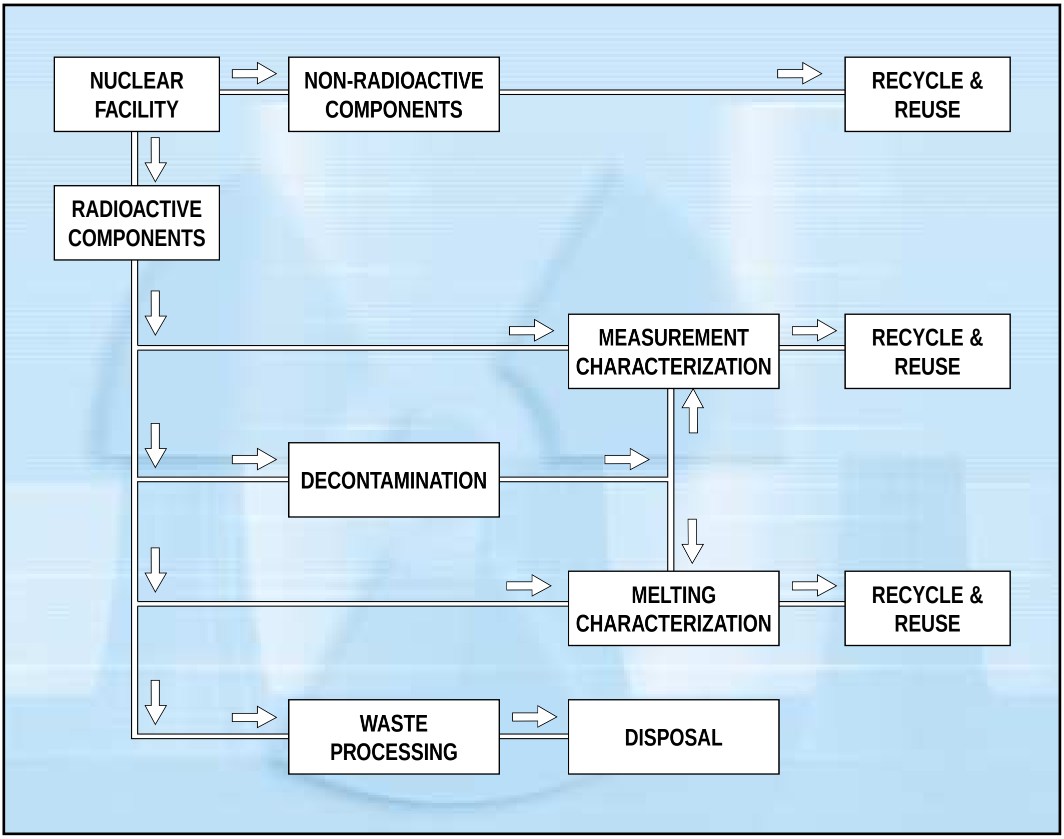

TECHNICAL REPORTS SERIES No. **401**

Methods for the Minimization of Radioactive Waste from Decontamination and Decommissioning of Nuclear Facilities

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 2001

METHODS FOR THE MINIMIZATION OF RADIOACTIVE WASTE FROM DECONTAMINATION AND DECOMMISSIONING OF NUCLEAR FACILITIES

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FOREWORD

The decommissioning of nuclear facilities has become a subject of great importance because of the large number of facilities that will have to be retired from service in the near future in many IAEA Member States. As a result of decommissioning and decontamination operations, a wide range and quantity of radioactive material has arisen, which may be considered as waste, or which may be recycled or reused when it continues to have an economic value. The amount of decommissioning waste can be very substantial, and therefore consideration of appropriate strategies for its minimization becomes a very important issue.

In recognition of the importance of this subject, the IAEA decided to prepare a technical report which would review information on the existing practice of minimizing radioactive waste arising from the decommissioning and decontamination of nuclear facilities. The report analyses the principles and factors to be considered when selecting a waste minimization strategy, such as the level of development or the availability of technology, national policies and regulations, technical traditions and economic considerations. The primary objective of the report is to identify all important stages and components in the decision making process when planning and implementing a waste minimization programme during decommissioning operations.

The IAEA wishes to express its appreciation to all those who took part in the preparation of this report, in particular to L. Teunckens of Belgium, who was involved in all steps of report preparation. The IAEA officer responsible for this report was V.M. Efremenkov of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

For nuclear facilities, decommissioning is the final phase in the life-cycle after siting, design, construction, commissioning and operation. It is a process which involves operations such as decontamination, dismantling of plant equipment and facilities, demolition of buildings and structures, and management of the resulting materials. All of these activities take into account the health and safety requirements of the operating personnel and the general public, and also any implications these activities have for the environment. The decommissioning of nuclear facilities has become a topic of great interest to many Member States because of the large number of facilities which were built many years ago and which will have to be retired from service in the near future.

As a result of these decontamination and decommissioning (D&D) operations, a wide range of materials arise. Some of them will be radioactive; some will continue to have an economic value and/or are in a form which can be recycled or reused. Others will have little or no economic value, and these are the wastes that have to be disposed of, or which must be stored if no accepted method of disposal exists, in either case at major economic cost to the industry and, ultimately, to the community at large. This report addresses the principles, factors, experiences and some projected future trends relevant to determining how to develop appropriate strategies for the minimization, segregation, reuse, recycling, storage and disposal of materials arising from D&D. It will assist Member States to take advantage of sustained technical progress in various countries when planning the decommissioning of nuclear facilities.

In this report, waste minimization is defined as the minimization of the generation and spread of radioactivity, and the minimization of the volume of radioactive wastes arising from the management of materials from D&D operations, to levels ‘as low as reasonably achievable’ (ALARA) both safety and economic factors being taken into account. This involves minimization of their impact on the environment and reduction in overall D&D costs.

It should be considered that the ultimate goal, i.e. the end ‘product’ of D&D operations, is the unconditional release or reuse of sites, facilities, installations, or materials for other purposes. Intermediate products of D&D can be facilities or installations that have been dismantled, or materials that have been decontaminated to permit their release or reuse for other nuclear applications. Materials that cannot be conditionally or unconditionally released or reused, and which have to be treated as radioactive wastes, can be considered as by-products of the D&D process. As such, in this report, waste minimization can be considered as a strategy for avoiding, as much as possible, the production of these undesirable by-products. Where by-products are unavoidable, steps are required to minimize their volumes.

1.2. OBJECTIVE

The objective of this report is to provide Member States and their decision makers (ranging from regulators, strategists, planners and designers, to operators) with relevant information on opportunities for minimizing radioactive wastes arising from the D&D of nuclear facilities. This will allow waste minimization options to be properly planned and assessed as part of national, site and plant waste management policies.

This objective will be achieved by: reviewing the sources and characteristics of radioactive materials arising from D&D activities; reviewing waste minimization principles and current practical applications, together with regulatory, technical, financial and political factors influencing waste minimization practices; and reviewing current trends in improving waste minimization practices during D&D.

The report also refers to radioactive waste minimization issues addressed in other IAEA publications relating to:

- The front end of the nuclear fuel cycle [1],
- Nuclear power plants and the back end of the nuclear fuel cycle [2],
- The recycle and reuse of radioactively contaminated materials arising from nuclear fuel cycle facilities [3],
- Decommissioning techniques for research reactors [4],
- Decommissioning of non-reactor nuclear facilities [5],
- Clearance levels for radionuclides in solid materials [6].

1.3. SCOPE AND STRUCTURE

The scope of this report includes discussion of the minimization of wastes arising from all non-fuel radioactive materials resulting from D&D activities across the entire nuclear industry. This covers materials which have been activated by neutron irradiation, as well as materials contaminated as a result of contact with radioactive substances.

Section 2 of this report identifies the strategic, tactical and technical issues in relation to D&D and describes the sources and characteristics of materials arising during these activities. Section 3 gives an overview of, and general considerations on, techniques for the decontamination and dismantling of nuclear facilities. Section 4 describes the principles of waste minimization and their implementation. Section 5 discusses factors relevant to the consideration of waste minimization options in decommissioning, as well as their implication for fulfilling the objective of recycling or releasing the materials resulting from decommissioning. Taking into account the strategic, technical, political, regulatory, economic and other constraining factors identified in the previous sections, Section 6 describes the likely future trends in materials selection, decontamination and dismantling methods, and in regulatory approaches in support of waste minimization. Finally, Section 7 comprises conclusions for this report. In addition, Appendices I, II and III include technical information regarding decontamination, dismantling and the radioactive characterization of materials arising from decommissioning operations. In Appendix IV, a summary of the approach to implementing a waste minimization strategy for the D&D of nuclear facilities is given.

It should be stressed that the aim of this report is to aid, rather than be prescriptive to, the decision making process in order to make waste minimization an inherent part of a total decommissioning strategy.

2. DECOMMISSIONING STRATEGIES, SOURCES AND CHARACTERISTICS OF RADIOACTIVE MATERIALS ARISING FROM D&D

2.1. STAGES OF NUCLEAR FACILITY DECOMMISSIONING

In other IAEA publications, three basic stages of decommissioning have been defined [7–9], in which removal of spent fuel, process fluids and operational wastes are normally pre-decommissioning activities. These definitions have mainly been applied to the decommissioning of reactor facilities. For some nuclear facilities, only the general philosophy of the sequential decommissioning stages could be applied. Therefore, as shown in later publications [5], the definitions of these basic stages have been adapted and are summarized as follows:

- Stage 1. Safe enclosure with surveillance.
- Stage 2. Extensive plant decontamination, partial dismantling and removal of plant systems. Limited release of the site for non-nuclear use.
- Stage 3. Decontamination and dismantling of the plant up to unconditional release of the site for non-nuclear use.

The possible decommissioning strategies are, in general, as follows:

- Complete decommissioning immediately after final shutdown operations;
- Maintaining the plant in a safe enclosure condition for a number of years, followed by complete dismantling;
- Dismantling in several steps, each being preceded and followed by a safe enclosure period of appropriate duration.

In addition, the decommissioning of a nuclear facility is usually achieved in three main phases:

- Initial cleanup and preliminary decontamination where necessary and/or feasible;
- Dismantling and removal of the systems and equipment, with decontamination as appropriate;
- Demolition or reuse (conditional or unconditional) of buildings and structures.

In general, there does not necessarily have to be any link between the defined stages and the three phases described above. Moreover, any sequence may involve intervening periods of safe enclosure, depending on the options chosen for the particular project.

The choice of a decommissioning strategy will mainly be based on technical, safety, regulatory and cost considerations, requiring an examination of the various possible approaches, together with a comparison of the advantages and drawbacks of each. A country’s general policies on nuclear energy development and its particular waste management policy may be major factors in the decision making process for selecting a decommissioning strategy.

Taking into account these general considerations and depending on the scale and the type of facility to be decommissioned and on the strategy chosen, different kinds and amounts of contaminated material will be produced by decommissioning operations (i.e. their characteristics, quantities, production rates, etc., will vary). For each option, it is necessary to consider minimizing the generation of activity and the volume of wastes for storage and disposal and the consequent environmental impact, as well as minimizing the total costs associated with contaminated material management. As a result, the strategies and techniques selected for decommissioning activities have a large impact on the minimization of wastes and this needs to be considered when selecting suitable options.

2.2. STRATEGIES FOR DECOMMISSIONING

When it is decided to finally shut down a nuclear installation, or when planning the operations for a final shutdown, a set of strategic, tactical and technical decisions has to be taken. Adequate and relevant waste minimization and waste management are important components in all these consequential decisions [10]. In practice, these three types of decision are all interlinked, and emerge from an iterative process of study and discussion. The decision making process used in selecting and implementing strategies for decommissioning is illustrated in Table I.

Strategic decommissioning decisions refer to those decisions that are concerned with establishing the best time to fully dismantle the installation, and the stages prior to complete dismantling, as indicated in Section 2.1. Adequate choices have to be made, based on an examination of the various possible approaches, with a comparison of the advantages, drawbacks and costs of each, and taking into consideration the country's nuclear policy on decommissioning and waste management [7, 11]. This should include:

- The liability of official bodies,
- The relevant regulations governing nuclear safety and radiation protection (including organization and procedures),
- The code/law of employment and the industrial safety rules,
- Social and economic considerations.

In the selection of a decommissioning strategy, the following technical, regulatory, economic and social considerations have to be taken into account, some of which form part of the main elements of a waste minimization strategy:

- Material condition of the installation after final shutdown. This involves an evaluation of the ageing state of equipment, structures and containment; making allowance for how this will change in the long term. The material condition defines the maintenance, surveillance and inspection requirements necessary to keep it in a safe shutdown state for the required period, avoiding degradation of equipment, structures and containment, minimizing the spread of contamination, and preventing D&D from becoming more difficult in a later phase.
- Radiological condition of the installation. This involves assessing the potential hazards, either while work is going on or during waiting periods. This will provide guidance on waste management and the waste minimization options to be adopted.
- Constraints due to nuclear safety and radiation protection, industrial safety and the related risk analysis studies make it possible to evaluate the best means of protection, to assess how the radiological aspects can be optimized, and to determine the requirements of maintenance, inspection, monitoring and surveillance. The possible deterioration of equipment, structures and containment should also be considered, as well as minimizing the spread of contamination and preventing D&D from becoming more difficult in a later phase.

TABLE I. DECISION MAKING PROCESS FOR SELECTING AND IMPLEMENTING STRATEGIES FOR DECOMMISSIONING

Step	Decisions required	Factors in decision making
Strategic	Time schedule for complete	Technical and economic examination decisions decommissioning of different approaches
	Stages prior to complete	National decommissioning and decommissioning waste management policy
		Technical, regulatory, economic and social considerations: — Material condition of the installation after final shutdown; — Radiological condition of the installation after final shutdown; — Constraints due to nuclear safety and protection and industrial safety; — Availability of waste management infrastructure; — Regulations governing recycle and reuse of materials; — Services concerned with operation, maintenance, instrumentation and surveillance; — Possibility of reusing site and buildings and of recovering plant, equipment and materials; — Existence of technical resources, specialist teams and local support; — Costs and financing; — Social considerations, public perception.
Tactical decisions	Inventory of decommissioning activities	Regulatory constraints Specific features of the installation
	Management of decommissioning activities	Best meeting of the safety and protection conditions at least cost
	Optimization of balance of costs, time schedule, worker doses	Individual and cumulative doses to workers

	Determination of technical approaches about:	Minimization of the quantity of wastes and effluents produced and optimization of the cost of their management
	— Decontamination or fixing of contamination — Large piece removal or size reduction — Cutting under water or in air — On-site or centralized waste handling — Access modes and contaminated material routing — Manipulation and handling equipment — Methods for protection, safety and security Work schedule, cost estimates, operations scheme	Tools and processes
Technical decisions	Most appropriate technical facilities Cutting tools and remotely controlled systems Decontamination processes Management of radioactive materials and effluents Methods of radiation protection and industrial safety	Technical characteristics of equipment and processes to meet the requirements of the tactical decisions

- Availability of a waste management infrastructure. This includes storage and disposal and an evaluation of the different amounts of radioactive materials which will be produced by the dismantling operations (i.e. their characteristics, quantities, production rates, etc.).
- Regulations governing the recycling of materials and equipment in the public domain and the various possibilities for waste storage. This is to avoid unnecessary storage of large amounts of radioactive wastes and takes into account national policy, the existence of a site, and the administrative and technical conditions of storage.
- Services concerned with operation, maintenance, instrumentation and surveillance. This is to guarantee safety and keep the equipment remaining in service (handling equipment, electrical supplies, ventilation, radiological surveillance instruments, fire monitoring, etc.) running and properly maintained, with particular attention paid to those parts of the plant which may deteriorate over the long term.
- Possibility of reusing the site and buildings, and of recovering plant, equipment and materials for nuclear or other purposes (without neglecting the social and political aspects). This presents important incentives for considering decontamination practices and significantly reducing the potential amount of radioactive wastes remaining.
- Existence of technical resources, specialist teams and local support for dismantling, decontamination and contaminated material handling. This includes considering the available means of waste minimization and evaluating how existing facilities on-site can be modified to meet the needs with minimum expenditure.
- Costs and financing. Knowledge of the cost of each possible approach is needed, including the cost of labour, materials and supplies, as well as financing costs and cost savings involved when applying waste minimization principles and techniques.
- Social considerations. These include public perception of radioactive waste treatment versus recycle and reuse options, which is usually taken into account in the procedure whereby proposals are submitted for approval by the safety authorities. The way in which this is done varies among Member States.

These factors, when considered, should facilitate the choice of decontamination and dismantling tactics and cutting tools, and should result in the most appropriate way of dealing with the contaminated materials produced.

Tactical decisions take account of the regulatory constraints and the specific features of the installation to be decommissioned. Within a given strategy, it is necessary to determine the tasks that need to be carried out in order to determine the technical approaches for their implementation, and to manage these tasks in order to optimize the balance of costs, time schedule, waste minimization and worker doses.

During these evaluations, the main technical approaches are chosen by:

- Deciding whether to decontaminate or to fix contamination, whether to carry out these operations with equipment in situ or in an associated workshop, or whether to use other existing facilities, locally or centrally, on or off the site;
- Deciding whether to cut materials into large pieces, and have additional size reduction in specialized areas, or whether to cut radioactive components directly in situ in order to make them compatible with transfer and disposal requirements;
- Deciding whether to handle radioactive materials directly on-site or in centralized facilities;
- Deciding whether to carry out cutting and handling operations under water or in air;
- Choosing the means and modes of access to the working areas and deciding on the routing of contaminated materials;
- Identifying suitable manipulation and handling equipment (robotic manipulators, carriers, etc.);
- Determining methods to be used for protection, safety and security.

Once these tactical decisions have been taken, the detailed working plan, including equipment orders and work contracts, can be prepared. Preparation can also start on work schedules, cost estimates and operations schemes, including safety studies, risk analysis and a description of tools and processes, and the related waste minimization options involved.

Taking technical decisions involves choosing the most appropriate technical facilities with which to carry out the operations as determined by the tactical decisions taken, including the choice of cutting tools and remotely controlled systems, processes for decontamination and for management of radioactive materials and effluents, and methods of radiation protection and industrial safety.

As can be appreciated, most of the factors that have to be considered when preparing the strategic, tactical and technical decisions required to choose an adequate decommissioning strategy for an installation are also the main elements used for choosing a waste minimization strategy. These elements can be grouped into four areas:

- Source reduction,
- Prevention of contamination spread,
- Recycle and reuse,
- Waste management optimization.

In developing such a strategy, it is necessary to understand clearly the processes involved and which streams actually produce contaminated materials.

On the basis of all these evaluations, it should be clear that waste minimization is an inherent part of any decommissioning strategy.

2.3. ARISINGS FROM DECONTAMINATION AND DISMANTLING

Radioactively contaminated materials arise from the decommissioning of all nuclear facilities such as nuclear power plants, fuel fabrication and reprocessing plants, and research facilities. When decommissioning nuclear facilities, some of the materials arising from the specific activities will be radioactive as a result of activation and/or contamination. In general, however, a large proportion of the arisings will be inactive, which means that they will be available for unconditional release.

In reactor facilities, most activated material is contained within the reactor vessel and its internal components, as well as in the biological shielding which surrounds the vessel. Typically, these components contain materials such as steel, aluminium, reinforced concrete, graphite and zirconium alloys. The radiological characterization of the activated materials can be estimated/calculated using analytical techniques [12–14].

