engineer - standard graduated engineer;
- technician - qualified operator in relevant branch with secondary school education;
- administrative worker - average worker in an administrative position;
- skilled worker - qualified craftsman, performing the qualified D&D activities;
- auxiliary worker - semi skilled worker, performing auxiliary works, normally superintended by skilled workers;
- averaged profession - as an alternative for the seven above listed professions when not sufficient data are available for the definition of the working group.

The above listed professions can be used for the definition of working groups for individual D&D techniques and for the definition of the specific composition for period-dependent activities which are used as auxiliary activities for hands-on D&D activities. The above listed representative professions can be replaced by an averaged profession which is used mostly in preliminary costing stages or in cases where it is difficult to identify the proper professions.

5.3.2 Non-productive working time components and increase factors

Individual working groups for hands-on decommissioning activities have also assigned a structure of non-effective working time components which reflects the time needed for preparing and supporting the execution of work for the given decommissioning activity like entering of the workers into the controlled area, breaks in work, moving of personnel during working time within controlled area, exit from controlled area, etc. These fractions are normally expressed in percentage related to effective working time calculated.

Non-productive time components may be defined for work within the controlled area and work outside of the controlled area. They are used for increasing the manpower calculated for individual D&D activities. A principal structure of the productive and non-productive components of the working time is presented in Figure 6.1.

Other reasons for increasing the manpower for hands-on D&D activities are the working constraints which make the work more difficult in comparison with the work under ideal conditions. It is expressed by increase factors which prolong the duration of the individual activities related to the working constraints for the personnel. Examples for implementing such increase factors are:

- The work in areas with dose rates which modifies the character of the working sequence in order to keep the exposure as low as possible;
- The work when using the protective means (starting from respirators up to protective overalls with additional air for breathing which lower the work effectiveness);
- Work on heights on scaffolding which requires additional supporting partial activities in order to achieve the original goals;
- Work in congested areas which prolongs the duration of the D&D activities;
- Work on complicated tasks; the sequence of performing of decommissioning activities requires additional ad hoc solutions during the performance of the given activity.

These data are normally contained in the database of calculation data mostly in the form of interval functions; it means that for identified intervals of selected parameters contained in the inventory database, the increase factors are defined.

5.3.3 Procurement of equipment for D&D techniques

The group of data for the procurement of equipment and tools for D&D activities is grouped according to the calculation methods as follows:

- The quantities of hand-held instruments and tools spent within the process (mostly hand-held instruments) are calculated based on deterioration factors and on quantities of the input variables.
- The costs for equipment used through the whole process are introduced into the costing system as a list of fixed cost items with the data for their need. The cost items are prepared as a list of items to be procured together with the dates of procurement.

5.3.4 Secondary waste and radioactive aerosols

Some methodologies for decommissioning costing also use elements of material and radioactivity flow for the calculation of secondary waste productions and for the calculation of the release of airborne radioactivity in order to evaluate the impact on the environment and on the personnel. Following basic approaches can be identified for the calculation of quantities of secondary wastes and released airborne radioactivity [38]:

- The generated secondary waste is calculated based on production factors for the waste, depending on the individual D&D techniques. The calculated quantities are used as input variables for the calculation of the parameters of individual waste management technologies. As an example, the volume of removed contaminated concrete by mechanical decontamination is calculated based on the decontaminated area and a production factor (dm^3/m^2) depending on the removal depth. Various factors can be developed.
- Factors for the generation of airborne radioactivity in the form of radioactive aerosols depend on the physical or chemical principles of the individual D&D techniques. The temperature of the process and the level of mechanical disintegration belong to the most important factors in the generation of radioactive aerosols. The data normally reflect the composition of the radio-nuclides in the contamination or the activation of the materials. The data are then used as input variables for the calculation of doses to the public and for the calculation of the exposure of the personnel.

6. Safety aspects of dismantling and decontamination techniques in decommissioning costing

6.1 Safety related parameters for D&D activities

Evaluation of safety related parameters for planned D&D activities belongs to the standard activities in decommissioning costing and planning and in the selection of the optimal decommissioning strategy. This section presents the approach that was implemented within a project of the International Atomic Energy Agency, 'Evaluation and Demonstration of Safety for Decommissioning of Nuclear Facilities' [36]. The methodology is presented in Appendix A of [36] for a test case for a nuclear power plant.

The methodology for the evaluation of safety related parameters was developed in the framework of the costing methodology OMEGA which implements the 'PSL' structure directly into costing [37].

Subjects of the evaluation of safety related parameters are:

- Collective effective doses to workers for planned D&D activities;
- Individual effective doses for the most exposed individuals performing the work in the most hazardous areas of the nuclear installation;
- Evaluation whether the D&D activities can be performed by manual or remote techniques.

The section gives an overview of the principles of these evaluations and presents the data on D&D techniques needed for such evaluations.

6.2 Principles of dose calculation for personnel

The principles of the calculation of manpower during dismantling, as applied in the OMEGA computer code, include calculation of the manpower components for individual professions of a working group and calculation of the exposure of individual professions for elementary manpower components, as follows [36]:

- Calculation of manpower for elementary decommissioning activities;
- Distribution of calculated manpower to individual professions of the working group;
- Extending the manpower for non-productive working time components;
- Calculation of external and internal exposure based on local radiological conditions, protective means and manpower components.

Calculation of manpower and exposure is different for groups of decommissioning activities. Three main types of decommissioning activities regarding exposure of personnel may be considered:

- *Hands-on decontamination and dismantling activities*. The exposure is dominated by dose rates at working distances of the equipment to be dismantled. The exposure can be controlled partially by the duration of stay of the workers in the vicinity of the dismantled equipment, by the application of more personnel or by the application of remote dismantling techniques or pre-dismantling decontamination of the equipment to be dismantled.
- *Work at technological facilities for radioactive waste processing*. The exposure is controlled by appropriate technical means at the working place for the workers, like shielding, and can normally be kept below the annual exposure limits.

- *Period dependent activities like surveillance, maintenance, management, technical support*. The exposure is controlled by organisation of the working time and can normally be kept below the annual exposure limits.

From the point of view of calculation of exposure, critical decommissioning activities are the dismantling activities, where the personnel during implementation of the decommissioning activity is closely present to the contaminated equipment. The dose uptake during the decommissioning activity is calculated as external and internal exposure of the workers. External exposure is calculated based on the duration of the activity and the dose rate at the working place, and the internal exposure is calculated based on the concentration of aerosols generated during the decommissioning activity and their conversion factors, considering the applied personnel protection means and breathing data.

The bottom-up principle, implemented in the methodology, enables to calculate the exposure data at the level of an elementary decommissioning activity. Each hands-on decommissioning activity is decomposed into elementary productive and non-productive manpower components and for each manpower component, the relevant radiological data are allocated based on the inventory data of the facility. The model time structure of an elementary decommissioning activity, as defined in the calculation model, is presented in Figure 6.1. The selected approach is the attempt to model the real sequence and the content of decommissioning activities of this type.