The process equipment and components used to contain the process material (whether it be reactor coolant or reprocessing liquid) become contaminated with fission products, activation products and transuranic isotopes. Other parts of the facility may be contaminated if there are any liquid, gaseous or particulate leaks.

Radioactively contaminated liquids can also result from the decommissioning of a facility, for example, the liquid wastes arising from the decontamination or flushing of systems. The types of radioactive contaminant in the liquid are dependent on the type of facility being decommissioned and the exact location in the process where the waste stream is being generated.

Inactive solid materials and liquids also arise from the decommissioning of nuclear facilities. If appropriate segregation and decontamination processes are available, the volume of radioactive materials requiring treatment can be reduced significantly. Typically, non-radioactive solid materials include items such as piping, pumps, tanks, duct work, structural equipment and electrical equipment. Inactive liquids and solid materials can be disposed of in accordance with applicable regulations and using conventional methods.

A volume estimation of the contaminated materials by type (activated, contaminated, alpha bearing versus non-alpha bearing), in relation to the methods and processes available for their treatment, is required. An accurate estimate of the volume of contaminated materials requires:

- Classification of facility systems and structures with respect to activity (activated, contaminated, non-contaminated, alpha bearing versus non-alpha bearing, etc.). This characterizes the type of material that will be generated, as well as characterizing further treatment, handling, packaging and disposal requirements.
- Development of a detailed mass/volume inventory of facility systems and structures.
- Estimation of the quantities and volumes of materials that can be decontaminated and/or measured, in view of conditional and/or unconditional release and/or recycle and reuse.
- Estimation of the quantities and volumes of compactible and incinerable, contaminated solid materials generated during decommissioning.
- Estimation of the quantities and volumes of contaminated solid materials which cannot be compacted or incinerated. As this category of material has a large impact on the technical equipment required for handling and conditioning, an accurate determination is required.
- Estimation of the quantities and general characteristics of contaminated liquids. The volume of liquids generated during decontamination and flushing operations will largely depend on the type of facility and its representative contaminants, the number of decontamination steps and their efficiency.
- Estimation of gaseous effluents and aerosols. Aerosols containing finely dispersed radioactive materials result from cutting and abrasive surface cleaning methods. Some cutting and cleaning methods produce large volumes of toxic smoke and fumes. Contamination control coupled with filters in the ventilation streams should be adequate in collecting and retaining the particulate material.

Table II shows examples of contaminated material generation from the complete decommissioning of: (1) a 250 MW(e) natural uranium graphite moderated gas cooled reactor (GCR) [10], (2) a 900–1300 MW(e) pressurized water reactor (PWR) [10], and (3) a reference reprocessing plant with a capacity of 5 Mg/d [15].

The activity level of most of these materials is usually low. To a large extent, they should be available for unconditional release after cleaning and/or adequate decontamination to the required release levels.

As a result of the process of radioactive decay, the activity decreases with time after plant shutdown. As such, deliberately delaying or conducting decommissioning and demolition of a plant in time separated stages will result in a subsequent decrease in the radioactive inventory over time, reducing significantly the quantities of materials with higher radioactivity levels. Relevant calculations have been made for various reactor types.

TABLE II. RADIOACTIVE MATERIAL GENERATION FROM THE COMPLETE DECOMMISSIONING OF SELECTED NUCLEAR FACILITIES

Radioactive material generated	Facility (Mg)		
	GCR (250 MW(e))	PWR (900–1300 MW(e))	Reprocessing plant (Capacity: 5 Mg/d)
Irradiated carbon steel	3000		
Activated steel		650	
Graphite	2500		
Activated concrete	600	300	
Contaminated ferritic steel	6000	2400	
Steel likely to be contaminated		1100	3400
Contaminated concrete	150	600	1850
Contaminated lagging	150	150	400
Contaminated technological wastes	1000	1000	300

As an example, results for a 1000 MW(e) PWR, giving the approximate masses and activities of steels from the active areas at various times after shutdown, are reproduced in Table III. This table shows the decreasing proportion of beta–gamma emitters remaining in low level radioactive steels as time progresses and which results from the decay of radionuclides such as ^{60}Co [16]. The table also shows the

TABLE III. TYPICAL MASSES AND ACTIVITIES IN STEELS FROM A 1000 MW(e) PWR CONTAINING VERY LOW LEVELS OF ACTIVITY

Activity		Period after reactor shutdown					
		5 years' decay		25 years' decay		100 years' decay	
Surface activity (Bq/cm²)	Average activity concentration (Bq/g)	Mass (Mg)	Total activity[a] (Bq)	Mass (Mg)	Total activity[b] (Bq)	Mass (Mg)	Total activity[c] (Bq)
37–370	10	800	8.0×10^9	440	4.4×10^9	240	2.4×10^9
3.7–37	1	1600	1.6×10^9	880	8.8×10^8	480	4.8×10^8
0.37–3.7	0.1	3200	3.2×10^8	1760	1.8×10^8	960	9.6×10^7

[a] 99.9% beta–gamma; 0.1% alpha.

[b] 99% beta–gamma; 1% alpha.

[c] 95% beta–gamma; 5% alpha.

progressive reduction in the quantities of steel remaining with radioactivity levels higher than 0.1 Bq/g or 0.37 Bq/cm². When comparing 5 year and 25 year data, the amount of steel contaminated to levels higher than 0.1 Bq/g or 0.37 Bq/cm² decreases by almost 50%. After 100 years, this proportion decreases by about 70%.

Quantities of tritiated water vapour may arise during decommissioning operations. If necessary, removal of the tritiated water vapour from the ventilated air can be accomplished in the manner indicated in Ref. [17].

From the radiological point of view, power and experimental reactors may be divided into two separate groups of components:

- The reactor itself (pressure vessel, internal structures and biological shielding), the constituent materials of which are primarily activated and which account for more than 90% of the total activity in the installation;
- The complete coolant circuits and secondary installations, which are primarily contaminated.

Taking the above into account, consideration may be given to postponing the dismantling of the reactor, to confine it and rapidly dismantle the coolant circuits and auxiliary plant after decontamination, thus reducing the annual cost of surveillance and maintenance.

In the special case of pool type reactors, the need to keep the water circuits in service (circulation, filtration and treatment), in order to ensure biological shielding above the pools, may make it desirable, for economic and operational reasons, to dismantle the plant shortly after final shutdown.

Fuel cycle installations (more particularly reprocessing plants) are usually contaminated by alpha emitters and fission products. Even after several decades, the resultant radioactive decay is not of significant benefit, either to worker protection or to radioactive material management or to the potential minimization of decommissioning waste. In this case, the radioactive material is confined partly by dynamic sealing, which means that the ventilation systems must be kept running. Also, in spite of washing down and the various acts of decontamination, a risk of corrosion from the chemicals used during operations remains; as a result, the annual cost of maintenance and surveillance can be substantial, leading to great expenditure with minimal benefit, rendering early dismantling desirable [7].

On the basis of the diversity in individual plant situations, it is inappropriate to consider general methodologies in order to make strategic, tactical and technical decisions for the decommissioning of nuclear facilities. Analyses need to be performed which lead to decisions being taken on specific decommissioning options, based on the results of individual evaluations from the operating period, and on the existing conditions of a specific installation. Waste minimization is an important element to be considered in taking these decisions.

3. SELECTION OF TECHNIQUES FOR DECONTAMINATION AND DISMANTLING OF NUCLEAR FACILITIES

The selection of decontamination and dismantling techniques is an important factor influencing the character and the amount of waste generated and should be carefully considered when planning and implementing waste minimization procedures. The process of technology evaluation and selection is always a trade-off between efficiency in achieving the identified goal (release limit, volume reduction, etc.), and the overall cost of the selected option. Although not exhaustive, this section provides an overview of the techniques that are used during the specific activities carried out during D&D operations. A range of available technologies is given, indicating factors to be considered when selecting D&D techniques for use in particular cases, with special emphasis on waste minimization. More detailed information on particular techniques can be found in specific publications [18–21].

Practical experience in D&D has shown that a universally applicable D&D process does not exist. As such, future users should familiarize themselves with the characteristics of the proposed techniques, in order to make adequate choices based on site and facility specific requirements.

3.1. DEFINITION AND GENERAL CONSIDERATIONS

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

- Reduce radiation exposure;
- Salvage equipment and materials;
- Reduce the volume of equipment and materials requiring storage and disposal in licensed disposal facilities;
- Restore the site and facility, or parts thereof, to an unconditional use state;
- Remove loose radioactive contaminants and fix the remaining contamination in place in preparation for protective storage or permanent disposal;
- Reduce the magnitude of the residual radioactive source in a protective storage mode (for public health and safety reasons) or reduce the protective storage period.

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. The question will arise, however, as to whether to decontaminate piping systems, tanks and components.

A strong case can be made in favour of leaving adherent contamination within piping and components in a dispersed form on the internal metal surfaces, rather than concentrating the radioactivity through decontamination. In most cases, decontamination is not sufficiently effective as to allow unconditional release of the item without further treatment after dismantling. Therefore, savings, both in occupational exposure and in cost, could be realized by simply removing the contaminated system and its components and performing only certain packaging activities (e.g. welding end caps onto pipe sections). However, the additional cost of materials disposal must be weighed in this scenario.

A decontamination programme may also require a facility capable of treating secondary wastes from decontamination, e.g. processing chemical solutions, aerosols, debris. The concentrated wastes, representing a more significant radiation source, must be solidified and shipped for disposal in licensed disposal facilities unless properly treated within 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 can increase:

- Occupational exposure rates,
- The potential for a release,
- 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 having performed extensive decontamination. Resolution of this question depends on specific facts, such as the exposure rate of the gamma emitting contamination, the level of the contamination, and the effectiveness of the containing component and piping (wall thickness) in reducing work area radiation fields.

3.2. RATIONALE FOR DECONTAMINATION AND COMPARISON OF DECONTAMINATION TECHNIQUES FOR MAINTENANCE AND FOR DECOMMISSIONING

There are two main reasons for considering the use of decontamination techniques. The first reason is the importance of removing contamination from components or systems in order to reduce dose levels in the installations. Access to the installations could then be made easier, so that it becomes possible to use hands-on techniques for dismantling rather than resorting to the more expensive use of robots or manipulators.

The second reason is that it may be possible to reduce the contamination of components or structures to such levels that they can be disposed of at a lower, and therefore more economical, waste treatment and disposal category or, indeed, disposed of as waste exempt from regulatory concern.

Many decontamination techniques have been developed in order to support maintenance work in nuclear installations. With relative success, the same techniques have also been adopted when decommissioning nuclear installations and components (Fig. 1). Objectives differ between these applications, however.

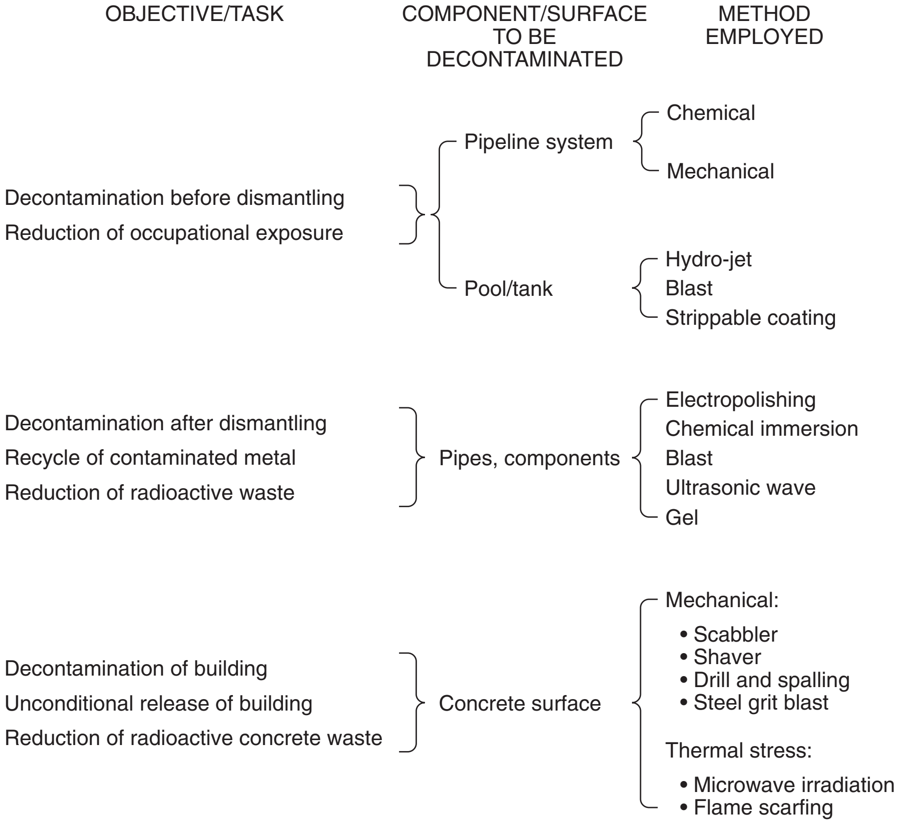


FIG. 1. Decontamination for decommissioning.

In maintenance work, the highest degree of decontamination is sought, avoiding any damage to the component and thereby enabling it to be reused. In contrast, the main aim of decontamination for decommissioning is the removal of as much activity as possible, not only to decategorize wastes, but to reach clearance levels that enable the material from the system to be reused without radiological restrictions. In many cases, it will be necessary to remove all oxides that are liable to trap contaminants, as well as removing a thin layer of structural material in order to achieve this aim. The radionuclides indeed tend to concentrate in the intergranular regions, together with other impurities accumulated during the growth of the metal grains. Therefore, much more aggressive decontamination methods are required than those used during the service life of a plant. In this view, technical methods presenting high decontamination factors (DFs) at high contamination levels do not always allow achievement of the very low levels required to release material without restriction, e.g. inner surfaces of piping.

During decontamination for maintenance, components and systems must not be damaged and the use of very aggressive decontamination methods is not appropriate. In decontamination for decommissioning, however, it is mainly the use of somewhat destructive techniques that presents the possibility of meeting the objective of releasing the material at clearance levels.

Another aspect in which techniques for the thorough decontamination of materials differ from maintenance or laboratory scale decontamination is in the need for industrialization. The large amounts of contaminated material produced during decommissioning procedures and which are available for decontamination generally do not favour methods or techniques that are labour intensive or difficult to handle or which present difficulties when automation is envisaged. The latter is also true in the case of full system decontamination for maintenance.

Other factors presenting differing influences on the choice of techniques are, for example, secondary waste production and the possibility of recycling products from decontamination processes. For both decontamination for maintenance and decontamination for decommissioning, they can be part of the parameters used in decision making.

The absolute requirement of effectively obtaining residual contamination levels below clearance levels is also a factor of primary influence when selecting the decontamination techniques to be used. Even if techniques for the decontamination of complex geometries (e.g. pipe bends, small diameter piping) exist, the non-accessibility of areas may prevent direct radiological measurements from being used to indicate that the clearance levels have been met.

Industry is currently in a transitional phase, moving from decontamination techniques for maintenance to decontamination for decommissioning. Limited data are available from decommissioning on the efficiency of usable techniques for meeting the low unconditional release criteria. In most cases, using available techniques, the clearance levels are only met in an asymptotic manner. Not all methods and techniques available present the possibility of decontaminating to below the required clearance levels. Consequently, in some cases, decontamination is carried out in different stages, the last step specifically aimed at attaining the required objectives.

On the basis of these considerations, when selecting a specific technique for system and/or component decontamination, the following requirements must be considered:

- **Safety:** Application of the method should not result in increased radiation hazards due to external contamination of workers or even inhalation of radioactive dust and aerosols formed during its implementation. It should not add other hazards such as chemical, electrical.
- **Efficiency:** The method should be capable of removing radioactivity from a surface to the level which would enable hands-on work to be undertaken instead of using robots, or which would permit recycle/reuse of material or, at least, assignment to a lower waste treatment and disposal category.
- **Cost effectiveness:** Where possible, equipment should be decontaminated and repaired for reuse. However, the method should not give rise to costs which would exceed the costs of waste treatment and disposal of the material.
- **Waste minimization:** The method should not give rise to large quantities of secondary waste, the treatment and disposal of which would result in excessive requirements as regards personnel and costs, thereby causing additional exposures.
- **Feasibility of industrialization:** Owing to the large quantities of contaminated materials involved, methods or techniques should not be labour intensive, difficult to handle, or difficult to automate.

3.3. SELECTION OF DECONTAMINATION TECHNOLOGIES

Very early on in the process of selecting decontamination technologies for decommissioning, it is important that a cost–benefit analysis be performed to establish whether it is actually worth decontaminating the component or facility, or to determine whether a mild decontamination at low cost is more advantageous than an aggressive decontamination at a higher cost. This analysis is usually accompanied by extensive experimental work being conducted on selected samples from the facility with a view to characterization before the final choice of a decontamination technique is made.

In order to achieve a good DF, a decontamination process must be designed for site specific application, taking into account a wide variety of parameters, some of which are listed below:

- Type of plant and plant process: reactor type, reprocessing plant, etc.
- Operating history of the plant.
- Type of substrate material: steel, zirconium alloy, concrete, etc.
- Type of surface: rough, porous, coated, etc.
- Form of contaminant: oxide, crud, sludge, etc.
- Composition of the contaminant: activation product, fission product, actinide, etc.
- External or internal surface to be cleaned.
- DF required.
- Destination of the components being decontaminated: disposal, reuse, etc.
- Time required for application.
- Proven effectiveness of the process relating to the existing contamination in the installation.
- Type of component: pipe, tank, etc.

Other factors which are important in selecting the method but which do not affect the DF are:

- Availability, cost and complexity of the decontamination equipment.
- Need to condition the secondary waste generated.
- Occupational and public doses resulting from decontamination.
- Other safety, environmental and social issues.
- Availability of trained staff.
- Extent to which the plant needs to be decontaminated in order to achieve acceptable conditions for decommissioning.
- Salvage value of materials which would otherwise be disposed of.
- Extent to which the facility must be modified to undertake the decontamination: isolate systems, enclose and ventilate spaces, etc.

In addition, the choice of a process or of a combination of several processes will finally depend on several other factors such as:

- Specific nature of the application and the complexity of the system;
- Feasibility of industrialization;
- Cost–benefit analysis, taking into account all aspects of the decontamination operation.

The decision on whether to proceed with decontamination and the final process selected will depend on the best overall balance of the above factors in respect of established general criteria (in terms of cost, time, safety, etc).

3.4. DECONTAMINATION TECHNIQUES FOR DECOMMISSIONING

Some specific characteristics of selected decontamination techniques used for segmented components and for the surfaces of buildings are discussed in the following sections. It should be noted that the information presented is not exhaustive. More details of the decontamination techniques for decommissioning can be found in Appendix I and in the literature [18–21].

3.4.1. Characteristics of selected decontamination techniques for segmented components

Simplified overviews of selected decontamination techniques in respect of their efficiency regarding some selection criteria can be found in many publications. Practical experience indicates that these overviews have to be considered with great care. Small changes in details of application of the selected techniques can have significant impacts on the qualification of influential parameters. Although the objective of this section is not to provide a detailed overview of all the advantages and disadvantages of available techniques, some specific considerations on selected categories of decontamination techniques are described.

Chemical decontamination comprises the use of concentrated or dilute solutions of different reagents in contact with the contaminated item to dissolve either the metal substrate or the contamination layer covering it. The required decontamination levels can be obtained by continuing the process as long as necessary, care being taken to ensure that tank walls or piping are not penetrated by corrosion.

In mild chemical decontamination processes, dissolution of the layer is intended to be non-destructive to the metal substrate and this technique is generally used in operating facilities. Aggressive chemical decontamination techniques involving dissolution of the metal base should only be considered in decommissioning programmes where reuse of the item will never occur. Chemical flushing is recommended for the remote decontamination of intact piping systems.

Chemical decontamination techniques have also proven to be effective in reducing the radioactivity of large surface areas such as drip trays as an alternative to partial or complete removal. They are also suitable for use on complex geometries as well as for a uniform treatment of inner and outer pipe surfaces. These techniques, however, require the efficient recycling of reactive chemicals. Insufficient recycling of decontamination products results in very large amounts of secondary wastes being generated which are difficult to treat.

Electrochemical decontamination (electropolishing) can be considered in principle to be a chemical decontamination assisted by an electrical field. Electropolishing is a process widely used in different industrial applications to remove the surface layer and to produce a smooth, polished surface on metals and alloys. It can be considered to be the opposite of electroplating, as metal layers are removed from a surface rather than being added as a coating.

Electrochemical decontamination has been applied either by soaking the surface in an electrolyte bath, or by using a pad moving over the surface to be decontaminated, the passage of electric current effecting the anodic dissolution and removal of metal and oxide layers from the component. The electrolyte is continuously recirculated for regeneration.

These processes can only be applied to conductive surfaces. They are highly effective and give a high DF. Their use is limited by the size of the bath (when soaking is used), and by the geometry of the surfaces and the available clearance around the part being treated (when the pad is used).

This makes the method rather difficult to apply for the industrial decontamination of surfaces with very complex geometries. Although the volume of effluents is minimized, handling the parts to be soaked or to be treated with the pad can lead to additional exposure to workers.

Decontamination by melting presents the particular advantage of redistributing a number of radionuclides among the ingots, slag and filter dust resulting from the melting process, thereby decontaminating the primary material.

Melting may provide an essential step when releasing components with complex geometries, simplifying monitoring procedures for radioactive metal characterization. In addition to its decontamination effects, the problem of inaccessible surfaces is eliminated and the remaining radioactivity is homogenized through the total mass of the ingot.

Melting, therefore, can be a last step in the decontamination and release of components with complex geometries, after these pieces have been decontaminated by, for example, chemical methods, which remove radionuclides such as ^{60}Co from the surface or surface layer of the material that would otherwise remain in the ingot after melting.

Mechanical and manual decontamination are physical techniques. More recently, mechanical decontamination has included washing and swabbing, as well as the use of foaming agents and peelable latex coatings. Mechanical techniques may also include wet or dry abrasive blasting, grinding of surfaces and removal of concrete by spalling or scarifying. These techniques are most applicable to the decontamination of structural surfaces. Some of them are also applicable to non-metallic surfaces such as plastics.

Abrasive blasting systems, both wet and dry, have been used with success. They provide mechanical methods, derived from conventional industry, that give very high DFs. The longer the operations are continued, the more destructive they are. Additionally, wet abrasive systems produce a mixture of dust and water droplets that might be difficult to treat. Care must be taken not to introduce the contamination into the material surface (hammering effect), thereby compromising the ability to meet clearance levels. These techniques are not appropriate for complicated surfaces where uniform access cannot be guaranteed.

In recent years, many innovative decontamination techniques have been proposed. Some of these are described in Section 6.6.1. Improvements in effectiveness are also obtained through the use of an appropriate combination of existing techniques.

3.4.2. Characteristics of selected decontamination techniques for building surfaces

When decontaminating building structures, mainly mechanical surface removal techniques have to be considered. Surface removal techniques are used when future scenarios include reuse of the site, when it is impractical to demolish the building (e.g. a laboratory within a building), or with a view to waste minimization. The techniques considered remove various depths of surface contamination and may be used to reduce the amount of contaminated material for disposal. By first using a surface removal technique, the volume of contaminant is limited to the surface material removed. The eventual demolition can then be handled in a more conventional manner. However, if a contaminated building is demolished, all of the debris is considered to be contaminated and therefore requires special handling.

Before taking a decision on the decontamination of building structures, a cost–benefit analysis should be prepared which considers such potential concerns as the packaging, shipping and burial costs involved when using a surface removal technique compared with those arising from conventional demolition and disposal.

Decontamination processes to be used for contaminated concrete depend greatly on the characteristics of the concrete surface to be cleaned. They can vary from very simple hand based processes to jackhammer or drilling removal techniques. The former are normally used for cleaning painted or smooth surfaces covered by loose contamination and the latter for decontaminating concrete where the contamination has penetrated deeply.

Simple processes, such as brushing, washing, scrubbing and vacuum cleaning, have been widely used since the need for decontamination/cleaning was first recognized in the nuclear industry, and each nuclear facility has, to some extent, a certain practical experience of these kinds of decontamination process.

These processes are generally labour intensive, but they have the advantage of being versatile. They are sometimes used as a first step, for example, to vacuum up dust and remove loose contamination before or during dismantling, to reduce dose rates and operator exposure, and to prepare items for more aggressive decontamination using stronger processes.

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

When decontaminating concrete surfaces, mainly mechanical scarifying techniques, such as needle scaling, scabbling, or shaving, are used.

Scarifiers physically abrade both coated and uncoated concrete and steel surfaces. The scarification process removes the top layers of contaminated surfaces down to the depth of sound, uncontaminated surfaces. Present-day refined scarifiers are not only very reliable tools, but they also provide the desired profile for new coating systems in the event that the facility is released for unconditional use.

Needle scalers are usually pneumatically driven and use uniform sets of 2, 3, or 4 mm needles to obtain a desired profile and performance. Needle sets use a reciprocating action to chip contamination from a surface. Most of the tools have specialized shrouding and vacuum attachments to collect removed dust and debris during needle scaling.

Needle scalers are exceptionally useful in tight, hard to access areas, as well as for wall and ceiling surface decontamination. This technique is a dry decontamination process and does not introduce water, chemicals or abrasives into the waste stream. Only the removed debris is collected for treatment and disposal. Production rates vary, depending on the desired surface profile.

Scabbling is a scarification process used to remove concrete surfaces. Scabbling tools typically incorporate several pneumatically operated piston heads to strike (i.e. chip) the concrete surface. Scabbling bits are equipped with tungsten carbide cutters. Both electrically and pneumatically driven machines are available. As scabbling can pose a cross-contamination hazard, vacuum attachments and shrouding configurations have to be incorporated.

Scabblers are best suited for removing thin layers (up to 25 mm thick) of contaminated concrete (including concrete blocks) or plastered bricks. Scrabbling is recommended for use in situations where:

- No airborne contamination can occur,
- 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 use on both large open areas and small areas.

As an alternative to scabbling, shaving machines have been developed. These machines are similar to normal scabbling units and are equipped with a quick change diamond tipped rotary cutting head. This head is designed to follow the contours of the surface being removed and to give a smooth surface finish, which is easier to measure and ready for painting. Depth adjustments can be set manually in order to minimize generation of waste. The machine is capable of cutting through bolts and other metal objects, which for the traditional scabbler would result in damage to the scabbling head. 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.

3.5. CONSIDERATIONS IN THE SELECTION OF DISMANTLING TECHNIQUES

Dismantling is an important part of the decommissioning process and comprises the disassembly and removal of any structure, system or component during decommissioning. Dismantling is required in order to allow components to be physically removed for storage or for further treatment prior to disposal. Dismantling and further segmentation will also be needed to complete the decontamination process, as part of the radioactive waste minimization strategy. In this case, specific factors, such as shape, activation level or disposition of the contamination, will have limited the effectiveness of the pre-dismantling decontamination.

Moreover, even though decontamination methods cannot attain levels of radioactivity which permit return to the public domain, it is still necessary that components and structures be cut up and size reduced in order that the resulting materials are volume minimized prior to storage or disposal as radioactive waste.

Dismantling techniques must be applicable to plant equipment and structures of very different sizes, made up of metals, reinforced concrete or even masonry, and ranging in thickness up to several metres.

These various items of plant structure and equipment may be surface contaminated or activated or both, which in certain cases prohibits worker access to the areas where they are located and imposes the use of remotely controlled machines.

There are a very large number of mechanical, thermal, electrothermal, pyrotechnic and other processes for cutting up, separating or breaking down the plant, equipment and structure of an installation. When the decommissioning of a nuclear installation is being planned, the selection of cutting tools or equipment should take account of several parameters:

- The performance of the equipment should be adequate.
- The equipment should be difficult to contaminate and easy to decontaminate, in order to limit radiation exposure of maintenance workers and limit the production of decontamination effluent.

- The equipment components should withstand radiation.
- The capability for tool removal from a remotely manipulated system for maintenance or repair should exist.
- The tool should be compatible with the working environment (accessibility to the working area and to the parts to be cut).
- The tool should be compatible with the conditions in the working area, e.g. for underwater work it should be watertight and corrosion resistant.

Use of the tool should not generate hazards other than those which can be controlled, monitored and treated (i.e. dust, particles, smoke, aerosols and liquid effluent).

3.6. DISMANTLING TECHNIQUES USED IN DECOMMISSIONING

Although a great variety of cutting tools are available, it is not always easy to find the appropriate tool, the operation and performance of which fits the situation and the particular requirements exactly. In practice, every tool has its own performance, conditions of use and field of application.

Some specific characteristics of selected dismantling techniques are discussed in the following sections. More details of dismantling techniques for decommissioning are provided in Appendix II. Further details can be found in the literature [20, 21].

3.6.1. Thermal and electrothermal cutting equipment

In general, electrothermal cutting tools such as oxygen and plasma arc torches, thermal lances, cutting electrodes, arc saws, etc., are very effective and capable of cutting materials of considerable thickness (several centimetres of steel). They are also easy to use. On the other hand, they produce substantial amounts of gaseous secondary wastes (smoke, aerosols) and consequently should be used with effective ventilation and air filtration systems, which increase the costs of cutting.

Most of these tools can be used under water. Data on tool performance, operating conditions and secondary wastes generated are available from various research projects and experiments as indicated in Refs [22–24].

3.6.2. Mechanical systems for cutting and fragmenting

Mechanical cutting tools such as circular saws, shears, disks, abrasive wheels, augers, diamond saws and cables, broaching tools, high pressure water jets with and without abrasives, etc., are usually slower than thermal and electrothermal cutting tools. Although they generate few or no aerosols and waste gases, they often produce solid particles, the dispersion of which must be avoided.

Most of these tools can be remotely operated, but the reaction forces require remote manipulators to be adapted. Their use under water can sometimes prove problematic.

Some specific types of equipment in particular are used for concrete destruction, such as large diameter diamond saws, diamond cables, reamer augers, pneumatic hammers and other percussion tools which generally produce large amounts of dust and debris [12].

4. WASTE MINIMIZATION FUNDAMENTALS

As indicated in Section 2, the objectives of waste minimization are to limit the generation and spread of radioactive contamination and to reduce the volume of wastes for storage and disposal, thereby limiting any consequent environmental impact, as well as the total costs associated with contaminated material management. The main elements of a waste minimization strategy can be grouped into four areas: source reduction, prevention of contamination spread, recycle and reuse, and waste management optimization.

4.1. FUNDAMENTAL PRINCIPLES

The above four areas important for waste minimization define four fundamental principles which should be considered when planning and implementing the waste minimization programme. These fundamental principles can be summarized as follows:

- Keep the generation of radioactive waste to the minimum possible or practicable;
- Minimize the spread of radioactivity leading to the creation of radioactive waste as much as possible by containing it to the greatest extent possible;
- Optimize possibilities for recycle and reuse of valuable components from existing and potential waste streams;
- Minimize the amount of radioactive waste that has been created by applying adequate treatment technology.

4.1.1. Control of radioactive waste generation

The generation of radioactive waste during the whole life-cycle of the facility shall be kept to the minimum practicable, in terms of both its activity and its volume, by appropriate design measures, facility operation and decommissioning practices. This includes the selection of appropriate technology, the selection and control of construction and operational materials, the recycle and reuse of materials, and the implementation of appropriate procedures. Emphasis should be placed on the segregation of different types of material in order to reduce the volume of radioactive waste and facilitate its management [25].

4.1.2. Prevention of contamination

It is important to minimize the spread of radioactive contamination with a view to reducing to the strict minimum the need for decontamination, and hence also minimize the creation of secondary waste. It is desirable that use be made of all means of preventing contamination, to the extent that they are economically justified and do not lead to additional risks and complications in decommissioning operations [8].

4.1.3. Recycle and reuse of materials

Consideration of the amounts of material arising from D&D highlights the importance of recycle and reuse within a waste minimization strategy. In addition, considering that the ultimate goal, i.e. the end product of D&D operations, is the unconditional release or reuse of sites, facilities, installations, or materials for other purposes, opportunities for release or recycle/reuse of materials should be maximized.

Implementation of recycle and reuse options requires the availability of suitable criteria, measurement methodology and instrumentation. Initiatives to support waste minimization in D&D should be set up in order to promote options for recycling or reusing materials, rather than to restrict this practice.

4.1.4. Reduction of radioactive waste volumes

In addition to reducing the amount of radioactive waste generated, it is also important after generation to minimize the volume of radioactive waste by appropriate treatment. The volume of radioactive waste resulting from decommissioning operations may be reduced by increased use of volume reduction processes, such as compaction, incineration, filtration and evaporation. These actions will extend the operating life of current disposal sites, limit the need for interim storage if disposal is not available, and reduce the number of shipments of waste [26].

4.2. PRACTICAL IMPLEMENTATION OF THE FUNDAMENTAL PRINCIPLES

Practical implementation of these fundamental principles can be achieved using administrative or organizational arrangements and technical approaches as given below. It must be re-emphasized that the first step of any waste minimization strategy is to keep the generation of radioactive wastes to a minimum. Application of adequate waste management technologies should be considered as a final step, when the creation of radioactive wastes is unavoidable.

4.2.1. Operational culture

The minimization of radioactive waste can be most easily achieved by minimizing opportunities for the creation and spread of radioactivity. The establishment of an appropriate policy and culture to achieve this is the primary responsibility of the plant management, during both operation and decommissioning. Waste minimization is an activity which should be maintained throughout the whole life-cycle of a plant. Management must also create this culture through leading by example and by creating a consultative team environment. This involves not just applying management procedures, but also educating the workforce in order to instil in it appropriate understanding, attitudes and patterns of behaviour.

Preparing efficient work plans with adequate work organization and selection of appropriate tools, instruments and materials will limit potential cross-contamination, provide optimized working times and minimize the generation of secondary waste from intervention work.

Workers must understand the need to minimize the waste generated in the tasks assigned to each of them. Generally, this involves alerting workers to the installation of contamination control tenting, containment of spills, etc., and instructing them to clean equipment and areas carefully after each operation and to avoid mixing non-contaminated wastes with contaminated wastes. Prompt countermeasures should be taken whenever contamination spread is detected. Specifically in the case of decommissioning operations, major reductions in waste generation can be achieved through training and the employment of administrative controls, contamination control tenting and confinement, and through the decontamination of selected materials and components to releasable or reusable levels.

Contamination control tenting needs to be used wherever the potential for airborne contamination exists, e.g. in cutting or grinding operations. Tents need to be fitted with cleanable prefilters and high efficiency particulate air (HEPA) filters with adequate air flow away from the worker in order to prevent inhalation. Plastic sheeting covered with absorbent pads (reusable if available) needs to be used under all pipe cuts where the potential for liquid spillage exists in order to minimize the spread of activity from such a source.

Components and tools used in the work may be decontaminated to clearance levels by one or more techniques. In particular, components or tools having simple geometry and smooth surfaces are well suited for decontamination by wiping, washing, dry cleaning or by use of more sophisticated techniques such as electropolishing or vibratory finishing. Tools cleaned in this manner may be reused repeatedly. In each case, the cost–benefit needs to be evaluated.

In addition to reducing the amount of contaminated waste generated by decommissioning, subsequent reduction in the volume of this waste by treatment methods outlined in Section 4.2.6 also needs to be encouraged.

4.2.2. Administrative controls and management initiatives

Administrative controls and management initiatives in operating facilities can contribute significantly to an adequate waste minimization strategy. Some of the steps that can be taken are:

- Collection and update of all information related to plant design (drawings, material specifications, various modifications and implementations) and also information related to the operating performance during plant life. The development of computerized database techniques can solve the problem of preserving and updating all the information needed for performing dismantling and decommissioning.
- Establishment of an organizational structure which ensures that the responsibilities for all aspects of contaminated material management are defined, and encouragement of best practices in waste minimization.
- Establishment of an accounting and tracing system to quantify the sources, types, amounts, activities and dispositions of contaminated materials.
- Identification of all points in the working areas and all stages in the process where it is possible to prevent materials from becoming radioactive or radioactively contaminated, e.g. by excluding packaging, by using recycled materials in the process or by making equipment changes. Individual processes should be reviewed periodically.
- Improvement of operational practices and management techniques and exchange of information and experience on sorting and segregating wastes at their sources in order to prevent mixing of different waste categories.
- Provision for the comprehensive education of operators. Through introductory courses and regular ‘refresher’ courses, the attempt must be made to foster operator awareness of the need to keep the generation of contaminated materials to a minimum.

In some Member States, the regulatory systems and administrative controls are highly developed, whilst in others they are still under development. In order to assist the operators of nuclear facilities or decommissioners in minimizing contaminated material consistent with safe operating practices, the relevant regulations must be in place and enforced.

The implementation of any waste minimization strategy is always an optimization exercise which takes into consideration factors such as worker doses, costs of recovering materials generated, disposal routes available for specific types of contaminated material, quantities of material generated in each category, and duration and costs of interim storage of wastes compared with the estimated ultimate disposal costs.

Ideally, a waste minimization strategy should be considered at the planning stage of any process development.

4.2.3. Technical factors to avoid the production of radioactive materials

Four significant technical factors to consider in avoiding or minimizing the production of radioactive materials are:

- Design of installations,
- Choice of materials,
- Maintenance of installations and systems,
- Cleanliness and decontamination.

The contents of this section only provide examples of preventive actions to take in order to avoid or to minimize the generation of radioactive materials. Current decommissioning activities generally involve facilities that were designed in the past without adequate consideration of these factors. On the basis of experience gained in decommissioning, additional recommendations are discussed in further detail in Section 6.

4.2.3.1. Design of installations

Building layout and component installation need to comply with a number of requirements. Wherever possible, the layout of pipework systems containing radioactive fluids should avoid crud traps such as those that occur at bends, seal flanges, stagnant legs. Pipes and components should be designed to provide easy drainage. Components need to be easily accessible and to have suitable working space.

4.2.3.2. Choice of materials

The choice of materials for fabricating components which will be in contact with the primary coolant of nuclear reactors needs to be made in such a way that the presence of elements which can become activated to form long lived and strong gamma emitting radioisotopes (e.g. cobalt, niobium, silver, molybdenum) is minimized. Where alloying elements such as nickel cannot be avoided, their concentration should be reduced as far as possible. For surfaces exposed to wear, alloys that are either cobalt free or that have greatly reduced cobalt content are being developed.

4.2.3.3. Maintenance of installations and systems

Adequate and routine attention needs to be paid to the water chemistry of feedwater and coolant systems in water cooled reactors. By maintaining high standards and observing accepted water specifications, the lowest possible volume of corrosion products will be generated and the chances of additional contamination due to fuel cladding failures minimized.