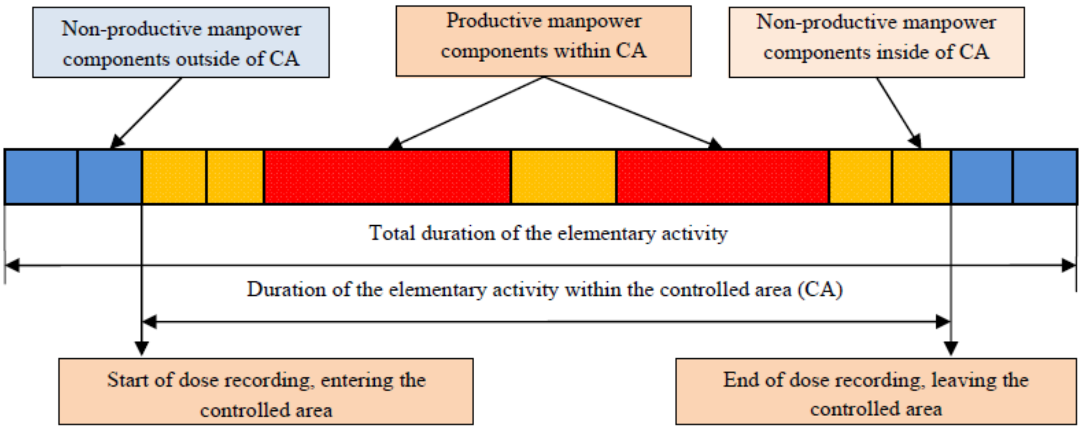


Figure 6.1 Principal composition of the working time for hands-on activities; productive and non-productive working time components of an elementary decommissioning activity

The first step is calculation of the productive manpower components. All other non-productive manpower components are calculated based on coefficients which increase the basic productive manpower. The productive manpower components, depending on the working conditions, can be increased based on the difference between the ideal and the local working conditions, like working in an ambient with ionising radiation, etc.

Another aspect which is taken into account when calculating the exposure of workers, are the different working conditions for different professions of the working group. For each decommissioning activity, a working group is defined - professions needed and number of workers per profession. The various professions of the working group are exposed differently from the contaminated equipment and/or from the average dose rates in the rooms and in the background of the controlled area.

In the case of internal exposure, the OMEGA code allocates to the personnel proper protection means, depending on the local conditions, in order to decrease the amount of inhaled aerosols. Therefore, the exposure of personnel is calculated at the level of the individual profession of the working group. As a summary the principal scheme for the calculation of the exposure of personnel is presented in Figure 6.2.

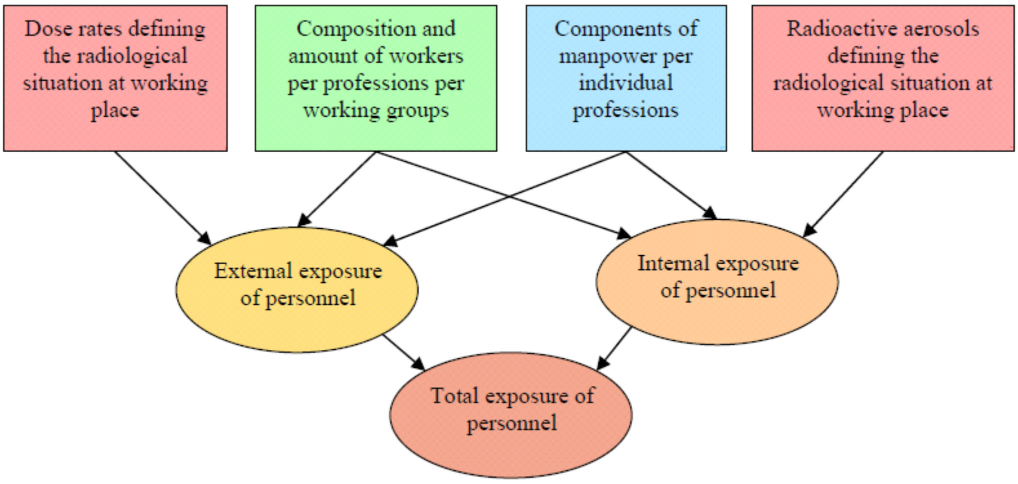


Figure 6.2 Principal scheme for the calculation of exposure of personnel

The main input data needed for the calculation of exposure of personnel are:

- The manpower components resolved according to the individual professions of the working group;
- The composition of the working group - professions and number of workers per profession;
- The dose rate data - dose rate at 0.5 m from the equipment (average working distance), average dose rate in individual rooms of the facility, average background dose rate of the facility;
- The concentration of aerosols in working places, depending on the release factors of the dismantling techniques, local and facility ventilation, personnel protection means allocated.

Calculation of the productive manpower for dismantling is then based on the mass of the equipment and the manpower unit factors for the individual categories of equipment. Various increase factors can be applied when calculating the productive manpower, like increase factors for work in environments with high dose rates, work on scaffolding, work in congested areas, work on complicated tasks, etc The manpower is further increased for non-productive working time components as presented in Figure 6.1.

The manpower calculated as total manpower for the elementary decommissioning activity is distributed down to the level of individual professions. These profession resolved manpower components are then used for the calculation of the exposure of individual professions of the working group.

6.3 Calculation of external exposure

The dose uptake during implementation of the planned decommissioning activities is evaluated for each of the individual decommissioning activities and has components as follows:

- The dose uptake caused by the dose rate at 0,5 m from the equipment (average working distance) to be dismantled;
- The dose uptake caused by the average dose rate in the room where the equipment is dismantled;
- The dose uptake caused by the average dose rate in the background of the controlled area of the facility.

The dose rate relevant for the calculation of the dose uptake during implementation of the preparatory and finishing activities, is the average dose rate in the room and in the background of the controlled area.

The individual professions of the working group are exposed in different ways in accordance with the type of work they perform. The most exposed professions are those who directly perform the dismantling activities and are most exposed to the dose rate of the dismantled equipment. For other professions, the average dose rate in the room is dominant. For the rest of the working time, the dose rate in the background of the controlled area is applied. These conditions are taken into account in the calculation of the dose uptake for the individual professions of the working group. They are expressed by coefficients of effective stay at working distance of the equipment and coefficients of effective stay in the average dose rate in the room.

The coefficients for dose rates from equipment range from 0,1 to 0,5. The 0.5 values are allocated to workers performing the cutting and the dismantling of the equipment. The lowest values are allocated to the foreman of the working group. The coefficients for the average dose rate from the room also range from 0,1 to 0,5. The lowest values are allocated to the dismantlers, the highest values to the workers supporting the dismantling activities.

The dose uptake for individual elementary decommissioning activities is calculated as the sum of the dose uptake for the individual professions of the working group for the individual productive and non-productive components of their working time. The calculation is performed for each elementary preparatory and finishing activity according to the rooms involved and for each inventory item in a room as recorded in the inventory database. The principle of calculation of dose uptake for dismantling activities is presented in Figure 6.3, including the data of the D&D activities needed for calculation.