In addition, periodic rinsing or decontamination of piping or isolated components and thorough decontamination of a plant preceding actual decommissioning will minimize residual contamination of surfaces. Moreover, ensuring that post-operational clean out of a plant is undertaken as soon as possible after shutdown is easier to achieve whilst the equipment is still operational.

In general, handling equipment, electrical supplies, ventilation systems, radiological surveillance instruments, etc., must be properly maintained, with particular attention paid to those parts which may become degraded. When replacements are required, a careful selection of equipment can result in a significant reduction in the generation of radioactive materials/components.

4.2.3.4. Cleanliness and decontamination

Pre-treatment (electropolishing in the case of metals) and application of appropriate coatings (for porous materials) can be useful in achieving reduced contamination buildup and in reducing the difficulty of subsequent decontamination. Concrete surfaces exposed to contamination under normal operation and during incidents may, with advantage, be protected with coatings (possibly of the readily removable type). It has been observed that contamination is concentrated to a large extent in the coating, preventing deep penetration into the porous material. In this manner, the quantity of contaminated concrete waste produced during final dismantling can be minimized.

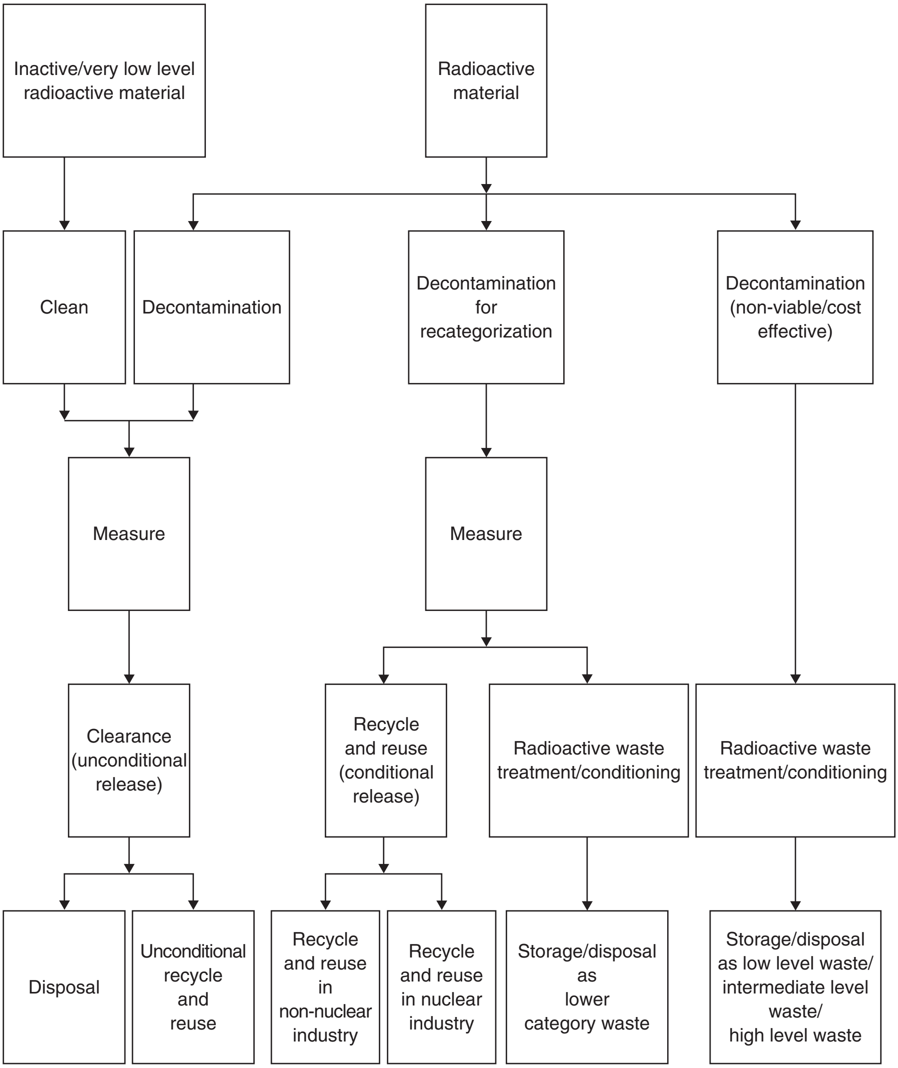


FIG. 2. Options for the segregation and characterization of suspect and radioactive material.

4.2.4. Characterization and segregation of materials during decommissioning

Proper characterization and segregation of materials arising during decommissioning operations are very important factors in waste minimization. Characterization helps develop a complete understanding of the physical, chemical and radiological characteristics of these materials in order to enable them to be segregated and to be sent for selected processing and/or disposal. Segregation favours the maximization of unconditional release; allows consideration of conditional release, reuse or recycling of materials; and permits reduction in the volume of radioactive wastes that do not meet clearance, recycling or reuse criteria.

The flowsheet shown in Fig. 2 illustrates the options for the segregation and routing of suspect or radioactive materials arising from D&D activities.

Characterization derives from a knowledge of the radiological state of an installation both before and during dismantling [27, 28]. In practice, this involves:

- Drawing up maps of contamination and of other radiation sources in order to determine the tactics and resources to be used for decommissioning the installation, and opting for particular techniques for cutting up and decontaminating;
- Continuously measuring dose rates and air contamination levels in the working area with a view to making the necessary arrangements for protecting workers and the environment;
- Checking the outcome of decontamination operations;
- Segregating and packaging the resulting materials;
- Monitoring the waste packages to ensure that they conform with the requirements for further treatment and/or with the regulations governing transport, storage and disposal;
- Measuring and documenting the radioactivity of materials, buildings and land, when these are to be returned to the public domain.

Each of these tasks has to meet specific criteria. A thorough knowledge of the operating history of the installation will also aid in the selection of measurement methods and equipment, and in the development of measurement procedures.

Much of the following information is also required as part of an appropriate waste characterization:

- Type of emitter (alpha, beta, gamma, X ray);
- Source of emission (loose or fixed contamination, or induced radioactivity);
- Physical state (solid, liquid or gas);
- Chemical composition;

- Geometry, surface area and volume of components to be measured;
- Level of radioactivity to be measured;
- Potential for interference from several sources of radiation, etc.

4.2.5. Measurement techniques and infrastructure

Measurement of initial activity in materials during decommissioning and of residual activity in materials after application of decontamination methods is very important, both for characterization/segregation of materials and for providing proper control before release of materials (conditional or unconditional) after decontamination.

A number of techniques for measuring the radioactivity of materials generated in decommissioning operations are available. A summary of these techniques can be found below.

Techniques for the measurement of radioactivity can be organized into three general groupings: direct measurements, indirect measurements and measurements by sampling [12, 29].

Direct measurements are taken using a radiation detector (i.e. gas proportional detectors, scintillators, ionization chambers) positioned near contact with the surface or object to be measured. Various detectors are available and the choice of detector depends on a number of factors, including the type of radiation to be measured (i.e. alpha, beta–gamma), the size and shape of the object or surface to be measured and the anticipated level of radiation. The detector is connected to electronics that convert the detector signal into a readout that can be related to the radioactivity contained in the object or occurring on the surface. Direct measurements may be used in waste minimization for the final release of buildings, objects and materials, provided that there are no circumstances which reduce the confidence of the direct measurement to unacceptable levels (i.e. inaccessible surfaces, radioisotopes that cannot be efficiently detected at scanning speeds suitable for handling large volumes of materials, high radiation backgrounds that do not allow for the accurate detection of clearance levels).

Indirect measurements are taken using a paper smear to swipe a known area of a surface or object in order to assess whether loose contamination is present. The smear is evaluated for contamination by performing a near contact measurement of it using radiation detectors that are suitable for the range of radionuclides anticipated as being present. Criteria used for the classification of materials resulting from decommissioning operations may require that the level of loose contamination on the material be evaluated and documented. Some of the technical challenges associated with smears involve the estimation of pick-up efficiency (as not all of the loose contamination on a material will be removed), and the fact that the measurement, once taken, is not reproducible, since any loose contamination has been removed to some extent by the act of taking the swipe.

When taking measurements by sampling, portions of materials are analysed by laboratory processes (i.e. chemical separation, and alpha, beta and gamma spectrometry) in order to identify the radionuclides present in the material and to determine their concentrations. Samples are often taken before direct and indirect measurements are taken, in order to determine which radionuclides, and their relative proportions, are to be expected in the material.

Uncertainty is introduced because of the challenges associated with obtaining representative samples from surfaces, objects and materials. This method is not usually used independently of direct and indirect measurements for the classification of materials prior to disposition owing to the expense of chemical separation and spectrometry. However, it may be very useful for measuring the radioactivity of objects having inaccessible surfaces. One example is the sampling of molten metal whereby a homogenized sample of metallic objects such as pipes, which are often not possible to measure, directly or indirectly, is provided. Samples are also used to develop scaling factors for radionuclides in materials in order that an easily executed direct measurement (i.e. gamma dose rate due to ^{137}Cs) may be used to infer the concentrations of other radionuclides that were generated in a similar fashion (i.e. other fission products).

Many technical challenges are encountered when taking measurements of radioactivity in support of waste minimization. An expanded discussion of these challenges can be found in Appendix III, together with further details on measurement methodology, including the advantages and disadvantages of each method.

4.2.6. Release of materials

A further requirement of waste minimization during D&D is the maximization of the amount of material which can be released either for unconditional recycle or reuse, or for conditional recycle or reuse, both within and outside the nuclear industry.

During the decommissioning of nuclear facilities, quantities of valuable metals and equipment may become available for recycle or reuse, provided that the radioactivity on or in them can be reduced to acceptable levels. Work is currently in progress within several international organizations (IAEA, OECD Nuclear Energy Agency and European Commission (EC)) aimed at defining the basis for establishing suitable criteria for unconditional release of materials and equipment, and for applying these criteria to actual waste management and decommissioning cases [12, 30, 31]. The difficulty here lies in proving that all of the material has been cleared to acceptable levels. In this respect, treatment of materials (e.g. scrap metal) by melting guarantees homogeneity of the final product and facilitates sampling and proving acceptability in order to gain unconditional release.

Some countries have already implemented unconditional release of materials on a case by case basis. For example, 900 Mg of metal scrap from the operation of the Würgassen nuclear power station is to be decontaminated and unconditionally reused as scrap metal [12]. The nuclear ship Otto Hahn (Germany) was decommissioned to Stage 3 by removing all the nuclear parts and cleaning up any residual activity. The ship can now be used as a conventional vessel [12]. From the decommissioning of the Niederaichbach power station (KKN), a total of about 3500 Mg of metal has been unconditionally released [31]. Examples of materials (carbon steel, stainless steel, concrete, soil, gravel, etc.) that have been disposed of with radiological restrictions, or of various metals that have been conditionally recycled through melting in a specific melter, are referenced in Ref. [30].

Remelting scrap, as such, is a particular method of decontamination. In this case, the reduction in activity of the final product results from the decontamination processes employed before melting and by the partition of the radionuclides within the melt, slag and dust generated during the melting operation. The EC is investigating remelting as it appears to be a promising method of conditioning steel waste with the purpose of achieving volume reduction, immobilization of radioactivity and possible recycling of the steel [31].

As indicated in Section 4.2.4, materials produced during the decommissioning of a nuclear facility are usually segregated, as much as possible, according to the final method of disposition after treatment. With reference to Fig. 2, six categories of material may be identified:

- Higher level radioactive waste which, usually after treatment and conditioning, is sent to some form of high integrity repository or storage facility;
- Lower level radioactive waste which undergoes appropriate treatment/ conditioning and is then sent to a storage or disposal facility;
- Radioactive materials which are destined for conditional recycle or reuse within the nuclear industry;
- Radioactive materials which are destined for conditional recycle or reuse within the non-nuclear industry;
- Unconditionally released materials which are destined for recycle or reuse;
- Unconditionally released materials which are destined for landfill disposal.

In order to facilitate the release practices, suitable criteria, measurement methodology and instrumentation must be available. This is particularly important for material destined for unconditional release (the last two categories), which usually represents a very large proportion of the material produced. The establishment of unconditional release criteria is a critical step towards satsifying the need for a consistent, internationally accepted standard. However, such criteria should be established in a manner that will encourage, rather than preclude, the future establishment of waste minimization practices. In addition, care should be taken in the development of these criteria, as state of the art instrumentation may be incapable of measuring these standards on an industrial scale.

Another important factor which must be considered in the unconditional reuse or recycle of material is the economic impact [12]. It is beyond the scope of this report to carry out a detailed economic study of this approach to waste management. However, the factors which should be considered in assessing the economics of recycling are briefly discussed below.

The monetary benefits of recycling or reusing materials are relatively obvious; there are no disposal costs for the materials and the scrap value of the item or its component materials may be realized.

Both factors depend on the circumstances prevailing in a particular country. For example, the cost of the least expensive disposal method can range from one to several thousand US dollars per cubic metre. Even at the lower value the cost savings can be significant. Similarly, the scrap value of an item depends on the nature of the individual item or the intrinsic value of the materials from which the item is made.

On the other hand, the monetary costs of reclaiming the scrap can be significant and include:

- Material and labour costs of decontaminating the materials.
- Costs of treating and disposing of the wastes arising from decontamination.
- Cost (labour and radiation dose) of undertaking the extra monitoring needed to select the items for recycle and of ensuring that they are below the release limits. The cost of this activity will increase as the level of the acceptable limits for release decreases, since the main problems with very low level waste are the measurability of the inherent activity and verification of the measuring techniques used.
- Cost of treating and disposing of secondary radioactive waste produced by the treatment process itself.
- Costs arising from the possible need to decontaminate the treatment process equipment.

It is obvious that there are many factors to be evaluated when considering the recycle/reuse of equipment and material. In addition to the criteria for unconditional recycle/reuse, more work needs to be done on the economic and safety aspects.

4.2.7. Processing/treatment of waste for volume reduction

Contaminated materials that are not subject to the waste minimization techniques discussed previously have to be considered as radioactive waste. The final objective in waste minimization during D&D is to ensure that the volumes of unreleasable radioactive materials remaining are minimized as far as practicable.

The methods of handling, treating, conditioning, packaging, storing, transporting and disposing of radioactive wastes arising from decommissioning will, in general, be similar to those used in other parts of the nuclear industry. Since most methods have been well covered in other IAEA reports [32–40], they will only be briefly reviewed here. However, owing to the specific nature of certain decommissioning wastes, special consideration may be necessary in certain areas.

The major requirement of any waste management strategy is to guarantee the safety of all the waste operations. Detailed consideration needs to be given to the types of waste and to the packaging, transportation and disposal requirements. The waste forms and packaging have to comply with national transport regulations and with the acceptance criteria at waste disposal sites.

In the following sections, the elements of a waste management programme for decommissioning are briefly reviewed, highlighting any differences between decommissioning wastes and those arising from other parts of the nuclear industry.

4.2.7.1. Requirements for waste treatment

As with radioactive wastes produced during facility operations, radioactive wastes resulting from decommissioning need to be treated according to the types of waste, concentrations of radionuclides and requirements for waste storage and/or disposal.

The choice of treatment processes will depend on a variety of parameters, including:

- The physical, chemical and radiological properties of the waste;
- The type of treatment processes available;
- The location of the requisite processing equipment, e.g. whether the treatment facilities are on-site or at a nearby location;
- The transportation, storage and disposal alternatives available;
- Economic considerations.

Where possible, the waste is pretreated to provide appropriate preparation and to facilitate subsequent waste treatment steps. Pretreatment steps could include:

- Administrative steps, including documentation of the details of the waste for accountability and operational purposes;
- Segregating and sorting waste in order to classify it for suitable treatment;
- Packaging in containers (bags, drums) suitable for transport to the treatment area;

- Decontamination, in order to facilitate further handling and treatment;
- Intermediate decay storage, which allows decay of short lived isotopes and thereby facilitates subsequent treatment steps.

(a) Treatment of solid wastes

Solid, low and intermediate level wastes are generally segregated into combustible, compactible and non-compactible forms [34].

Incineration of combustible wastes gives a large overall volume reduction and produces a stable waste product (ash) which can be readily immobilized using a variety of methods which employ different matrices, such as concrete and bitumen. Numerous types of incinerator are in use or under development for processing radioactive wastes, e.g. excess or controlled air incinerators, fluidized bed incinerator [35].

Low force compaction is the least expensive and an easier to operate volume reduction process than high force compaction. High force compactors can give somewhat better reduction factors. Compaction units are also amenable to automation, which can improve operational efficiency and radiation protection aspects.

Treatment of solid wastes that are not combustible or compactible generally requires some segmentation [12] in order that standard types of disposal container can be used. The extent to which segmentation is required depends on the capacity of the transport methods and on the size or weight restrictions that exist at the disposal site. Where the cost of disposal is very high, the melting of metals could be considered as a means of reducing the volume considerably. The cost effectiveness of this approach can be improved if the metal can be used as additional shielding for other waste. Where possible, it may be considerably cheaper to remove, ship and dispose of large units, for example, the pressure vessel, in one piece [41].

As a result of the waste’s radiological characteristics and the special requirements for the disposal of alpha bearing wastes, there may be an incentive or even a requirement to segregate waste streams during processing and packaging.

(b) Processing of liquid wastes

A large number of processes are available for reducing the volume and immobilizing the low and intermediate level liquid wastes which will arise from the decommissioning of nuclear facilities [36]. Processes which reduce the volume of radioactive liquid wastes include: filtration, flocculation, precipitation, ion exchange and evaporation. However, certain liquids used during decontamination, for example, concentrated acids, may require special treatment processes.

The concentrated radioactive residues contained in the ion exchange media, filters, or concentrator bottom liquids, require conditioning for their immobilization.

Matrix materials that are used for immobilization include cement, bitumen, a variety of polymers, glasses and ceramics [33].

4.2.7.2. Transport, storage and disposal of conditioned wastes

Discussion of regulations for the transport of radioactive materials is outside the scope of this report. However, it is important to recognize that these regulations are demanding in terms of both cost and the time taken to implement them. Therefore, an additional monetary benefit derived from waste minimization is the concomitant reduction in the costs of transporting radioactive waste from the site of arising to the site of disposal.

The methods of storage and disposal of radioactive wastes are governed by applicable national (and international) regulations, by the availability of appropriate storage and disposal facilities, and by the need to achieve an optimum cost–benefit ratio for accomplishing the disposal. The type and specific activity of the radioactive material present in the waste are the two most important factors used in selecting the storage and disposal method. Other important factors are the size of the package and the difficulty in handling the package during disposal.

The principal methods of disposal [38–42] are near surface disposal and emplacement in rock cavities or repositories within deep geological formations. Near surface disposal is generally employed for low and intermediate level radioactive wastes. Rock cavities can potentially be used for all kinds of solid, low and intermediate level waste. Disposal in deep geological formations is envisaged for high level wastes having significant quantities of long lived radionuclides.

The choice of disposal method is dependent on the conditions prevailing in the country and on many other factors specific to the disposal system to be developed. Generally, near surface disposal and rock cavity concepts appear to be the most viable for disposal of decommissioning waste.