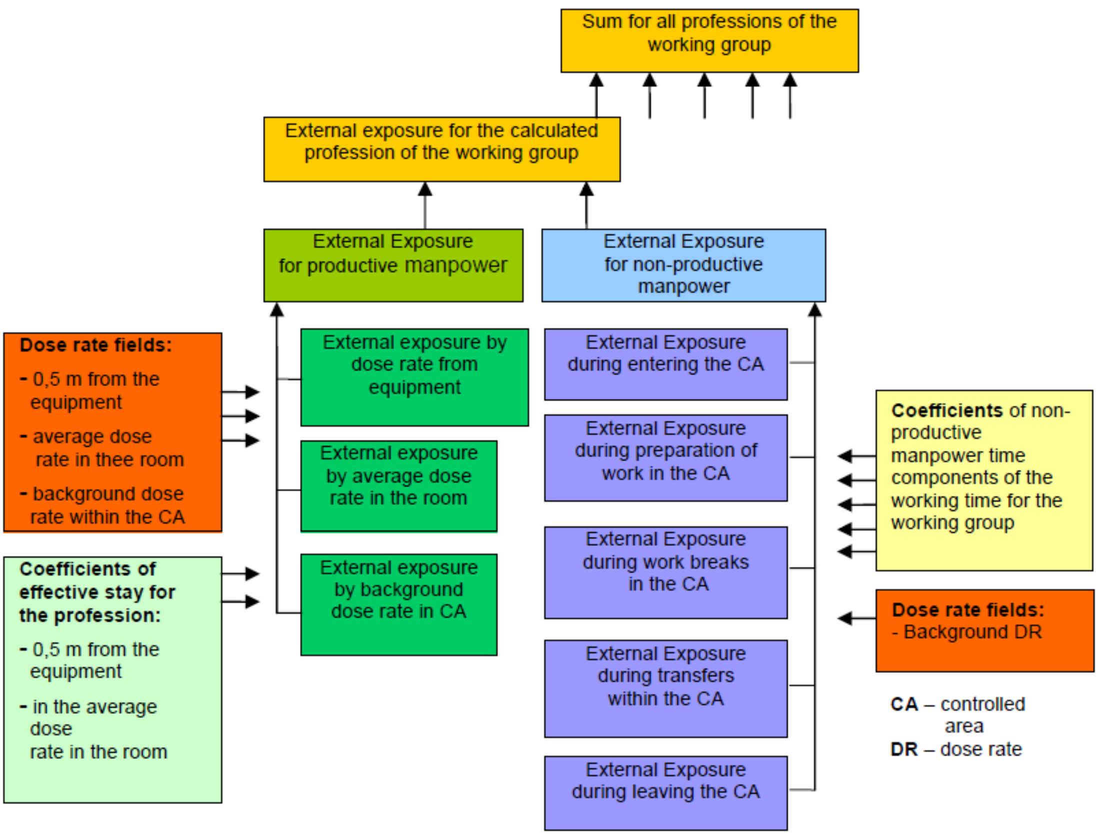


Figure 6.3 Concept of calculation of the dose uptake for individual dismantling activities

6.4 Calculation of internal exposure

The calculation of internal exposure is based on the following input data:

- Productive and non-productive manpower components;
- Volume concentration of aerosols at the working place;
- Average volume concentration of aerosols in the rooms;
- Background volume concentration of aerosols in the controlled area;
- Breathing data;
- Conversion factors for individual radio-nuclides (Sv/Bq);
- Retention factors of protective means.

Manpower components are the same as in the case of external exposure. Volume activities of aerosols at the working place are calculated using the release factors of individual radio-nuclides resulting from the use of the specific decontamination and dismantling techniques or other operations. Other data may result from the database of calculation parameters. As an example, the retention factor for a simple filter respirator is considered to be 0.9, for portable breathing sets 0.999, and for whole body intervention clothing with external air supply 0.9999.

In the OMEGA code, it is first evaluated what would be the internal dose for the worker if he would not use any protective means, and based on this calculated hypothetical value, the code allocates the necessary protective means in order to keep the dose as low as reasonable achievable. The calculation of the effective dose from internal exposure is then performed under the assumption that the worker uses the allocated protective means. The average volume activity of aerosols in the room and the average volume activity of aerosols in the background of the controlled area are estimated values. The principle of calculation is presented in Figure 6.4.

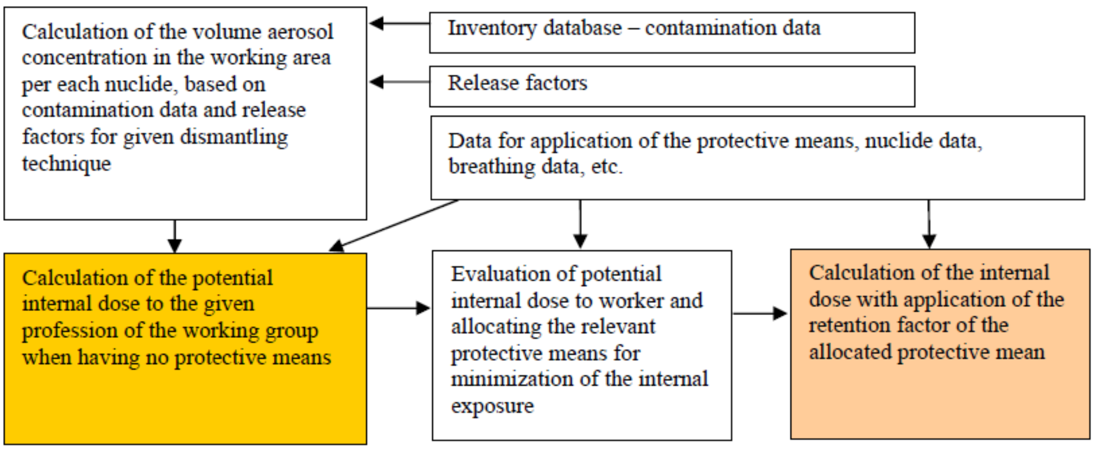


Figure 6.4 Principle of calculation of internal dose during dismantling

6.5 Evaluation of individual effective dose for individuals involved in D&D activities

The sum of the external and the internal doses for the individual professions of a working group is summed and presented as the total collective dose for the individual professions, and after summing over all professions of the working group, is presented as the overall dose for the discrete elementary decommissioning activity. According to the general procedures for the protection of workers, the dose for the individual workers should be evaluated and controlled according to the ALARA principle and should in any case be lower then the annual limit of 20 mSv per individual.

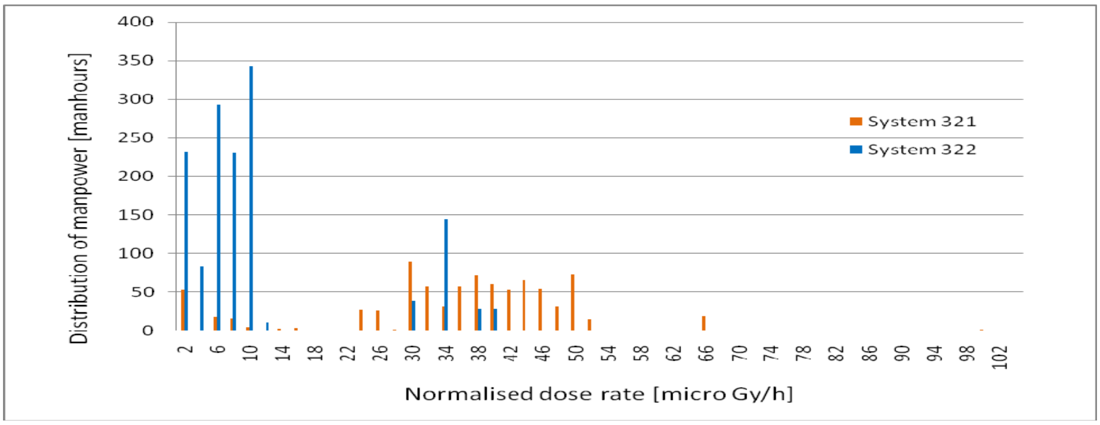
The bottom-up principle and profession resolved approach implemented in the calculation of decommissioning parameters in the OMEGA code, enables to evaluate analytically the dose to individuals during implementation of the discrete elementary decommissioning activities. By summing the data over the duration of the given decommissioning phase, it is possible to evaluate whether the annual limit of 20 mSv per year is respected. The principle applied is:

- For each elementary decommissioning activity, the dose is calculated for each profession of the working group separately. The calculation depends on profession resolved coefficients of stay in the dose rates of the main components. The dose calculation involves all productive and non-productive time components, spent by each member of the profession in the controlled area. This approach corresponds with the real organisation of the working time within the controlled area and recording of the dose data for individuals.
- Each profession can have in principle several members. The manpower within the controlled area and the dose calculated for the profession as a whole is distributed to each individual of the profession according to the number of workers for the given profession of the working group. The dose calculated at this level has already the character of an individual effective dose.
- The manpower allocated to an individual represents the real duration of the discrete elementary activity per individual within the controlled area. When dividing the dose rate allocated to an individual by the manpower, the normalised dose rate for the elementary decommissioning activity is calculated. Normalisation in this case means the relation to the overall duration of an elementary activity within the controlled area. This dose rate represents the averaged level of radiological risk for the individual of the given profession of the working group.
- A table of manpower spectrum is constructed, having on the horizontal axis the normalised dose rate in selected intervals (for example 2 μGy/h) and on the vertical axis the data of manpower components that fit with the given interval of the normalised dose rate as picked up from the database of calculated data. Parallel to the spectrum of manpower, the individual effective dose spectrum can be reconstructed. The individual effective dose components are calculated as the product of the manpower component in the given interval of the normalised dose rate and the mean value of the interval.
- By summing the data over the whole range of the normalised dose rate scale, the total effective dose for an individual can be calculated. The calculated effective dose is then divided by the duration (unit are years) of the evaluated decommissioning phase and the result is compared with the annual limit of 20 mSv for individuals.

The manpower spectrum and the individual effective dose spectrum can be developed for the entire decommissioning project or for a selected group of decommissioning activities. The shape of the spectrum shows the distribution of the exposure risk specific for individuals in the evaluated decommissioning activities or in its sub-phases. The distribution is facility or system specific, related to the radiological situation in the facility systems and structures. A demonstration of the results in the form of a manpower spectrum and individual effective doses is presented in Figure 6.5. The model case involves the dismantling of two systems - the contaminated system 321 and a low contaminated system 322.

The total duration of the elementary decommissioning activities performed by one working group can be developed by identification of the critical path of the involved elementary dismantling activities. The total individual effective dose is calculated as the sum of the elements of the individual effective dose spectra and can be compared with the duration of the critical path and the annual limit for individual effective doses for the personnel. Various scenarios can be implemented for optimisation when the calculated individual effective dose exceeds the annual limit like:

- Application of pre-dismantling decontamination.
- Involving more identical working groups or prolonging the critical decommissioning activities (‘diluting’ the manpower in time). The minimum number of personnel for critical operations can be optimised.
- Managing the performance of the decommissioning activities - for example by mixing the activities performed under higher exposure risk with activities with lower exposure risk.
- Implementation of remote controlled operations. The ratio cost versus ‘saved Sieverts’ can be evaluated.
- Deferring the dismantling. The time point, when the individual dose will be under the annual limit for all professions, can be calculated. The duration and the extent of safe enclosure phases in deferred dismantling can thus be justified analytically.



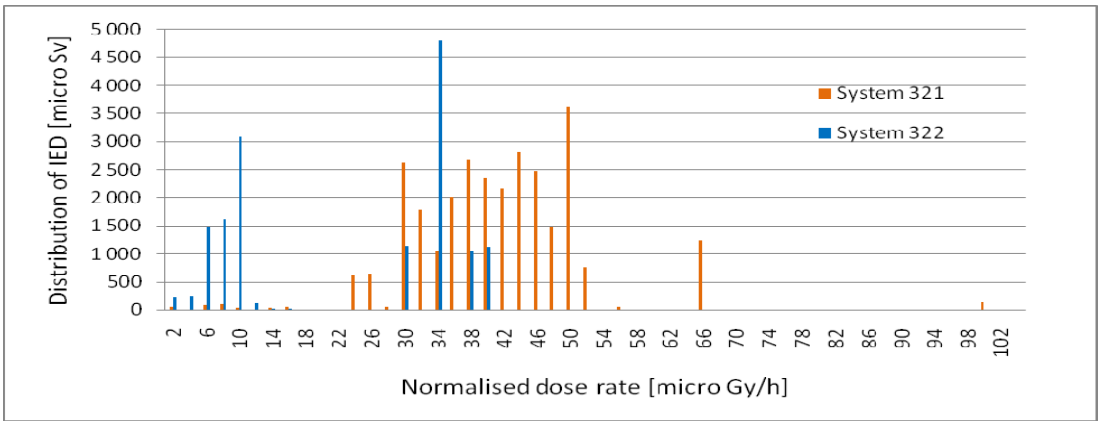


Figure 6.5 Example of distribution of manpower and individual effective dose

6.6 Evaluation of the level of the dose rate for the implementation of remote dismantling

One of the methods for reducing the exposure of personnel during dismantling is the application of remote dismantling [6]. In this case, the OMEGA code automatically selects remote dismantling methods based on the actual dose rate in the vicinity of the equipment to be dismantled and on the pre-selected value of the dose rate for the application of remote dismantling techniques. Implementation of remote dismantling decreases the exposure of personnel due to the fact that the personnel is located in shielded working places. However, the manpower needed for performing the decommissioning activities is significantly higher (approx. 5 - 10 times) and the costs for the work are also higher, in a rate similar to the manpower.

Optimisation of the level of the dose rate at the equipment for implementing remote dismantling can be performed in the computer code OMEGA effectively when all inventory data for the entire nuclear power plant are available. The optimization is nuclear power plant specific, and depends on the real radiological state of the plant. The calculation methodology as applied in the OMEGA code enables to select automatically the application of manual or remote dismantling techniques based on:

- The actual dose rate at the equipment to be dismantled (recovered for the date of start of dismantling);
- The dose rate limit for the application of remote dismantling - defined by the user.

The method can be used for evaluation of the optimal level for the application of remote dismantling and for implementing a cost benefit analysis relating to the type of costs and manpower versus the dose uptake during dismantling. Model calculations were performed for the primary circuit of the nuclear power plant A1 in Slovakia. The results are presented in Figure 6.6 and show that the optimal level for the application of remote dismantling is approximately in the interval between 100 - 200 µGy/hour.