5. FACTORS AND CONSTRAINTS INFLUENCING WASTE MINIMIZATION IN DECOMMISSIONING

5.1. INTRODUCTION

It is an essential element of a strategy to minimize waste from the decommissioning of nuclear facilities that requirements to facilitate decontamination and dismantling be fully considered and included during the design, construction and operation, and in any refurbishment. Some examples include the use of low cobalt content steels and alloys, as well as corrosion resistant alloys in reactors. During operations, the chemistry of liquids and gases should be monitored and controlled. Provision should be made for the easy drainage of all liquids from systems, and very smooth surfaces, amenable to decontamination, should be created whenever possible.

When discussing decommissioning operations, it must be emphasized that economic considerations can be a major driving force when considering segregation, release, recycle and reuse practices in preference to disposal alternatives for radioactive and non-radioactive materials arising from the D&D of nuclear facilities. It should be clear, however, that segregation, release, recycle and reuse practices are typical examples of industrial activity that are controlled by multiple, sometimes contradictory, factors. Consequently, some level of optimization forms an inherent part of the determination of whether segregation, release, recycle and reuse practices will be applied on a larger scale in the nuclear industry. An overview of the major influential factors is given in the following paragraphs.

5.2. FACTORS INFLUENCING WASTE MINIMIZATION

5.2.1. Technical feasibility/availability of technology for waste minimization

The availability of technically and economically proven techniques for the dismantling, segmentation, decontamination, measurement and processing of components and materials is essential to any decommissioning programme for nuclear facilities. In addition, the availability of technically and economically proven means for the segregation, release, recycling and reuse of materials from the D&D of nuclear facilities is essential to any waste minimization strategy. Laboratory or pilot scale processes may be developed and enhanced in capacity and efficiency, which may require the expenditure of additional effort, time and resources. In any case, regulatory approval will be required for the selected technology.

In addition, technically feasible methods of D&D should not give rise to large quantities of secondary waste, and the treatment and disposal of these secondary wastes should not result in prohibitive requirements with respect to labour, the costs involved, or the potentially adverse impacts on workers, the public and the environment.

The decision on whether to proceed with recycle and reuse options, however, also largely depends on the characteristics of the material, the type and level of contamination (alpha, beta–gamma, loose or fixed, depth of penetration, absence or degree of activation), the nature and duration of storage, the accessibility of surfaces for decontamination and measurement, and the compatibility of materials with processes (e.g. potential for explosion or combustion).

Additional technical challenges may result from the material having been exposed to heat (i.e. from irradiated fuel), which may result in increased depth of penetration and possibly long term leaching of contamination.

In addition, appropriate methodologies and monitoring techniques (procedures and instrumentation) for the radiological characterization of materials to the clearance levels discussed in Section 5.2.3 are essential for the implementation of recycle and reuse options. Considerations of particular relevance to this subject are:

- Type and composition of the material to be characterized, its physical properties and geometry and the quantities to be measured;
- Degree of surface surveying required;
- Natural and ambient background level (limit of detection) and the natural radionuclide content of the material;
- Radioactivity distribution on and/or within the material;
- Types of radionuclide to be measured and the presence and significance of difficult to measure radionuclides;
- Required confidence level;
- Costs and performance levels of available detection devices.

5.2.2. Economic considerations

The choice of segregation, release, recycle and reuse options in waste minimization during D&D is usually justified on the basis of cost–benefit analyses. Some aspects to be considered in the preparation of such analyses include:

- The cost of retrieval and processing of materials, including removal, characterization, decontamination, melting, transport, licensing, etc.;
- Contingency funding required to offset financial risk due to unforeseen events (legislative aspects, technical constraints, public relations requirements);
- Marketability of the material, as determined by the availability of new resources, and the alternative cost of new (basic) material (for various reasons these costs may be lower or higher);
- An evaluation of the waste management option, as low costs of radioactive waste handling, storage and disposal mitigate against recycle and reuse activities;
- Credits/benefits based on national policies promoting recycle and reuse practices, i.e. tax incentives.

In this context, important financial drivers of waste minimization may be promoted by the authorities and the radioactive waste management agencies in order to encourage options for the recycle or reuse of materials, rather than for their restriction. Financial incentives could be provided in relation to the decreasing amounts of radioactive waste produced by nuclear installation operators. As such, the generally accepted principle that ‘the polluter pays’ should be applied. General reflections on overall cost savings when considering ‘global optimization’ principles are given in Section 5.4.

5.2.3. Radiological factors applied to release practices

International surveys indicate that the criteria actually applied to release practices vary widely among Member States [43, 44]. Sometimes, these criteria are based on nationally applicable regulations, whereas in other practices they are based on a case by case evaluation. Historical examples of clearance criteria from specific projects in various countries are indicated in Tables IV and V [45]. The limits adopted for alpha emitters are generally one tenth of the limits indicated.

In some cases (United States of America and Sweden), limits are three to ten times higher for smaller contaminated areas (spot contamination or ‘hot spots’). Additionally, some countries (Finland, Belgium) specify separate limits for alpha and beta–gamma emitters, while others (USA, United Kingdom) maintain nuclide specific limits. Some of the regulations specifically indicate that decontamination prior to clearance is considered acceptable (Belgium, Germany and the USA).

Nuclide specific limits have been applied in some countries (France, Germany, Sweden, UK and the USA). In Germany, a specific formula has also been applied in some projects/plants to set limit values for those nuclides that can be handled without regulatory control. In addition, further restrictions have been applied in terms of total activity, total mass and total volume in some of the projects/plants in Belgium, Germany and Sweden.

Conditional release levels have been applied on a case by case basis, depending on the end use of the materials [46–49], and in certain cases specific formulas have been applied for restricted release, or specific values applied for the products of metal melting in designated melters (Germany, Sweden).

Aspects of toxicity on specific releases to controlled disposal grounds are, in most cases, limited by national environmental protection acts (e.g. in Belgium, Germany, Sweden and the UK), although additional limitations have sometimes been imposed on the basis of the type of material (Canada), the destination of disposal (France), or the conditions specified by inspectors (UK).

The variability in criteria applied in projects/plants in various countries has also shown that release criteria are significant factors in determining whether recycle and reuse practices can be applied on a large scale. The difference of up to two orders of magnitude in release limits applied in practices in different countries is unacceptable for an open trade market. For understandable reasons, this situation is an obstacle to public acceptance of the recycle/reuse principles. This inconsistency of values is due

TABLE IV. EXAMPLES OF SURFACE CONTAMINATION LIMITS FOR BETA–GAMMA EMITTERS APPLIED IN SPECIFIC PROJECTS FOR UNRESTRICTED REUSE OR UNRESTRICTED DISPOSAL

Surface contamination limit (Bq/cm^2)	Country	Additional information
0.37	Germany	Averaged over 100 cm^2 for fixed and removable contamination and for each single item Applied to scrap metal originating from nuclear installations
0.50		Applied to scrap metal and concrete originating from nuclear installations
0.37	Slovakia	Case by case decision on materials from decommissioning, 100% direct surface measurements
0.40	Finland	Removable surface contamination over 0.1 m^2 for accessible surfaces Applied to radioactive substances originating from application in nuclear energy production
0.40	Belgium	Mean value for removable surface contamination over 300 cm^2, for beta–gamma emitters and alpha emitters with low radiotoxicity
0.83	USA	Surface contamination above background over no more than 1 m^2, with a maximum of 2.5 Bq/cm^2 above background if the contaminated area does not exceed 100 m^2
1.00	Italy	Case by case decision for a limited amount of material from decommissioning
1.00	Canada	Averaged over 100 cm^2 for total contamination, 100% survey of all surfaces
3.70	France	Materials from decommissioning, 100% direct surface measurements
4.00	Sweden	Mean value for removable surface contamination over 100 m^2, with a maximum of 40 Bq/cm^2 if the contaminated area does not exceed 10 cm^2 Applied to radioactive substances originating from application in nuclear energy production
4.00	India	Averaged over 100 cm^2 for fixed uranium contamination Applied to scrap metal originating from refining facilities The material is considered for free release if the concentration of uranium in the slag is less than 4 ppm [45]

TABLE V. EXAMPLES OF SPECIFIC ACTIVITY LIMITS APPLIED IN SPECIFIC PROJECTS FOR UNRESTRICTED REUSE OR UNRESTRICTED DISPOSAL

Specific activity limit (Bq/g)	Country	Additional information
0.10	Germany	Specific activity limit regardless of type of emission Applied to scrap metal originating from nuclear installations
1.00		Specific activity limit regardless of type of emission Reuse of metal in a general melting facility
0.10–2.00		Specific activity limit for beta–gamma emitters
0.10	Slovakia	Specific activity limit for beta–gamma emitters
0.10	Sweden	Specific activity limit regardless of type of emission Over and above the natural activity that occurs in similar materials outside the nuclear installation (primarily used for limiting the activity in materials that, having been melted down, can be reused in new products) Applied to radioactive substances originating from application in nuclear energy production
5.00		Specific activity limit for beta–gamma emitters (artificial activity)
0.40	UK	Specific activity limit regardless of type of emission Total activity for solids, other than closed sources, that are substantially insoluble in water
1.00	Belgium	Specific activity limit for beta–gamma emitters
1.00	Italy	Specific activity limit for beta–gamma emitters
n.a.	USA	No specific activity criterion has been developed or approved

to the absence of an international agreement on rules concerning clearance values. In several publications it has been stated that it is vitally important to arrive at internationally accepted criteria for the release and recycle of material from nuclear installations [50, 51]. Clearance criteria must be based on reasonable assumptions with respect to dose and other hazards and associated risks, and considered in the context of global optimization, thereby helping to conserve the world's non-renewable resources. If clearance criteria were excessively restrictive, large quantities of material would require disposal as 'radioactive waste', resulting in potentially greatly enhanced costs and changed environmental impacts [50, 52].

In addition, many derived clearance levels are close to, or below, current limits of detection for practicable field instrumentation. Consequently, instrumentation and/or operational procedures which are expensive in both time and cost are required. Where this is not feasible, materials must be deemed to be above the clearance level and treated accordingly, again with significant cost and changed environmental impacts.

Both the IAEA and the EC have been working for several years on proposals/directives dealing with this matter [6, 53, 54].

5.2.4. National policy, regulatory climate, public acceptance and legal liability

5.2.4.1. National policy

The availability of national policies and long term strategies developed in support of recycle and reuse principles may have a profound impact on the efficiency and extent of recycle and reuse practices [49, 55, 56]. These practices must be supported by a coherent dialogue among legislators, competent authorities and the public in order to gain acceptance for release practices and to promote options for the recycle or reuse of materials, rather than for their restriction. In the absence of a national policy promoting recycle and reuse, practitioners should optimize opportunities for input in policy development, i.e. by using results from real demonstration projects.

5.2.4.2. Public acceptance

Gaining public acceptance of an option for the disposal of materials arising from the D&D of nuclear facilities will play a role in the successful implementation of that option.

Recycle/reuse outside the nuclear industry and disposal/replacement each present different public acceptance issues [50]. Gaining public acceptance of the practice of recycling materials containing traces of radionuclides may be problematic because of the stigma associated with the nuclear industry in most industrialized countries.

However, products containing low levels of added or naturally occurring radioactivity are widely used, and substantial quantities of radioactive scrap metal have been successfully recycled in a number of countries. Public perceptions of risk related to products containing radioactive materials (e.g. smoke detectors) are influenced by product familiarity, benefit and the extent to which the radioactive aspects of the product are publicized. Notwithstanding the large quantities of naturally occurring radionuclides released in the course of mining/refining metals, petroleum, phosphate and coal, the public generally does not attach a nuclear stigma to these industries.

Radioactive waste disposal repositories are subject to similar public scrutiny and heightened sensitivity. Replacement/disposal options will present requirements for increased disposal capacity in excess of the capacity of currently operating facilities. Moreover, the siting and licensing of radioactive waste facilities have been the subject of intense political debate.

Ultimately, public perceptions regarding the acceptability of both radioactive material management alternatives will influence significantly the implementation of either alternative. Consequently, provision of additional information on the relative risks of both management alternatives could be a determining factor in the formation of public opinion and in the decision making process. Other factors include inequitable social or geographical shifts in the impacts resulting from the disposition of radioactive materials. The distribution of impacts among world regions differs between recycle/reuse and disposal/replacement. Radioactive materials would probably be recycled or disposed of in appropriate facilities located in their country of origin. Radioactive material inventory is greatest in relatively industrialized countries; therefore the impacts of recycling and of disposal would most likely occur in these regions. In contrast, the increased mining and processing of raw materials required for material replacement is equally likely to take place in less developed countries.

Establishment of a successful recycle and reuse policy is highly dependent on making information available to the public, communicating with the public and involving the public.

5.2.4.3. Legal liability

When analysing disposal options for radioactive materials, entities engaging in recycle and reuse practices should take into consideration that they assume full legal responsibility for all arisings from those activities.

5.2.5. Disposal options: Availability and limitations

The availability of, or access to, fully developed treatment and disposal routes for large volumes of radioactive waste on a national or international basis will not normally provide good incentives for recycle and reuse options, particularly in those cases where the cost is incurred irrespective of whether the capacity is used or not.

In addition, if acceptance criteria considered the exclusion of material having the potential for recycle/reuse, then recycle and reuse practices would be promoted. If disposal is not available, there will be more incentive to develop recycle and reuse and options.

5.2.6. Hazards and risks

The disposal of nuclear fuel cycle materials inevitably entails some level of risk to workers, the public and the environment, including radiological and non-radiological risks. As indicated in Section 5.2.3, the radiological consequences for workers, the public and the environment of technically feasible methods for recycle and reuse should be comparable to existing radioactive waste management options.

However, although the radiological health risks from either recycling or disposal and replacement are relatively low, this is often not the case for non-radiological risks. Both alternatives carry substantial health risks from workplace and transportation accidents, as well as exposure of workers and the public to chemicals that are carcinogenic or toxic. Of these two types of risk, the accident fatality and injury risks to the public and workers are higher and much more immediate. Health risks to individuals from chemical exposures and accidents are summarized in Ref. [50].

Many aspects of replacement processes are conducted within environments that are less stringently regulated than the environment in which recycle/reuse alternatives would operate. Replacement necessarily involves coal mining, iron ore mining and coke production, occupations that have relatively high accident rates. Consequently, the risks to workers from replacement/disposal alternatives exceed those from recycling alternatives.

Moreover, because of the multiple stages involved in replacement/disposal practices, transportation requirements usually exceed those associated with recycle/reuse practices. Replacement must consider not only shipment of wastes, but also transportation of the coal and ores necessary for steel production. Accordingly, the risk attributable to potential transportation accidents is often an order of magnitude higher for replacement/disposal.

Similarly, the potential for adverse environmental impacts is also much higher for replacement/disposal alternatives. Although recycle and reuse alternatives will impact the environment by utilizing relatively small amounts of low level waste disposal capacity, replacement/disposal presents adverse impacts of greater severity to the environment from land use, disruption and the damage that results from mining and related processes. A general summary of the environmental impacts of both radioactive scrap metal management alternatives is presented in Ref. [50].

Other environmental impacts attributable to replacement/disposal practices include increased leaching of heavy metals from soils and mining wastes into surface water and groundwater, increased sedimentation in streams and rivers, emissions of toxic chemicals from mining operations, waste piles and coke production, and increased energy requirements. Energy requirements for radioactive scrap metal replacement, for example, may be twice those of recycling.

Finally, recycling radioactive material would help conserve valuable natural resources. For example, one analysis concluded that the use of recycled radioactive scrap metal would reduce related raw material consumption by 90%(mainly coal) and mining wastes by 97% [57].

5.3. METHODOLOGY FOR DECISION MAKING BASED ON FACTORS INFLUENCING RECYCLE AND REUSE

As indicated in the previous sections, substantial quantities of materials (predominantly metal and concrete substances) are likely to be generated in the near future from the D&D of nuclear facilities. A significant portion of this material will either be uncontaminated or only slightly contaminated with radionuclides. On the basis of the large amounts of material involved and the practical experience gained in current operational and decommissioning programmes [46, 58], the implementation of recycle and reuse options can be justified. Smaller volumes may not benefit from the economy of scale.

In the previous sections, it was indicated that recycle and reuse practices may be influenced by multiple factors. Some major influences have been listed and discussed. When considering these influential factors in the context of recycle and reuse, it should be clear that some level of optimization is required, and that, on a case by case basis, the ranking and relevance of the factors listed above will differ.

When evaluating the various influential factors for a specific recycle and reuse option, a linear decision tree approach could be adopted, as indicated in Fig. 3, in which the various factors are evaluated. The limitations of a linear approach are that influential factors may only be considered one at a time, and in descending order of priority. In addition, factors which are mutually influential cannot be considered in combination.

An alternative to a linear decision tree is a decision matrix approach which allows the simultaneous evaluation of many factors. Using this method, the options for the disposition of a material may be matrixed against the applicable influential factors for that programme. Moreover, a weighting value may be accorded to each factor and this can be used as a multiplier for the scores of individual factors in order to reflect the priorities of the specific programme. Adopting various values for these weighting factors allows some sensitivity analyses to be carried out, in order to resolve the most critical influences. The final result of this example analysis would be a relative, numerical ranking of the options (the score for each option) (Table VI).

TABLE VI. EXAMPLE OF A GENERIC DECISION MATRIX WITH DISPOSITION OPTIONS

Option	Cost		Technical feasibility		Risk		Availability of disposal		Full cycle impact		Final score (%)
	Weight (%)	Score	Weight (%)	Score	Weight (%)	Score	Weight (%)	Score	Weight (%)	Score	
Disposal/production of new materials	V_1	C_1	W_1	F_1	X_1	R_1	Y_1	D_1	Z_1	I_1	Σ_1
Radioactive waste storage	V_2	C_2	W_2	F_2	X_2	R_2	Y_2	D_2	Z_2	I_2	Σ_2
Characterization, clearance to recycling, balance to contaminated metal melt	V_3	C_3	W_3	F_3	X_3	R_3	Y_3	D_3	Z_3	I_3	Σ_3
Characterization, decontamination, clearance, balance to contaminated metal melt	V_4	C_4	W_4	F_4	X_4	R_4	Y_4	D_4	Z_4	I_4	Σ_4

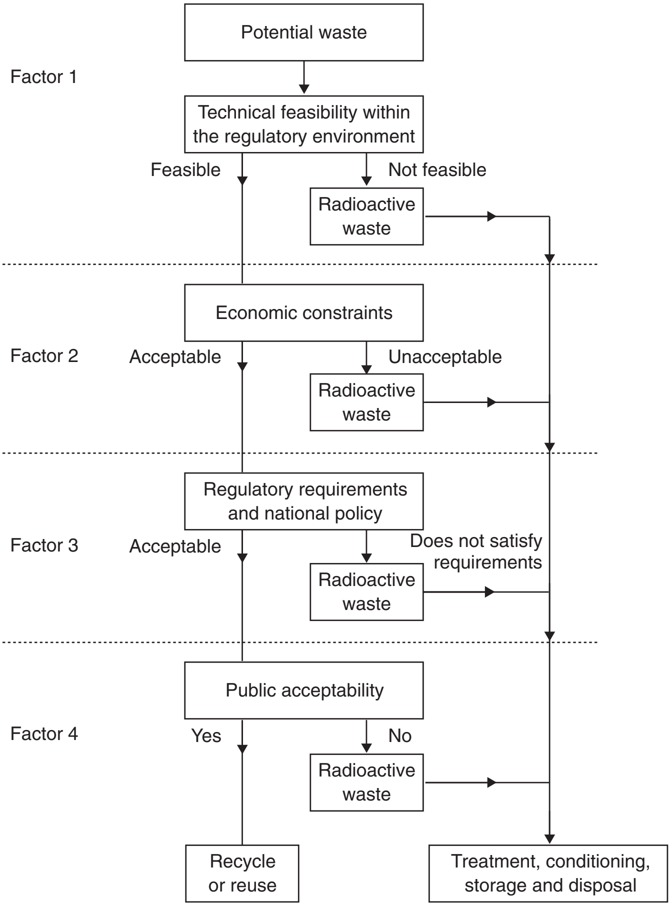


FIG. 3. Linear decision tree approach for recycle and reuse applications.