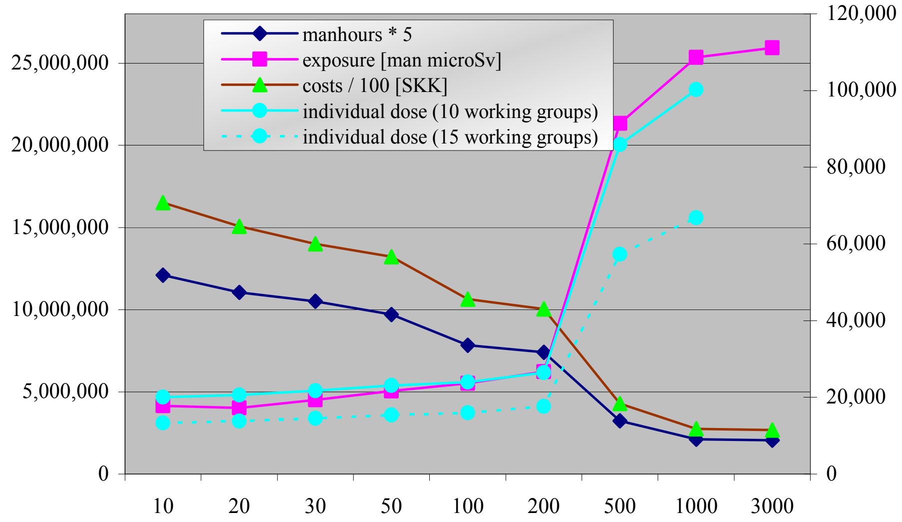


Figure 6.6 Evaluation of costs for dismantling of selected sections of the primary circuit of the nuclear power plant A1 (Slovak Republic) versus dose uptake by varying the limit for application of remote dismantling

7. Organisation of data from dismantling and decontamination techniques in databases

7.1 Structure of data in databases for D&D techniques

The data for decontamination and dismantling (D&D) activities can be effectively organised in formats that involve at least following main groups of data:

- Working group definition:
  - Professions of the working group;
  - Number of personnel for each profession;
  - Labour cost unit factors for each profession.
- Process data:
  - Manpower unit factor for the decommissioning category (-ies) considered;
  - Unit factors for individual material and equipment items with investment character; the quantities are required to be calculated;
  - Cost unit factors for the sum of other investment items;
  - Unit factors for expenses; general media (electricity, water, desalinated water, etc.); the quantities are required to be calculated;
  - Unit factors for expenses; specific media spent in the process; the quantities are required to be calculated;
  - Cost unit factors for the sum of other expenses items;
  - Data for procurement of equipment/instruments;
  - Data on deterioration of equipment/instruments;
  - Unit factors for generation of secondary waste;
  - Coefficients for the generation of radioactive aerosols;
  - Text files with description of D&D techniques.
- General data:
  - Cost unit factors for items with an investment character and for expenses items for which the quantities are calculated;
  - Data on non-productive time components;
  - Increase factors for working constraints.

7.2 Facility inventory data related to D&D techniques and to the 'PSL' structure

The 'PSL' structure represents in principle the classification system of decommissioning activities structured in 11 chapters. The main aim was to develop a structure for presenting the costs and other parameters for decommissioning. From this point of view (systems of decommissioning activities), the standardised structure can be used as a basis for the calculation structure for the calculation of costs for decommissioning and other decommissioning parameters [34]. Those issues of individual decommissioning projects which are project specific, like the decommissioning work breakdown structure, can then be constructed using the items of the standardised calculation structure.

The calculation structure used for the calculation of decommissioning costs and other decommissioning parameters is in general the result of an interaction of the list of decommissioning activities (to be done within a decommissioning project) and the inventory database of the facility. Sets of room-oriented decommissioning activities are repeated according to the structure building object - floor - room and a set of decommissioning activities are generated for each inventory item within the room. Such structures are repeated in various sections of the calculation structure for typical decommissioning activities like dismantling, decontamination of building surfaces, radiation monitoring of premises and other activities.

Other sections of the calculation structures are independent of the inventory database and have their own conditions for the generation of calculation items.

The standardised cost calculation structure is characterised by the fact that it involves the published 'PSL' structure of decommissioning activities [33], and in relevant sections (for example for dismantling) it uses the elements of the decommissioning inventory database for generating the individual calculation items. Therefore, the structure of the facility inventory database should also reflect these requirements, i.e., it should also contain the data needed for the generation of the standardised calculation structure.

This requirement also involves the D&D activities which are distributed in several segments of the Chapters 4 and 7 of the 'PSL' structure [33].

The 'PSL' structure has also some specific features which reflect the fact that similar or the same decommissioning activities (for example the D&D activities) are distributed in more sections. Therefore, the facility inventory database should facilitate the generation of the standardised cost calculation structure.

In order to achieve the standardised costs calculation structure, the implementation of the 'PSL' structure of decommissioning activities can be characterized in the following steps:

- Development of the detailed standardised structure of activities with numbered levels;
- Development of the decommissioning database with data elements enabling the generation of the standardized calculation structure;
- Generation of the standardized calculation structure;
- Management of the standardized calculation structure.

The first step represents the development of the detailed standardised structure of decommissioning activities by extending the three numbered levels of the published standardised structure. The extending represents 3 to 5 additional numbered levels, depending on the section of the standardised structure. In this way, a set of templates of the standardised structure can be developed which are used for generating the standardised calculation structure in interaction with the decommissioning inventory database.

The second step is characterized by implementing additional database parameters related to items of the premises and to decommissioning activities:

- *Type of the building object*. The parameter is used for the generation of sections of the standardised calculation structure relevant for nuclear building objects with a reactor, without a reactor, or for non-nuclear facilities, especially in Chapters 4 and 7 of the definition of the standardised structure [33].
- *Type of the decommissioning inventory item*. The parameter is used for the definition of the group of equipment, like types of building surfaces, types of technological equipment and types of civil structure items. The data are used for defining the section of the standardised structure where the database items are to be implemented. The database parameters 'type of equipment' enables to organise the generation of relevant sections of the cost calculation structure.

- *Category of the decommissioning inventory item*. The parameter is used for selecting the calculation procedure for the item of the calculation structure and for selecting the calculation data dependent on the category.
- *'PSL' identification number (PSL number)*. An identification number from the detailed standardized structure used for generating the calculation structure of the decommissioning option. The parameter is used for defining the calculation item within the detailed numbered standardisation structure. The 'PSL' number is also used for formatting calculated data into the 'PSL' format.

The category of equipment is the identification number from the list of categories of equipment. The categories of equipment are defined according their physical dimensions, physical properties, thickness of materials, material composition and typical use of the equipment. For individual categories of equipment typical properties can then be defined like:

- *Material properties*: material composition and ratio of individual materials;
- *Physical properties*: ratio mass to inner or outer surface area;
- *Radiological properties*: ratio dose rate/contamination.

Categorisation considers the following types of database elements:

- *Building surfaces*: the subject of categorization are the properties of the surface items in view of their decontamination (chemical, mechanical, …).
- *Technological elements*: armatures, valves, pipes, etc. The subject of categorization is the shape, dimensions, materials, wall thickness etc. Special categories can be defined also for items which are present in the nuclear facility in significant amounts, for example the primary pipes.
- *Building materials*: concretes, steel constructions, pre-fabricated elements, etc. The subject of categorization is material, thickness, inner structure (reinforcing).

Depending on the level of decommissioning costing, the extent of decommissioning categories may vary from 20 to 30 for preliminary studies, and up to approx. 150 to 200 for final decommissioning costing. The principle of categorisation has proved to be very efficient.

The 'PSL' identification number in the decommissioning database enables the generation of the standardised cost calculation structure for special systems like reactor structures, refuelling machines or other complex systems. This principle is important for that sections of the standardised cost calculation structure where the structure of the database is assembled according to the proposed dismantling procedure, like in the case of reactors.

For the generation of the standardized calculation structure in the third step, it is necessary to develop additional data which enable the generation of a room oriented calculation structure according to the definition of individual sections of the standardized structure.

The principles, presented in this section have a special meaning especially for D&D activities, due to their manifold character and allocation within many sections of the 'PSL' structure.

7.3 Principal relations of the main groups of data related to D&D activities

This section presents two examples of a data structure for categories and for unit factors, their mutual relations and graphical interpretation.

7.3.1 Categories of equipment

An example of a structure of data for categories of D&D activities is given in the graphical presentation of Figure 7.1.

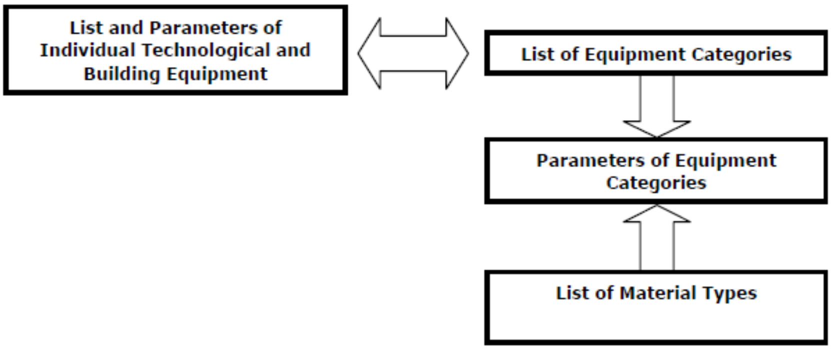


Figure 7.1 Relation between equipment and equipment categories

The list of equipment categories which are used for the categorisation of the systems and structures for allocating unit factors for dismantling and demolition; includes:

- An identification number;
- The name of the equipment category;
- An abbreviation of the category (optional).

The list of material types defines the categories of primary and secondary radioactive wastes (including gaseous and liquid effluents); the data are used in a system procedure for organising the material flow in the framework of a decommissioning option; the structure of the data includes:

- An identification number;
- The name of the material type;
- An abbreviation of the material type (optional).

The parameters of the categories include (each category consists of one or more material types):

- An identification number of the category;
- An identification number of the material type;
- The ratio of weight of the material type to the weight of the category (%);
- The ratio of the outer surface of the material type to the outer surface of the category (%);
- The ratio of the outer surface activity of the material type to the outer surface activity of the category (%);
- The ratio of the inner surface of the material type to the inner surface of the category (%);
- The ratio of the inner surface activity of the material type to the inner surface activity of the equipment category (%);
- The ratio of the mass activity of the material type to the mass activity of the category (%).

7.3.2 Unit Factors

An example of a structure of data for unit factors for D&D activities is given in the graphical presentation of Figure 7.2.

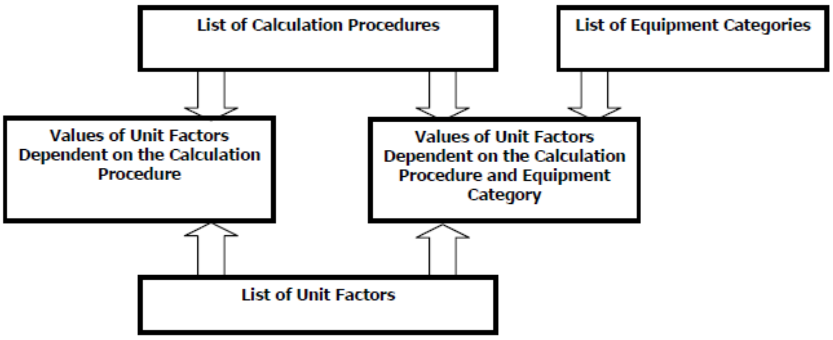


Figure 7.2 Scheme of relations of unit factor tables

The structure includes:

- A list of calculation procedures containing an identification number and the name of the calculation procedure (identification number of the working group);
- A list of unit factors containing an identification number and the name of the unit factor;
- Values of unit factors dependent on the calculation procedure – the table contains the identification number of the calculation procedure, the identification number of the unit factor and the value of the unit factor for a given calculation D&D procedure;
- Values of unit factors dependent on the calculation procedure and category – the table contains the identification number of the calculation procedure, the identification number of the unit factor, the identification number of the equipment category and the value of the unit factor for a given calculation procedure and equipment category.

8. Implementation of dismantling and decontamination techniques in the ‘PSL’ structure

In this section, examples are given of the implementation of D&D activities into a costing system. Depending on the subject of dismantling, the breakdown of dismantling activities can be organised basically as a room-oriented structure of dismantling activities or as a system-oriented structure of dismantling activities:

- The room-oriented approach is used for rooms containing mostly equipment of a general character which can be found in any nuclear facility.
- The system-oriented approach is used for complex systems like reactors, for developing specific work breakdown structures. This approach can be applied for segmenting of components on-site and for one-piece removal of components.

The approach for the identification of auxiliary preparatory and finishing activities for supporting the D&D activities is presented at the end of the section.

8.1 Room oriented approaches to modelling of dismantling activities

The room oriented structure of dismantling activities is the basic approach used for the dismantling of equipment which is located in rooms with small and medium sizes (not the large rooms like the reactor hall). The equipment within these rooms mostly belongs to the categories of pipes, valves, etc. for which the standard decommissioning categories and unit factors can be used (not the complex equipment). The principle is presented in Figure 8.1.

The set of preparatory, dismantling and finishing activities is generated for each room registered in the inventory database. The activities are generated in full extent for each room including the calculation procedures and the default input data. The user then makes the selection of activities taking into account specific properties or conditions for individual rooms.