5.4. IMPLICATIONS OF INFLUENTIAL FACTORS ON WASTE MINIMIZATION IN DECOMMISSIONING: GLOBAL OPTIMIZATION

As indicated in Section 1.1, it can be considered that the ultimate goal of D&D, i.e. the end product of D&D operations, is the unconditional release or reuse of sites, facilities, installations, or materials for other purposes. Waste minimization in this report has been considered as a strategy for avoiding, as much as possible, the production of undesirable by-products of decommissioning, i.e. radioactive wastes.

In this section, factors have been discussed which are relevant to the consideration of waste minimization options in decommissioning. It should be clear that initiatives to support waste minimization in D&D should include those that eliminate or minimize the effects of the entire range of individual, influential factors. Several aspects of relevance to this subject are discussed in Section 6 of this report.

Recycle and reuse are the main factors influenting waste minimization during D&D activities. In general, a recycle and reuse strategy should present a net benefit when considering the health and safety of workers, the public and the environment. As such, a full life-cycle analysis of recycle and reuse should not only include radiological impact, but also the risk and environmental impact associated with material generation and energy consumption.

Reducing the quantities of wastes that must be disposed of or stored will reduce the potential risks to people and to the environment and thus reduce potential future expenses and liabilities. Such savings constitute a substantial benefit.

In addition, the overall objective of recycle and reuse practices, as part of the waste minimization concept, should be to reduce the environmental impact of the wastes, as well as the total costs involved. In practice, it is usually a trade-off between the benefits accruing from the programme and the costs of achieving these benefits. Therefore, when considering global optimization, it is important to consider the costs of the individual contributions in obtaining a net benefit status for recycle and reuse.

As a result, global optimization should be considered as a means of improving the effectiveness of choice between various material management and waste management alternatives, and in addition to radiation protection. This should address a broad range of issues, including non-radiological detriments such as: health risks from chemical exposures, industrial accidents and transport activities; non-radiological environmental impacts on land, air, water and other resources; and social and economic impacts (e.g. public acceptance, market factors and equity issues).

Furthermore, the concept of global optimization contains specifically interesting and challenging aspects, as the risks at the front end (e.g. mining of ores) are usually greater in magnitude and are incurred in countries different from those in which the benefits are enjoyed and the recycling risks incurred.

6. FUTURE DEVELOPMENTS FOR WASTE MINIMIZATION IN D&D

6.1. INTRODUCTION

Most of the older nuclear facilities which have reached, or are now nearing, the end of their operational lifetime were designed and constructed without due consideration of future decommissioning or waste minimization. Application of available dismantling techniques, proper characterization of facilities and equipment to be decontaminated, full-scale application of recycling practices and implementation of adequate waste minimization approaches are not always easy to achieve at such facilities.

As a result of the ‘negative’ experiences acquired during decommissioning operations at certain installations, several ‘problem’ areas have been identified and recommendations formulated that should be considered when designing new facilities or when developing future D&D practices, in particular with regard to minimization of radioactive waste production.

This section summarizes actions to enhance waste minimization during D&D activities. A summary of the approach used for implementing a waste minimization strategy for the D&D of nuclear facilities is given in Appendix IV.

6.2. CONSIDERATIONS FOR WASTE MINIMIZATION IN D&D AT THE DESIGN PHASE OF NUCLEAR INSTALLATIONS

In order to facilitate decommissioning and minimize production of contaminated materials during D&D, it is important that new designs in the nuclear industry consider possibilities for [10]:

- Limiting costs of maintenance and surveillance during waiting periods prior to dismantling;
- Minimizing additional facilities required to ensure safety and protection during operations;
- Reducing radiation exposure of (decommissioning) workers;
- Facilitating final dismantling, disassembly and cutting and the resulting operations of manipulation and handling;
- Reducing costs of dismantling work and costs of any additional equipment needed;
- Optimizing waste minimization, reducing the amounts of radioactive material and effluents produced, and making these compatible with the requirements for storage and transportation;
- Allowing complete dismantling of installations and restoration of sites to the public domain.

Meeting these objectives requires that structures and equipment be designed in such a way that:

- Activation of materials is limited as much as possible;
- Contamination of plant and equipment can be avoided as much as possible;

- Contaminated or active areas can be easily separated from non-contaminated areas;
- Adequate space and access points are provided to allow the use of special tools and equipment for remote operation and handling, and also to allow the installation of appropriate shielding;
- Plant and equipment items can be easily dismantled, handled and transported, and that openings are provided to allow for easy removal of components and materials from the active area;
- Equipment and buildings can be easily decontaminated;
- Sampling and measurements taken for characterization during decommissioning are facilitated.

Moreover, it is important that design studies incorporate an outline of the dismantling scenario. Such a scenario will probably have to be duly reviewed as technology develops and experience is gained, but it should allow the proposal of upper limits on equipment size and weight in order to facilitate the handling of dismantled parts, as well as making provision for the necessary access points, handling routes and lifting equipment. Most of these arrangements proposed for decommissioning should also facilitate operation of the nuclear installation, contribute to its safety and facilitate its maintenance. As such, any additional capital expenditure that may be required should be balanced by savings on maintenance, and by a reduction in the cost of dismantling.

In addition, from the design stage on, the establishment should be organized and drawings should be issued and archived in such a way that all documentation is fully up-to-date when decommissioning is decided upon [59].

Furthermore, experience gained to date in decommissioning allows the outlining of methods of construction and operation that should facilitate the decommissioning of future installations, with reference to three kinds of decommissioning activity: materials management; contamination and decontamination; and dismantling operations such as the cutting, handling and transfer of materials.

6.3. METHODS TO MINIMIZE CONTAMINATION PROBLEMS

A well-designed facility would take account of features which would minimize contamination problems arising during both operation and decommissioning [18]. However, these features should not jeopardize the primary objective of the facility, namely, its safe and efficient operation. In general, designs and techniques aimed at improving operation and maintenance will be beneficial during decommissioning. A variety of design features and techniques are available to reduce or prevent contamination of components and minimize associated problems. A few of these are briefly described below.

6.3.1. Building and equipment layout

Nowadays, it is accepted practice to take decommissioning needs into account during plant design. A considerable amount of information on this topic is available and it is not the purpose of this section to reproduce it [5]. However, some useful feedback may be given from practical decommissioning work by way of examples of particular difficulties experienced.

Normal design practice for nuclear facilities separates active and inactive areas, which should make decommissioning easier. Also, building ventilation systems are designed to move air from inactive to active areas, which should reduce both the amount and severity of contamination of inactive areas [18].

In cell ventilation, ducts should be made of corrosion resistant materials appropriate to the conditions envisaged, for example, stainless steel in chemical reprocessing cells, with the supply being installed in the lower part of the cells and the exhaust in the upper part. In order to prevent contamination of ventilation ducts, it is advisable to install at least a pre-filter, or possibly the complete filter banks, in a gallery adjacent to the cells. This eliminates the risk of high levels of internal contamination occurring in downstream ventilation ducts. In addition, the design of ventilation ducts should make provision for cleaning the ducts. Installation should also allow sufficient access to the duct accessories and to the walls, ceiling and floor of the area around the ducts.

Reducing the pipe layout of primary and auxiliary systems and minimizing the number of valves not only facilitates plant operation but also decommissioning. Pipe penetrations through walls, floors or ceilings should be made as straightforward as possible. Shielding to limit radiation shine paths should reflect the needs of decommissioning and should use lead, cast iron or heavy concrete blocks. Experience has shown that some arrangements, in which the pipes are embedded in concrete, make dismantling and contamination monitoring extremely difficult, particularly for small diameter or curved pipe penetrations. Penetration areas should be provided with simple metallic constructions that can be filled up with lead or stainless steel blocks or aggregates. Ventilation ducts should not cross from one floor to another, either in a concrete floor or in a ceiling. As such, all penetration systems should remain accessible.

Equipment and piping containing radioactive liquids, and especially equipment and piping employing components that might leak, should be located in rooms having drains to active collection tanks. Drip trays with connections to drains should be located under items which might leak but need not be located in special rooms. Such collection systems should be designed to avoid stagnation or spillage of radioactive liquids.

Pools and storage ponds should be equipped with stainless steel liners and stainless steel should be used for inserts, storage racks and baskets. Floors should facilitate the elimination of dust and fines and should have sufficient inclination towards a sump, from where the water can be routed to a water purification system. Mechanical filters should be placed as close to the suction point as possible. A water skimming/cleaning system is highly advisable.

Internal structures in tanks and equipment should be avoided, as these increase areas of potential and persistant contamination. Whenever possible, heating and cooling circuits, thermocouples, and other measurement and control items should be installed on the outside of the equipment. If this is not practicable, they should be arranged so that they have no connection to the bottom of the tank or to the equipment, or positioned in such a way that ‘dead’ zones or deposits do not occur. If necessary, facilities should be provided which allow the material contents to be agitated in order to keep any solids suspended.

Where solids deposition may occur, built-in jet nozzles or connections through which mobile jet lances can be introduced into tanks should be provided to enable solids removal and the removal of residues from tank wall surfaces by, for example, high pressure water jetting. Equipment and tanks should be designed to allow complete emptying.

Care should also be taken that electrical cables are installed in sealed, corrosion resistant protection ducts that can be easily decontaminated.

Provision for undertaking both the remote inspection of cells and the remote measurement of radiation fields is also very helpful.

Appropriate tools needed for interventions should be available and active workshops should be provided for equipment repair and adaptation of contaminated tools.

6.3.2. Selection of components

Contamination problems can be reduced considerably by judicious selection of materials and design of components [18].

The amount of contamination resulting from the activation of trace elements in core components and corrosion products in the primary coolant of a reactor can be minimized by reducing the levels of these elements. For example, stable ^{59}Co in steels or Stellite parts in core or other primary system components which are susceptible to erosion or corrosion can be activated to form ^{60}Co, one of the major radionuclides of concern during decommissioning. Where possible and economic, materials with low cobalt content should be specified. In many countries, steels having low cobalt content are being used or proposed for in-core components [60, 61]. This general principle can be applied to operating stations during replacement of components or retrofitting of systems.

Activated or contaminated concrete is also a major possible source of radioactive waste during the decommissioning of many types of facility [62]. This concrete includes the neutron activated biological shield surrounding the reactor vessel, and floors and walls contaminated as a result of spills during operation. Two design approaches have been considered for use in the construction of biological shields in order to minimize neutron activated concrete in the waste.

The first approach consists of fabricating the entire biological shield from precast, steel reinforced, interlocking blocks held together with steel bands and bolts. In this design, only the activated blocks need be removed for controlled disposal. The block approach eliminates the need for blasting or for other methods which generate dust and which may contaminate non-activated concrete, thereby increasing the waste volume.

The second technique consists of fabricating the inner part of the biological shield from a material similar to plaster (possibly applied in layers), which could be easily demolished and which would permit simplified removal of only the radioactive portions. The practicality and cost effectiveness of these approaches still need to be proven, especially for power reactors.

Other proposals have considered that the presence of certain trace elements (Cs, Co, rare earths) in the concrete’s constituents, as well as in the reinforcing bars, should be avoided as far as possible [63, 64]. In addition, the neutron absorption capability of the innermost layers of the biological shield could be increased by adding an easily dismantled absorbent shield between the reactor vessel and the biological shield.

Surface contamination on floors and walls can be minimized by using steel plates or gratings instead of concrete slabs. The steel flooring may be decontaminated to unconditional release levels more easily than concrete, thus reducing the volume of waste.

Furthermore, scarification of concrete floors may cause contamination of clean floor or wall areas, thereby increasing waste volumes. However, if the concrete floors and walls in active areas are prepared with a smooth surface finish and protected with an epoxy or similar coating, decontamination of the concrete will be much easier and active waste volumes from this source reduced.

The design of rooms or cubicles for components containing contaminated fluids should include drip trays and floor curbs having sufficient capacity to contain the maximum envisaged spill or leak resulting from component rupture. The curbs should direct spills to floor drains which have sufficient tankage to collect all waste. Care should be taken not to permit oil spills to mix with water-based drainage.

The spread of contamination during decommissioning can also be reduced by designing components to be more easily dismantled. For example, the use of modular blocks to build shielding walls could, where feasible, reduce the spread of contaminated dust during demolition of these structures.

6.3.3. Reducing leakage and crud traps

Each component in a liquid process system can contribute to an increase in the contamination problem, either by providing traps where crud can build up or by providing a path along which the radioactive liquid can leak out and cause local or widespread contamination [18]. For a given level of quality assurance and safety, contamination problems should be reduced if the number of flanges, joints, elbows and other crud traps can be reduced and if pipes or tubes have a sufficient inclination. Where possible, the use of welded rather than flanged joints should also reduce leakage of contaminated liquids. However, this benefit should be weighed against potentially greater difficulties arising during dismantling. The designers of new facilities should give consideration to these practices, provided that safety and operational requirements are met.

6.3.4. Quality control

Programmes for ensuring good quality control and compliance with standards are very important in the nuclear industry [18]. Normally, quality control actions arise from a number of technical requirements of much higher priority than decommissioning. In some cases, these actions are beneficial from a D&D viewpoint. In the past, many design and operational initiatives in these areas have resulted in reductions in the number of contamination problems, for example:

- Improvements in the quality of cladding and welds for fuel elements have resulted in there being fewer defects and less alpha and fission product contamination in the primary heat transport systems in reactors and fuel bays.
- The use of better seals in joints and valves for liquid filled systems results in reduced leakage and reduced external contamination.
- Tighter specifications for surface conditions of steam generator materials and electropolishing of steam generator channel heads reduce contamination by major radionuclides.

Care must be taken in the design phase to avoid chemical interference that might lead to the formation of undesirable, highly active third phases and cruds and the blocking of liquid transfer systems by uncontrolled precipitation, crystallization or solids formation.

6.3.5. Limiting corrosion

The corrosion rate of the piping and components in process systems, for example, the primary heat transport system in a water reactor, can be reduced considerably by exercising tight control of the chemistry of the system [18]. This would reduce the amount of radioactive crud in the coolant and also the amount which settles out in the oxide layer which forms on components. A powerful purification system using filters and ion exchangers is necessary to maintain control of the levels of crud and dislodged solids in the coolant. Additionally, such a purification capability can enhance the entrapment of activity during plant shutdown.

In reprocessing plants, the selection of new materials should take into account the acidic nature of the process fluid.

6.3.6. Minimizing the spread of contamination

In order to minimize the accidental spread of contamination to clean areas, nuclear facilities are zoned into active and inactive areas, with control points for materials, equipment and personnel between zones [18]. Careful maintenance of these zones is particularly important during decommissioning, when there exists a great potential for the spread of contamination, and zone boundaries may be changed more frequently as decommissioning proceeds. Care taken in checking for external contamination on waste packages and vehicles coming from active zones, especially when the flow of material is high, can help reduce the spread of contamination. The design of installations should also provide for adequate interim waste storage during operations and for waste movements and tracking.

As D&D proceed, it is often very difficult to maintain good ventilation and auxiliary portable ventilation equipment may be required to supplement the regular system. In addition, during the design and construction of the equipment or tools to be used during dismantling, provision should be made for local ventilation near, or connected to, local operations. This should be of value in minimizing the spread of contamination. The use of ventilated tent enclosures around any decommissioning processes which result in large quantities of dust should also significantly reduce contamination spread.

Special attention should be paid to the handling of nuclear fuel. In any case, the loss of integrity should be avoided, but if this occurs, steps should be taken during operation and decommissioning to minimize the consequences.

6.4. METHODS TO FACILITATE DECONTAMINATION

During the design of nuclear facilities, ways to facilitate the cleanup of contamination should be assessed and, if possible, incorporated into the design [18].

One method which is widely used and which is very effective, especially if the potential for liquid-borne contamination exists, is the scaling of concrete floors and walls. Even the highest quality concrete has pores into which water can penetrate, often to depths of 10–20 cm. All concrete floors and walls which are likely to be exposed to water-borne contamination should be protected by a wear resistant barrier such as epoxy paint or steel cladding. In addition, the concrete surface itself can be made less porous by employing a suitable mix and appropriate application techniques during installation.

Process systems which need to be chemically decontaminated at fairly frequent intervals, for example, the primary heat transport system in a reactor, should be designed to enable them to be easily filled and completely drained after decontamination. Ideally, all systems carrying radioactive liquids should be designed with suitable connection points, vents and drains, providing that these do not affect operational safety, in order that the systems can be decontaminated and drained with the minimum expenditure of effort.

Where practicable, all components and equipment should be fabricated with smooth surfaces and with the minimum number of crevices in order to reduce entrapment of contamination. Equipment which could be exposed to airborne or spray-borne activity should be protected to prevent contamination of parts. This procedure is often used in hot cells, where, for example, the manipulator arms are covered with sleeves which are sealed. This permits easy decontamination of equipment when it is removed for repair or disposal.

Tanks, pipes, components and systems which are likely to become highly radioactive should be connected directly to sumps and storage tanks which are part of the liquid radioactive waste treatment system. Of course, direct connection of critical systems (e.g. the reactor’s primary heat transport system) to the radioactive waste treatment system would not be permitted for reactor safety reasons.

Hazardous materials, such as asbestos, flammable materials, should not be included in the design if they have to be removed before the decontamination process can be started; this applies especially in areas likely to have high radiation fields. The presence of such materials could delay decontamination and increase occupational exposure since the operators would have to take more care in removing them and thus spend more time in the radiation fields. Adequate access to equipment which needs to be decontaminated must be provided, along with suitable areas in which to lay down portable decontamination equipment if this is required. Designers should ensure that adequate space is left around the equipment and that access to cubicles and rooms is provided in order that connections can be made to the system being decontaminated and to enable the areas around the equipment to be cleaned up.

In addition, the plant owners and regulators should ensure that the operating team is fully trained in order that the plant will operate efficiently and with full implementation of the ALARA principle. A well trained and motivated operational staff can facilitate future decontamination by minimizing the spread of contamination during operation and maintenance work and by keeping records of spills or where other untoward events have occurred.

6.5. METHODS TO FACILITATE DEMOLITION AND SEGMENTATION

A well-designed facility should also take account of features which would facilitate demolition and segmentation during both operation and decommissioning [18]. As for the methods required to minimize contamination problems, these features should not jeopardize the primary objective of the facility, i.e. its safe and efficient operation. A variety of concepts have been used or proposed for inclusion at the design and construction stages in order to facilitate the demolition, removal or segmentation of components or equipment in a nuclear plant. A few of these concepts are discussed below.

6.5.1. Minimum use of hazardous materials

During the selection of materials at the design stage, the use of hazardous materials such as flammable coatings or asbestos should be excluded if possible [18] as the operators would have to spend more time dismantling these materials as a result of the special precautions that would have to be taken. These materials could also complicate waste management and disposal.

6.5.2. Improved layout

Spacing around components should be such that access is provided for personnel and equipment in order to allow the components to be disconnected or dismantled easily [18]. Doors, hatches and hallways should be sized, taking into account the equipment to be removed, unless the walls around the item are designed to be demolished easily.

6.5.3. Preplacement of dismantling aids

Preplacement of selected dismantling aids could facilitate the dismantling and segmentation of components and reduce occupational exposures [18].

Tracks used to guide remotely operated cutting devices or manipulators or to allow translation of lifting equipment, such as monorails and hoists, can be installed much more quickly during construction than after items have become radioactive. This should reduce demolition time. Also, major pieces of equipment such as pumps and tanks should be equipped with attachment points to facilitate removal. However, by the time these aids are used during decommissioning, the type of cutting equipment may have changed and the aids rendered obsolete.

If it is probable that the demolition of monolithic concrete structures will be undertaken using explosives, holes to hold the explosives could be preformed in the concrete during construction. Holes should be capped and positioned perpendicular to incident radiation in order to prevent streaming. The safeness of applying this approach to a particular facility would have to be assessed on a case by case basis.

6.5.4. Shielding

Several methods have been used or proposed to facilitate the removal of concrete shielding during decommissioning and to segregate active from inactive concrete [18]. However, application of these methods to a particular facility must be studied on a case by case basis.

Provided that other design and safety requirements are met, shielding and dividing walls should be constructed from modular components rather than from poured concrete in order to facilitate easy demolition. If necessary, the modules can be interlocked or given additional structural strength by means of an iron girder frame. Where concrete structures have both shielding and constructional strength functions, the modular concept may be inappropriate.

If modular construction cannot be applied, it may be possible to exploit planes of weakness and thereby assist the dismantlers during the demolition of concrete structures.

As an alternative to modular construction, composite shield construction could, in some cases, reduce demolition times. For example, it might be possible to construct certain shielding walls with an inner and an outer steel wall, the inner space being filled with shielding material. Such walls should be much easier to dismantle than reinforced concrete walls and should be just as suitable, unless the wall is required for significant structural reasons.

In all of the above examples, the wall designs should not result in a loss of shielding capacity nor compromise any other design requirements.

6.5.5. Connectors

During design, connectors, fasteners, hold-down devices and simple, plain shaped supports should be utilized to ensure the avoidance of traps and dead holes because they can be removed easily during dismantling [18]. However, the designs should ensure that the premature release or loosening of these devices does not occur inadvertently during operation.

Anchor points, which are required to facilitate the removal of equipment, should, in some cases, be installed during construction.

6.5.6. Documentation and planning

Dismantling and demolition can be greatly facilitated if good records are available and if a good strategy and detailed plans have been devised [18].

The records should consist of drawings, photographs, models, and operational and maintenance records, including data on the operational wastes, information on radiation surveys, etc. The documentation systems should be designed for long term maintainability and readability. It is the responsibility of the owners, designers, builders and operators to ensure that these data are available for the decommissioner in a readily usable form, even if dismantling is not to begin until a much later date. The designers and owners should establish a suitable database which would be continued by the builders and operators.

The decommissioning operators should ensure that a good strategy and detailed plan are developed in order that decontamination and dismantling are facilitated. For example, this plan should ensure that the appropriate equipment is available, a comprehensive radiological survey has been carried out, crews are well trained and that detailed scheduling programmes have been drawn up.

6.6. DEVELOPMENT AND IMPROVEMENT OF TECHNIQUES FOR D&D

6.6.1. Development and improvement of decontamination techniques

A large number of decontamination techniques are available for use in the decommissioning process (Appendix I). Not all of them are capable of reaching the residual contamination levels needed to meet the established release requirements. As discussed in Section 3, in some cases, decontamination is carried out in stages with a final step aimed at reaching the desired levels.

A number of initiatives have been taken or are being carried out in order to develop and/or demonstrate decontamination technologies for decommissioning in general, and to gain unconditional release of materials in particular. Not all of them have reached the same state of maturity and this should be taken into account when making selections with regard to application.

Improvement of decontamination techniques is envisaged, by development of new, innovative technologies as well as by further development of existing techniques. Novel technologies being studied include the following:

Microbiological degradation: Microbiological degradation is used to decontaminate concrete and steel. The technique uses microbes to penetrate surfaces and to degrade them in such a way that they and their contamination can be more readily removed. The decontamination concept [65, 66] has been proven on a laboratory scale [67]. Its potential advantages include minimization of radioactive waste, less intensive use of labour and the avoidance of capital expenditure on mechanical equipment.

Light ablation: Light ablation uses the absorption of light energy and its conversion to heat to selectively remove surface coatings or contamination. Decontamination by light ablation is being tested in US Department of Energy (USDOE) demonstration projects and up to 6 mm layers of concrete can be removed [68–70]. Work is also under way in Europe using an ultraviolet laser for the decontamination of plastic or metal tanks or chambers [71].

R&D work continues, aimed at improving a number of existing techniques, and the following are of current interest:

Aggressive chemical processes: Aggressive chemical processes operating in aqueous media and utilizing strong acids and bases are generally used as reactants, as well as strong oxidation–reduction pairs such as Ce^{4+}/Ce^{3+}. Not surprisingly, these processes generate large quantities of liquid wastes, although reagent regeneration systems with ion exchange cleanup can limit this volume. A process for the electrochemical decontamination of alpha wastes has also been successfully tested [72].

Foams: A recent development, using recirculating foam, has been tested [73]. The most satisfactory forms use biodegradable surfactants in combination with strong acids and bases. One advantage is that their action can be enhanced by injecting ozone rich oxygen to reoxidize the redox agent. Foams, as well as laser systems, have the potential advantage of separating operators from the contamination and both techniques eliminate the contamination trapped in the oxide layer and the substrate.

Carbon dioxide blasting: Carbon dioxide blasting is a variation of grit blasting, in which CO_2 pellets are used as the cleaning and decontamination medium [68, 74]. One advantage of the process is that most of the secondary waste is CO_2 gas which is easy to treat [75] and successful applications have been made [76].

Sponge blasting: Another variant of the blasting technique is sponge blasting, in which sponges made of water-based urethane are blasted onto a surface, which causes them to expand and contract, thereby creating a scrubbing effect. An ‘aggressive’ grade of sponge, impregnated with abrasives, can be used to erode through material such as paints, protective coatings and rust [20].

Abrasive blasting: The decontamination of metals using abrasive blasting (wet and dry) as a means of achieving unconditional release levels has been successfully demonstrated [52]. A semi-industrial scale trial demonstrated that the wet process, in comparison with the dry system, was less efficient, had higher costs and produced more secondary wastes. On the basis of the results achieved in this demonstration programme, an industrial scale dry abrasive blasting unit was installed in order to decontaminate 1500 Mg of contaminated metal.

In addition to the above work, some substantial programmes, covering a range of techniques, are being targeted on recycling and release. The USDOE has a programme on technologies for decommissioning and recycling under its environmental restoration programme [77], and in the UK a significant R&D programme is under way on the use of melting technology for gaining unconditional release [78]. Whilst this technique is well known to have advantages for monitoring, efforts are also being made to improve the effectiveness of decontamination. Some countries, such as Belgium, Germany, Sweden, the UK and the USA, have successfully recycled metal by melting [50, 78, 79].

A method of separating the radioactive contamination from bulk concrete is under development. The separation is achieved by thermal treatment followed by milling and sieving. Pilot scale testing proved successful when employed on the concrete derived from the decommissioning of the VAK plant in Germany [80].

6.6.2. Development and improvement of dismantling techniques

A very large number of methods are already available to meet the requirements of dismantling various kinds of nuclear installation. However, in many cases it is still necessary to improve their performance, broaden their field of application and properly control the impact of their use on the immediate environment. In some cases, automation and remote control would appear to be necessary, either to make the equipment more effective or to allow it to be used inside hazardous areas. More particularly, with a view to improving performance, it is essential to:

- Improve the capacity of tools for cutting thick steels such as those used on vessels, flanges and lids from large reactors;
- Increase the operating speed of systems for breaking up concrete, while restricting the amount of debris produced;
- Adapt tools which perform satisfactorily in conventional industry to underwater work and, above all, to ‘nuclearize’ them.

As an example, some specific processes are not yet considered as being commonly used, and are considered to require additional development:

Cutting steel by cracking: Extraneous metal is deposited by an electrode on the part to be cut; the underlying metal is embrittled and cracked when cooled. This process is limited to use on low thickness metal (15–20 mm) and is difficult to use. Its only value is to prevent the spread of contamination contained inside the vessel being cut up [81, 82].

Lasers: Laser techniques are being developed for cutting steel and concrete [83–85]. The laser sources are too large, either to be brought into the active area or to be remotely handled. One approach is to route the beam from the source using a polyarticulated, remotely controlled arm fitted with mirrors. In order to be useful, this system needs improvement, including provision for higher power at the point of application, cooling of the mirrors, protection of the articulated arm as it moves about, improving the method of system control, and making it usable under water.

Cutting thicknesses using lasers with power ratings of 2–10 kW are limited to 30 mm for stainless steel. It must be stressed that with fixed, very high power lasers, thick steel can be cut as long as the part can be moved in front of the beam (this method has been tested for cutting up PWR pipework by RANDEC, the Japanese utilities group).

Electrolytic cutting: In this operation, an electrode (cathode) penetrates into the metal to be cut, at the same time as an electrolyte flows around the cut. The part being cut forms the anode and is gradually destroyed; the electrolyte carries away the metal particles produced by the cut for recovery. This process is well proven in conventional industry and can cut considerable thicknesses (up to 30 cm), make highly precise cuts and control secondary wastes which can be easily treated.

The technique is fairly slow and methods for using it remotely in an industrial framework have yet to be developed [86]. Interesting results have been obtained from cutting tests on unirradiated test pieces representing the walls of a PWR vessel (ferritic steel 22NiMoCr37 lined with stainless steel with a combined thickness of 143 mm).

Pyrotechnic cutting: The effectiveness of the explosive cutting of pipes, concrete, etc., needs no further demonstration. The remaining problem is to make this process compatible with the working conditions of nuclear installation decommissioning (it must be possible to position the charges, avoid spreading contamination, avoid shaking nearby installations still functioning, recover debris without undue dispersion, etc.). This process has already proved its worth in cutting pipes with wall thicknesses of up to 3 cm. Charge carriers make it possible for the explosive to be positioned by remote control.

Tests have been carried out on cutting concrete from the biological shield, separating steel liners from cell walls and cutting up pressure vessels. The results of these tests are of considerable interest and suggest that these techniques are fully competitive. In addition, work performed at full scale on the German HDR reactor showed that it was possible to use this process without undue risk and under acceptable conditions [31, 87].

A number of other techniques are also worth mentioning, such as microwaves, which can be used to ‘descale’ concrete, or even to cut it [88], the portable arc saw for cutting steam generator pipes, or the use under water of high pressure jets containing abrasives [24, 89]. Further information on these various types of equipment can be found in the annual reports of the Commission of the European Communities [90].

6.6.3. Development and improvement of measurement techniques

A number of measurement systems exist which are applicable to waste management in general and unconditional release in particular (Appendix III). New developments are in progress, aimed at improving measurements for unconditional release. Not all of them are at the same stage of maturity and this must be taken into account before selecting them for use.

Further work has been carried out on mass activity measurements using an automated large scale radioactivity measurement facility, in order to extend its capability to measure more than 100 Mg of different materials from a WWER reactor [91]. The complex nuclide mixtures and the age of the materials made the measurements difficult and only some of the material could be released. However, it was demonstrated that when the measurement and evaluation procedures were adapted to meet the specific requirements of the project, a modified model of the measurement facility could be successfully used for materials having a high concentration of nuclides that are difficult to measure.

In the past, spectrometric radiation detectors such as NaI(Tl) and Ge(Li), and more recently high purity germanium detectors, have been used extensively to measure ground contamination or to estimate dose rates created by natural radioactivity in soils. During the later stages of decommissioning, the large surfaces of buildings, etc., often remain to be monitored in order to ensure that release levels have been achieved. Currently, this can be done using strategies for analysing samples taken from the surface or by measuring the surface activity using large proportional counts. An alternative approach under development uses a collimated in situ gamma spectrometer [92]. Prototype equipment has been tested at seven facilities in Germany and France. Comparisons were made between the established method and the in situ technique and in most cases the device has been shown to be capable of meeting the required release criteria.

The use of long range alpha detection (LRAD) is being developed. LRAD is sensitive to all forms of ionizing radiation but is particularly suited to the measurement of alpha particles [93]. Instead of detecting radiation directly, the LRAD technique detects the ions created in the surrounding air. Its particular potential advantage over existing techniques is in situations where direct measurements are difficult to achieve. Thus, air can, for example, be passed through contaminated piping and transported to an ion detector. Similarly, an object could be placed in a chamber and the air ionized by passage over it. The LRAD concept is well proven but full commercialization has not yet been achieved.

6.7. DEVELOPMENT AND IMPROVEMENT OF THE REGULATORY APPROACH

As indicated in Section 2.3, substantial quantities of contaminated materials (predominantly steel and concrete) are likely to be generated from decommissioning and dismantling nuclear facilities. Without an adequate waste minimization strategy, which includes having acceptable release standards, these potentially valuable materials cannot be systematically recovered from the radioactive waste management system through decontamination and/or reuse or recycle practices. A significant portion of this material is only slightly, or not at all, contaminated with radioactivity. Disposal of radioactive scrap metals currently relies on disposal at licensed low level waste disposal facilities or, less commonly, on release on the basis of a detailed evaluation.

The availability of national as well as corporate policies and global long term strategies in support of waste minimization principles, in which release of material and recycle and reuse options may play a major part, can have a profound impact on the efficiency and extent of waste minimization practices. These practices must be supported by a coherent dialogue among legislators, competent authorities and the public in order to gain acceptance for waste minimization through release practices and to promote options for the recycle or reuse of materials, rather than for their restriction. In the absence of a national policy promoting recycle and reuse, practitioners should take the initiative in providing input into policy development, i.e. using acceptable principles and the results from real demonstration projects.

As such, a recent comparison of the relative merits of disposal and replacement versus recycle and reuse practices shows that recycle and reuse lower health risks to humans and reduce environmental impacts by more than a factor of two. Moreover, disposal and replacement alternatives for radioactive scrap metal management may involve the imposition of more detrimental health and environmental impacts in ore producing countries than those associated with countries involved in recycling [30].

On the basis of these evaluations, however, it has to be accepted that the degree to which the practice of releasing materials can be said to do “more good than harm” varies, depending on a number of factors, and affects radiological health risks as well as non-radiological health risks and environmental impacts. However, some present indications are that practices which take major environmental impacts and non-radiological health effects into consideration, in addition to radiological health risks, strongly support recycle and reuse options. This approach also has the advantage of matching acceptable decommissioning strategies with proposed waste minimization options while keeping risk to the public at an appropriately low level.

In addition, a strong case can be made that waste minimization and material recycling standards need to be developed within the broad context of health risks due to radioactivity in the environment and the potential hazards posed by the relatively large amounts of unregulated, naturally occurring radioactive materials dealt with in several other industries.

A technological basis for implementing the criteria is also an integral component of the process. Measurement capability for surface activity on components depends on the contamination mechanism (e.g. wet or dry), on surface characteristics (roughness, chemistry and material), on decontamination methods and on the type of wipe test applied. In some instances, the use of state of the art instrumentation may be insufficient to meet the requirements of risk based standards.

On the whole, a global waste minimization strategy supported by adequate recycle and reuse practices requires a set of acceptable international release standards. These standards should be based on realistic scenarios that make use of available data from existing practices. As such, further research is needed to calibrate/validate the models and calculations used to derive risk based release levels. This should be based on data derived from existing practices, in order that excessive and costly conservatism can be avoided. Moreover, in addition to radiological health risks, other types of health and environmental risk should also be considered in the development of release levels.

In addition, careful consideration should be given to public acceptance of the practice of recycling materials derived from D&D. Policies that bring public acceptance of recycle and reuse practices into line with public perceptions of risk related to products containing radioactive materials (e.g. smoke alarms) should be developed and supported. Public perceptions are influenced by product familiarity, benefit and the extent to which the radioactive aspects of the product are publicized.

7. CONCLUSIONS

For nuclear facilities, decommissioning is the final phase in the life-cycle after siting, design, construction, commissioning and operation. It is a process involving operations such as decontamination, dismantling of plant equipment and facilities, demolition of buildings and structures and management of resulting materials. It also takes into account the health and safety requirements of operating personnel and the general public, and any implications for the environment. The ultimate goal, i.e. the end product of D&D operations, can be considered to be the unconditional release or reuse of sites, facilities, installations or materials for other purposes.

Any D&D strategy should include a strategic approach in order to minimize the production of radioactive wastes. The aim of a waste minimization strategy is to maximize the opportunities for release or recycle/reuse of materials, and where residual radioactive wastes are unavoidable, to minimize their volumes for storage and disposal.

The fundamental principles of waste minimization to be followed during D&D have been identified and the essential components are:

- Prevention, i.e. minimization of waste generation;
- Containment, i.e. minimization of the spread of contamination;

- Reutilization, i.e. recycle and reuse of materials and components;
- Consolidation, i.e. reduction of waste volumes.

A large number of factors and constraints are involved in determining an optimized waste minimization strategy during D&D. The key issue is to achieve the right balance between the global economic and environmental impacts of disposal/replacement versus recycle/reuse options. If only local factors and the short time-frame are considered, this may compromise the overall cost effectiveness and safety of a selected option in the longer term, which may extend beyond the local scale.

Appropriate administrative control, management and operational culture are fundamental to the successful implementation of any waste minimization strategy. As such, waste minimization during D&D begins at the design stage of a nuclear facility. There are many cost effective ways of designing features into new plants which facilitate the minimization of waste during decommissioning, and which bring major benefits to the overall economics of nuclear power by reducing the through-life costs of a plant.

Many waste management technologies are available for reducing waste volumes. In particular, decontamination appears to provide more opportunities for waste minimization than does decommissioning, i.e. dismantling and demolition. The acceptability of different techniques, however, varies from country to country, and strategies need to be tailored accordingly.

Segregation and characterization of contaminated materials are the key elements of waste minimization. They both depend on the application of appropriate criteria and on measurement techniques which are practicable on an industrial scale, particularly where materials are to be released for recycle or reuse. An essential prerequisite is a complete understanding of the physical, chemical and radiological characteristics of the materials which remain, in order to segregate these materials and send them either for treatment and disposal, or for recycle and reuse.

A strong safety culture and a generally and rigorously applied regulatory system are elements that should nowadays generate a reasonable level of public acceptance. However, there are currently divergent opinions among countries with regard to release levels, which is unhelpful for recycle and reuse and subsequent waste minimization.

Together with technical and economic considerations, public perception and the application of radiation protection principles are the most important elements for the realization of recycle and reuse opportunities. The principles of radiation protection used to derive and justify the release levels are based upon extrapolation of current limits for dose formation in nuclear operations. At present, these levels are very low and in fact overlap with those in some non-nuclear industries.

Public acceptance requires that initiatives taken have regard for public perception. Therefore, there is a need to address the risks associated with unconditional release of materials in comparison with other perceived and accepted non-nuclear risks, and this should form part of a complete system analysis. By not doing so, the of perception that there are two types of risk, unacceptable nuclear ones and all the others, is reinforced.

If the potential benefits of waste minimization during D&D are to be realized, it is necessary to harmonize regulatory policies and obtain generally agreed requirements for release on a global basis in order that a global optimization of resources in relation to disposal, recycle and reuse can be achieved.