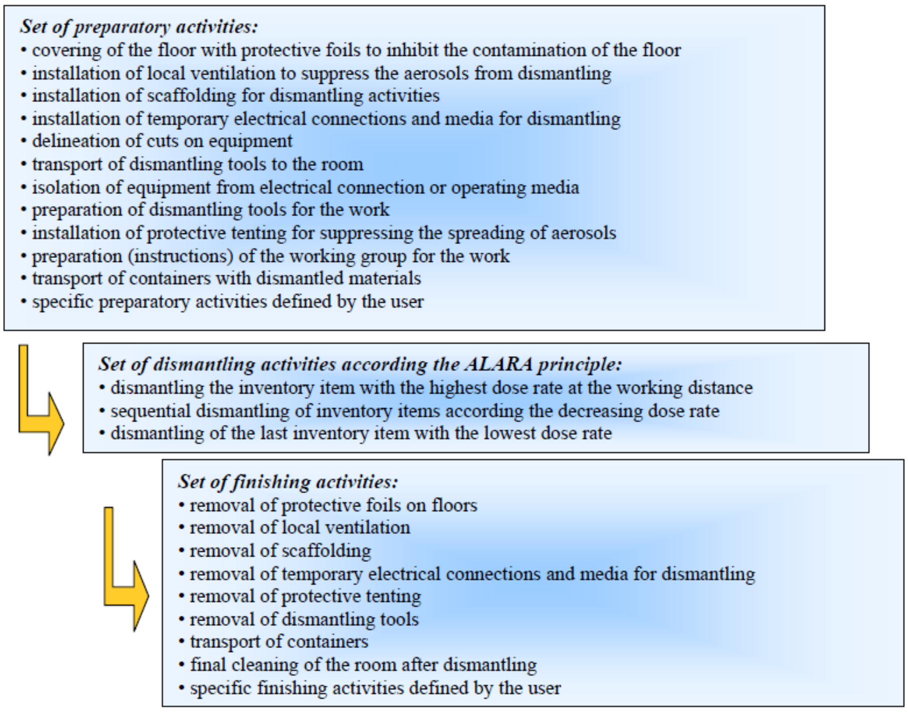


Figure 8.1 Principle of modelling a room oriented dismantling scenario

8.2 System oriented approaches to modelling of dismantling activities

A system oriented approach for organising decommissioning activities is mostly applied for equipment with large dimensions and complex structures, like reactors, refuelling machines, large components of the primary circuit, etc. The procedures are specific for each component and normally the dismantling procedure is the inverse of the construction procedure. The structure of the decommissioning activities is specific to the dismantled system and typically is organised according to the individual construction sub-assemblies of the dismantled system, normally as the procedure inverse to construction. This procedure is facilitated by the fact that the technical documentation to complex systems like construction, materials, recommended procedures for maintenance, etc., is organised according to the sub-assemblies.

The approach to modelling of a system oriented dismantling is presented in Figure 8.2. The set of preparatory, dismantling and finishing activities is in the calculation structure repeated for each construction sub-assembly. The set of preparatory and finishing activities is the same as for the room oriented approach and again the user selects the relevant activities for calculation. Additional specific activities can be defined by the user. In comparison with the room oriented approach, additional sets of activities can be defined at the beginning and at the end of the dismantling sequence for general preparatory and finishing activities, and a set of auxiliary activities parallel to the dismantling sequence, such as continuous supporting activities like radiological monitoring, waste removal, maintenance of dismantling equipment, etc.

The selection of these additional preparatory, finishing and supporting activities depends on the constructional complexity of the system to be dismantled and on the dismantling system used. These specific activities are defined case-by-case and normally are defined as period-dependent activities for which the duration, the personnel and the radiological conditions are defined.

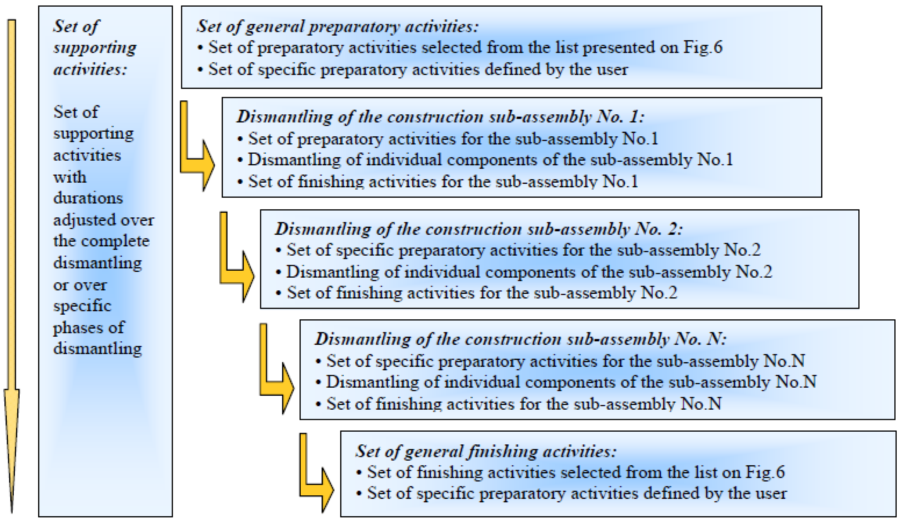


Figure 8.2 Principle of modelling a system oriented dismantling scenario

8.3 Definition of the extent of preparatory and finishing activities

The extent of preparatory and finishing activities can be identified for individual rooms separately based on an expert review of the properties of individual rooms and based on the inventory content of each room. The identification can be done in a matrix form. An example is presented in Table 8.1.

Table 8.1 Example of the selection of preparatory and finishing activities in a room oriented approach

Floor	Room	Preparatory dismantling activities												Finishing decommissioning activities : removal of …							
		radiation survey	protective foils	local ventilation	scaffolding	electricity & media	delineation of cuts	transport of tools	isolation of equipment	preparation of tools	protective tenting	preparation of the WG	preparation of containers	protective foils	local ventilation	scaffolding	electricity & media	protective tenting	tools	containers with waste	final cleaning of the room
Floor No.1	Room F1-1	x	x	x		x	x	x		x	x	x	x	x	x		x	x	x	x	x
	Room F1-2	x	x	x		x	x						x	x	x	x	x		x	x	x
	Room F1-3	x	x				x						x	x			x		x	x	x
	Room F1-4	x	x	x		x	x	x		x	x	x	x	x	x		x	x	x	x	x
Floor No.2	Room F2-1	x	x	x		x	x	x		x	x	x	x	x	x		x	x		x	x
	Room F2-2	x	x	x	x		x				x		x	x	x	x		x	x	x	x
	Room F2-3	x	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x
Floor No. 3	Room F3-1																				
	Room F3-2	x	x	x	x	x	x				x		x	x	x	x	x	x		x	x
	Room F3-3	x	x	x	x	x		x		x	x	x	x	x	x	x	x	x	x	x	x

9. Selection of dismantling and decontamination techniques for calculation in costing

This section gives an overview of some principles for the selection of D&D techniques within the preparation of cost calculation structures based on the 'PSL' structure.

9.1 Organisation of data for techniques in selection matrixes

In practical decommissioning costing, the principle of categorisation can be implemented by developing selection matrixes which have in vertical direction the decommissioning categories and in horizontal the D&D techniques. The principle is shown in Table 9.1 which represents an example of the allocation of dismantling techniques to dismantling categories [6]. The optimal techniques applicable for the given category are presented in a green colour. Other applicable techniques are presented in a blue colour. The unit factor approach requires that for all combinations as presented in Table 9.1, the unit factors should be developed. In addition to the categories of systems, the same approach is used for the categorisation of other elements of the inventory database which are the main cost drivers in D&D techniques such as:

- Building surfaces for decontamination and for final radiation survey. The surfaces are categorised to enable the selection of the proper decontamination techniques (chemical or mechanical as the main techniques) and the surfaces for final radiological monitoring.
- Materials of the structures. The main types of materials having a relation to the main techniques for demolition should be considered, such as reinforced concretes (several categories should be defined depending on the thickness of the concrete walls), plain concrete, masonry, panels, steel constructions, etc.

9.2 Industrial, manual and remote control D&D activities

D&D activities within a decommissioning project can be implemented in various ways, such as:

- Manual D&D activities performed within the controlled area of the nuclear facility;
- Remote controlled D&D activities performed within the controlled area of the nuclear facility;
- Dismantling of the industrial type outside of the controlled area of the facility.

Remote controlled dismantling techniques are implemented in the case of high dose rates at the working places. This should be taken into consideration and evaluated in the decision making and planning phases of decommissioning. The basic differences compared to manual dismantling are the higher manpower unit factors (approx. 5 - 10 times) and lower exposure of personnel which normally can be kept below the annual dose limits for individuals.

A principle scheme for computer based decision on the selection of a dismantling mode is presented in [6]. The OMEGA code automatically implements remote controlled techniques by evaluating the dose rate at the start of dismantling. If the dose rate is below the defined limit for the implementation of remote controlled techniques, the code calculates the dismantling by manual techniques. If the dose rate is higher than a predefined limit, the code calculates the dismantling by remote controlled techniques. A simplified scheme of the procedure is given in Figure 9.1.

The point of decision in Figure 9.1 is simplified. In reality, the code evaluates the average dose in the room, the dose rates and the estimated manpower for manual dismantling of individual equipment, and a set of coefficients can be defined by the user in order not to overestimate the need for remote dismantling.

Table 9.1 Principle structure of a selection matrix for D&D techniques

Dismantling category	HDCT	COBO	PLSM	OCHC	MSW	OACT	PLHC	MNOC	MAND	MAPL	GROC	GRPL
Piping (SS), diameter =< D25 mm												
Piping (SS), diameter over 25 mm												
Piping (CS), diameter =< D25 mm												
Piping (CS), diameter over 25 mm												
Tanks (SS)												
Tanks and containers (CS)												
Heat exchangers (SS)												
Heat exchangers (CS)												
Pumps (SS, CS), mass <= 50 kg												
Pumps (SS), mass over 50 kg												
Pumps (CS), mass > 50 kg												
Ventilators (SS, CS), mass <= 50 kg												
Ventilators (SS), mass > 50 kg												
Ventilators (CS), mass > 50 kg												
Valves (SS)												
Valves (CS)												
Electric motors, mass <= 50 kg												
Electric motors, mass > 50 kg												
Air conditioning components - piping (SS)												
Air conditioning systems others (SS)												
Air conditioning components - piping (CS)												
Air conditioning systems others (CS)												
Air conditioning systems, (Al)												
Electrical cables & conductors												
General electric equipment, (CS) mass <= 50 kg												
General electric equipment, (CS) mass > 50 kg												
Thermal insulations, non-metal covering												
Steel constructions, (CS)												
Small piece components, shielding (CS)												
Hoisting equipment (CS), electrical tackles												
Digestors, sampling boxes (CS)												
Piping throughputs, gulleys												
Hermetic and shielding doors (CS)												
Stainless steel linings, (SS)												
Carbon steel linings, (CS)												
Other general equipment												
Casing of technological equipment (CS)												
Casing of technological equipment (SS)												

Note: The examples of techniques as presented in the table are:

- HDCT Hydraulic shears cutting
- COBO Core boring
- PLSM Plasma cutting
- OCHC Oxygen cutting - hydraulic cutting (combined technique)
- MSAW Mechanical cutting by saw
- OACT Oxygen cutting (oxygen - acetylene cutting)
- PLHC Plasma cutting - hydraulic cutting (combined technique)
- MNOC Manual dismantling - oxygen cutting (combined technique)
- MAND Manual dismantling (by tools)
- MAPL Manual dismantling - plasma cutting (combined technique)
- GROC Grinding - oxygen cutting (combined technique)
- GRPL Grinding - plasma cutting (combined technique)

The scheme in Figure 9.1 also involves the case of dismantling outside of the controlled area. The procedure is the same as in the case of dismantling within the controlled area, but the set of preparatory and finishing activities is reduced and does not involve the activities related to radioactivity. The procedure is the same as in industrial dismantling.

The basic set of preparatory activities for remote dismantling is the same as for manual dismantling. For remote controlled activities the set is extended with activities specific for remote controlled operations like testing the cutting system, preparation and setting of the system for cutting, preparation of the system for the collection of waste and the installation of shielding and others. Similarly, for finishing activities there are additional activities inverse to the preparatory activities, like dismantling of the shielding, removal of the cutting system and removal of the waste collection system.

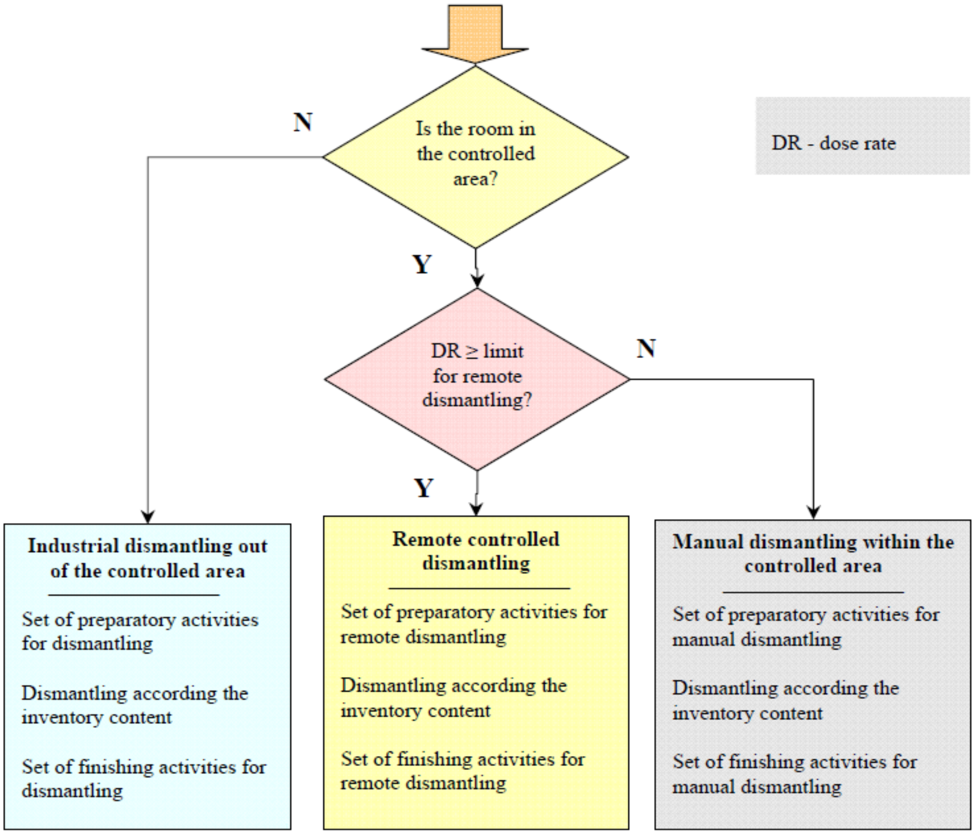


Figure 9.1 Principal scheme for the selection of the mode for D&D activities

10. References

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Annex 1 Reviewers of the Report

Draft Report

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Quality Review

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