As such, the role of the management of a nuclear operator and of the policy makers is, among others, to communicate with the public and to create an environment of confidence. Radioactive waste management and related activities such as decommissioning are key issues in the process of gaining public acceptance of the nuclear industry in general and the nuclear fuel cycle in particular. This is being experienced in many countries.

Appendix I

DECONTAMINATION TECHNIQUES FOR DECOMMISSIONING

General descriptions and considerations of the selection of decontamination technologies for decommissioning are given in Section 3.3 of this report. Developing techniques are outlined in Section 6.6.2. This appendix gives more information on the general considerations, guidelines, advantages and disadvantages of established decontamination techniques. More details may also be found in special publications [18, 20, 21, 94].

I.1. CHEMICAL DECONTAMINATION

I.1.1. General considerations

Chemical decontamination is usually carried out by circulating the appropriate reagents in the system. However, segmented parts can be decontaminated by immersing them in a tank containing the reagent, which must then be agitated. The application of a specific chemical decontamination procedure depends on many factors, e.g. shape and dimensions of the item to be decontaminated, type and nature of the chemical reagents, type of material and contamination, availability of proper process equipment.

Many chemical reagents and techniques have been developed for the routine decontamination of systems during both operation and decommissioning of nuclear facilities. Chemical decontamination processes are basically divided into two groups: mild chemicals, which include non-corrosive reagents such as detergents, complexing agents or dilute acids or alkalies; and aggressive chemicals, which include concentrated strong acids or alkalies and other corrosive reagents. The dividing line between these two groups usually equates to a concentration of about 1–10% of the active reagent [18].

Mild chemical decontamination techniques have generally been used for items where the main purpose is to remove contamination without attacking the base material. Their advantages are low corrosion rates and low chemical concentrations which ease the problem of treating the spent decontamination solutions as secondary waste. Although some low concentration decontamination techniques have low DFs and require long contact times, these may be made more effective by combining them with processes that use non-corrosive oxidizing or reducing agents, complexing and chelating agents and applying them in several stages. In many cases, their effectiveness can also be improved by increasing the treatment temperature, usually in the range of 20–90°C. The selection of redox and chelating agents will depend on the composition of the surface corrosion products to be removed.

Aggressive chemical and electrochemical decontamination techniques can involve one or more stages using different chemical solutions with intermediate rinses. Process advantages include short time application and high DFs (usually 10–100). Process limitations include high chemical concentrations and the creation of potential problems for effluent treatment systems.

A multistep process, namely, the application of a strongly oxidizing solution followed by a complexing agent in an acid solution, is a technique commonly used for removing the contaminated oxide layer from metal surfaces such as stainless steel. The first (alkaline) stage is intended to oxidize the chromium oxides in order to yield soluble chromate ions. The second (acid) stage is primarily a dissolution reaction for the complexing of dissolved metals.

Alkaline permanganate is the most common reagent used at the first stage. At the second stage, a variety of reagents such as ammonium citrate, or ammonium citrate followed by EDTA, oxalic acid, a mixture of citric and oxalic acids, sulphuric acid, etc., have been used successfully for various applications in the decontamination of stainless steel, carbon steel, Inconel, Zircaloy cladding, etc. Sulphuric, phosphoric, hydrochloric and hydrofluoric acids and other reagents have been successfully used separately as aggressive decontaminants, generally at concentrations of 2–15%. The required decontamination level may necessitate repeating the process a number of times. Care must be taken if the dissolution process could result in unacceptable surface corrosion, e.g. where direct reuse of an item is the required aim. Chemical techniques are generally suitable for use on complex geometries, as well as for the uniform treatment of the inner and outer surfaces of equipment, particularly where good contact between the chemical and the surface is provided, e.g. by tank immersion.

Factors considered for on-line chemical decontamination are also valid for the immersion process. However, because the tanks are usually open at the top, a proper ventilation system must be installed and special care must be taken to avoid contact between the operators and the highly corrosive reagents. It should be noted that chemical reactions at excessively high temperatures may result in undesirable effects, such as the generation of toxic or explosive gases, e.g. hydrogen.

Chemical decontamination requires the efficient recycling of reactive chemicals, as insufficient recycling of decontamination products can result in the generation of large amounts of secondary wastes which are difficult to treat. Chemical decontamination may generate mixed wastes and it can result in corrosion and safety problems when misapplied. In addition, it requires the use of different reagents for different surfaces and also requires drainage control. For large jobs, it generally requires the construction of chemical storage and collection equipment and the addressing of criticality concerns, where applicable. Chemical decontamination is not usually effective on porous surfaces.

In general, a knowledge of chemical cleaning methodology is a prerequisite for assessing decontamination technology, as most of the procedures and chemicals used to decontaminate nuclear material and equipment have been used for cleaning in the chemical processing industry. Both chemical cleaning and decontamination require the application of the same areas of knowledge and experience: chemistry of fouling and corrosion, and technology for waste removal and processing. Furthermore, the same engineering knowledge is required to devise suitable procedures for mixing, pumping and heating solvents and other chemical cleaning constituents. Compliance with basic health and safety practices in the use of chemical reagents is required, in addition to the radiological safety aspects. As a minimum, workers should undergo a training programme and be equipped with spectacles, full body protective coveralls, impermeable gloves and foot covers. Additional safety equipment depends on the toxicity of the contaminants and the decontamination components.

For decommissioning programmes, there exists a wide range of compositions to choose from, since corrosion of the substrate metal is of little concern. Certain chemical compositions exhibit a time dependency in the mixing, heating, recirculation and drainage cycle, which affects both the chemical solution stability and the solubility of the contained contamination. Each process under consideration would have to be evaluated for the effect of a loss of flow accident and associated cooling of the solvent. Factors considered would include toxic or explosive gas generation and excessive corrosion. The selected process must include provision for appropriate emergency procedures, e.g. emergency drainage, gas detection and emergency ventilation.

During the decontamination process, as the concentration of the contaminants in the solution increases, the item being cleaned may become recontaminated. This problem can be minimized by cleaning the least contaminated items first and by cleaning or replacing the solution if the concentration of contaminants exceeds certain levels.

Some multistep processes are commonly used for removing highly adhesive contamination layers. In many cases, chemical decontamination can be used as a single step in complex processes, for example, before electrochemical decontamination, items covered with thick oxide layers are submitted to chemical decontamination in order to reduce the oxide coatings.

An overview of the characteristics and applications of the mild and aggressive chemical decontamination techniques is shown in Table VII.

I.1.2. Spent decontamination solutions

The selection of the chemical reagent directly affects the features of the secondary wastes arising from the process. Continuously renewing the solution

TABLE VII. OVERVIEW OF CHEMICAL/ELECTROCHEMICAL DECONTAMINATION OF METAL

Technique/reagent	Fields of application	Advantages	Limitations	Remarks
Mild chemical decontamination, e.g.: • Detergents • Creams • Foams • Dilute acids/alkalis	Decontamination of large flat pieces on-site Decontamination of doors, pools, liners, reactor containment in situ	Easy to use Inexpensive Low exposure of workers	Only removes loose contamination High secondary waste generation: • If additional wet cleaning is needed • Involves use of pads, brushes, rubber, gloves, etc. Not applicable to porous surfaces	Measures needed to prevent recontamination, e.g. in large area applications
Aggressive chemical decontamination, e.g.: • Concentrated acids/alkalis • Oxidizing/reducing reagents	Removal of thin layers of metal surfaces, e.g. corrosion Decontamination of relatively complex components and shapes	Removal of highly contaminated surface Decontamination to release limits feasible if sufficient materials is removed Commercially available, relatively inexpensive Low secondary waste production if reagent is reused (regeneration and/or removal of contaminants)	Dismantling, segmentation, etc., required Application on-site usually necessitates use of baths to achieve effective effective decontamination Higher exposure of workers	Additional ventilation required Possible increased hazard from toxic or corrosive solutions or gases Multistep/alternate treatments often used

Electrochemical decontamination: • Bath operation • Pad operation	Decontamination of disassembled components Decontamination of localized ‘hot spots’ and regular surfaces	Fast with high DF Low volume of secondary waste production	May not be effective for hidden surfaces having poor electrolyte contact Possible high exposure of workers Not applicable to complex or inaccessible surfaces

increases decontamination effectiveness, but the quantity of spent solution left to treat and to dispose of also increases dramatically. In more recent years, the regeneration of chemicals has become a fundamental step in all chemical decontamination processes. Several conventional chemical processes can be used for regenerating the spent solutions, either on their own or in combination, including ion exchange, evaporation/distillation and electrodialysis.

The problem of limiting the secondary wastes arising from the decontamination process may result in the selection of processes other than chemical decontamination, e.g. electropolishing or ultrasound using chemicals. As stated previously, only a detailed cost–benefit analysis can provide the actual criteria for selecting the best option for decontamination.

I.1.3. Selection of appropriate chemical decontamination techniques

When selecting a suitable chemical decontamination process, in addition to the general considerations given in Section 3.3 and in view of the variety of chemical decontamination processes available, several criteria must be considered in a detailed analysis based on site specific conditions. Most of the criteria are related to the specific features of a nuclear installation, such as:

- Location of the contamination (e.g. inner versus outer surfaces of closed fluid systems);
- Physical integrity status of the systems;
- Materials (e.g. steel, concrete);
- History of operation (to determine contamination strata profile);
- Nature of the contamination (e.g. oxide, crud, particulate, sludge);
- Effectiveness of previously used chemical decontamination processes;
- Distribution of contamination (e.g. surface, cracks, homogeneous distribution in bulk material);
- Exposure with regard to human health and the environment;
- Safety, environmental and social issues;
- Exposure level reduction requirements (e.g. recycling versus disposal);
- Quantity and type of secondary waste from decontamination and conditioning;
- Ultimate placement of decontaminated materials;
- Time;
- Costs.

Taking into account the general considerations presented in these paragraphs on chemical decontamination, an overview of the main advantages and disadvantages of this technique can be given to allow selection of the most appropriate technique.

I.1.4. Advantages

The main advantages of chemical decontamination are as follows:

- It is relatively simple and similar to ‘classical’ cleaning employed in conventional industry for which considerable experience exists. It may also be relatively inexpensive in the case where additional equipment is not required.
- It is a known practice in many nuclear plants and facilities.
- It can, with proper selection of chemicals, remove almost all radionuclides from the decontaminated surface. Problems of recontamination can be reduced by continuously rinsing the surface with water.
- It can, when employing strong mineral acids, achieve a DF of more than 100, and in many cases the item may be decontaminated up to releasable levels.
- It can also remove radioactivity from internal and hidden surfaces. However, in this case its effectiveness may be low and measurement at release levels will be a problem.
- It has relatively fewer problems with airborne contamination; it being amenable to a closed system approach.

I.1.5. Disadvantages

There are several disadvantages with this method:

- The main disadvantage of chemical decontamination is the generation of relatively high volumes of liquid secondary wastes compared with other processes such as electrochemical decontamination. Moreover, in some cases, for example, for internal and hidden surfaces, the effectiveness of the decontamination may be relatively low.
- Usually the solution must be heated up to 70°C or 90°C in order to improve the kinetics of the decontamination process.
- A further disadvantage is that corrosive and toxic reagents may need to be handled in order to obtain high DFs.
- Chemical decontamination is not usually effective on porous surfaces.

I.2. ELECTROCHEMICAL DECONTAMINATION

I.2.1. General considerations

Electrochemical decontamination (electropolishing) can be considered in principle to be a chemical decontamination assisted by an electrical field.

Electropolishing is a process widely used in non-nuclear industrial applications to produce a smooth polished surface on metals and alloys. It can be considered to be the opposite of electroplating, as metal layers are removed from a surface rather than being added as a coating.

Electrochemical decontamination uses direct electric current, which results in the anodic dissolution and removal of metal and oxide layers from the component. The dissolution can be achieved by soaking the items to be decontaminated in an electrolyte bath fitted with anodes. This method is useful for decontaminating items whose surfaces are not easily accessible. Electric current can also be delivered to a component by moving a pad over the surface to be decontaminated, and this is an efficient method to use on regular surfaces.

For in-tank electropolishing, at least two (stainless steel) tanks are required. One tank contains the electrolyte, electrodes and parts to be decontaminated. The other tank holds the water used for rinsing the parts after decontamination. Low voltage power supply amperages up to 2700 A are common depending on the surface being treated. To control vapours released from the electrolyte during the electropolishing process, an extraction hood is located alongside the electropolishing tank. Provision for heating and agitating the electrolyte and rinsing the tank is also made.

Electrochemical decontamination processes can only be applied when removing radionuclide contamination from conducting surfaces, such as iron based alloys (including stainless steel), copper, aluminium, lead and molybdenum. They are highly effective and give a high DF. Important operating parameters for electrochemical decontamination are electrolyte concentration, operating temperature, electrode potential and current density.

The effectiveness of the decontamination can be limited by the presence materials adhering to the surface of the items to be decontaminated. Materials such as oil, grease, oxides (rust) and paint or other coatings should be removed before decontamination. When soaking is used, electrochemical decontamination is limited by the size of the bath; when the pad is used, it is limited by the geometry of the surfaces and the available clearance around the part being treated. This makes the method almost impractical to use for the industrial decontamination of complex geometries.

I.2.2. Chemical reagents

Phosphoric acid is normally used as the electrolyte in electropolishing because it is stable, non-aggressive and applicable to a variety of alloy systems. Moreover, the non-drying nature of phosphoric acid helps minimize airborne contamination and the good complexing characteristics of phosphoric acid with metal ions is a significant factor in minimizing recontamination by the electrolyte.

Other electrolytes, such as nitric acid and sodium sulphate, have been investigated and proposed as alternatives to phosphoric and sulphuric acids. The need for new electrolytes was initially motivated by the incompatibility of phosphoric and sulphuric acids with the existing treatment facilities and by the possibility of producing secondary liquid wastes which are easier to process or to regenerate.

I.2.3. Secondary waste generation

Electrochemical decontamination by electropolishing causes a steady increase in the level of iron dissolved in the phosphoric acid. If the iron content exceeds 100 g/dm^3, a precipitation of iron phosphate occurs and this reduces the efficiency of the decontamination process. Therefore, the acid has to be exchanged or regenerated periodically. In doing so, the volume of effluents is minimized. However, handling the parts to be soaked or the pad can lead to additional worker exposure.

I.2.4. Guidelines for selecting appropriate electrochemical decontamination techniques

When selecting a suitable electrochemical decontamination process, criteria must be considered in a detailed analysis based on site specific conditions. These are similar to the criteria mentioned in Sections 3.3 and I.1.3, but take into account the fact that electrochemical decontamination processes require conducting surfaces.

I.2.5. Advantages

Electrochemical decontamination processes offer several advantages:

- Electropolishing is commercially available. Major equipment is relatively inexpensive and the process and procedures are fairly simple. It is capable of decontaminating to background levels for decommissioning purposes, removing practically all radionuclides and giving, typically, DFs of more than 100.
- Electropolishing can decontaminate planar areas, corners, recessed geometries, tanks, etc., where measurement up to release levels does not cause any problem. It produces a smooth polished surface that is more difficult to recontaminate. The thickness of metal removed during decontamination is generally less than 25 µm.
- When compared with the volume of liquids required for chemical decontamination, electrolyte volumes for electrochemical decontamination are relatively low.

I.2.6. Disadvantages

Electrochemical decontamination processes also have several drawbacks:

- Electrochemical decontamination by the most widely used process (i.e. in-tank) necessitates removal of the item to be decontaminated from the plant and immersion in the tank of electrolyte. For the in situ process, access of the device into the item to be decontaminated is required. Thus, the use of electrochemical decontamination is limited by the size of the bath when soaking is used, and by the geometry of the surfaces and the available clearances around the part being treated when the pad is used. This makes the method less amenable to the industrial decontamination of complex geometries (i.e. pipes).
- Electropolishing does not remove (or removes with difficulty) fuel fines, sludge or any insulating material from the surfaces.
- Hidden parts, such as the insides of tubes, are poorly treated.
- Handling components can lead to additional exposure of workers.

I.3. MECHANICAL DECONTAMINATION OF EQUIPMENT AND COMPONENTS

I.3.1. General considerations

Mechanical decontamination methods can be classified as either surface cleaning (e.g. sweeping, wiping, scrubbing) or surface removal (e.g. grit blasting, scarifying, drilling and spalling). Mechanical decontamination can be used as an alternative, employed simultaneously or sequentially with chemical decontamination.

In general, mechanical decontamination methods can be used on any surface, with very good results being achieved. When these methods are used in conjunction with chemical methods, an even better result is realized. Moreover, when dealing with porous surfaces, mechanical methods may be the only option.

As with chemical decontamination, the selection of the most effective technique depends on many variables, such as the contaminants involved, surface material and cost. For example, the selected treatment may have to be applied several times in order to meet the established cleanup criteria. As each of these techniques can be modified to suit site specific conditions, the actual effectiveness and feasibility of implementing each technique under those conditions should be explored in feasibility studies before being implemented.

Surface cleaning techniques are used when contamination is limited to near surface material. Some techniques may remove thin layers of the surface during removal of the contamination. Certain surface cleaning techniques generate contaminated liquids that need to be collected and treated. Many surface cleaning techniques can be used for decontaminating both equipment and buildings and some surface cleaning techniques can be used as a secondary treatment following surface removal.

As these techniques are so versatile, it may be advantageous to locate a centralized decontamination facility on-site in which one or more of these techniques may be used. Such a facility could then be used to decontaminate dismantled or segmented components.

There are two general disadvantages to mechanical methods. First, the methods require that the surface of the workpiece be accessible (i.e. the workpiece should generally be free of crevices and corners that the process equipment cannot easily or effectively access).

Second, if the necessary precautions are not taken, many methods may produce airborne dusts. If contamination is a concern, this requires that containment be provided to maintain worker safety and to prevent the spread of contamination.

I.3.2. Abrasive blasting decontamination systems

I.3.2.1. General considerations

A wet abrasive blasting system is a closed loop, liquid abrasive decontamination technique. The system uses a combination of water, abrasive media and compressed air and is normally applied in a self-contained, leakproof, stainless steel enclosure. There is no danger of airborne contamination as a self-contained air ventilation system with an absolute filter maintains negative pressure inside the cabinet. Radioactive waste is mechanically separated from the cleaning media, e.g. by cyclone/centrifuge separation, sieving. Water can be filtered and recycled; no soluble or hazardous chemicals being required.

Wet abrasive cleaning is being used in many nuclear facilities to remove smearable and fixed contamination from metal surfaces such as structural steel, scaffolding, components, hand tools and machine parts. The equipment can be used on close tolerance parts such as turbine blades or valves where the removal of metal is not desired, or it can be adjusted to remove high levels of corrosion and paint by varying the air pressure and the amount of abrasive media.

The dry abrasive blasting technique, commonly termed sand blasting and abrasive jetting, has been used in non-nuclear industries since the late 1800s. This technique, which uses abrasive materials suspended in a medium that is propelled onto the surface being treated, results in the uniform removal of surface contamination. Compressed air or blasting turbines are normally used to carry the abrasive. Removed surface material and abrasive are collected and placed in appropriate containers for treatment and/or disposal. Recirculation of abrasives allows the generation of secondary wastes to be minimized.

Dry abrasive blasting is applicable to most surface materials except those that might be shattered by the abrasive, such as glass or Plexiglas. Its use on aluminium or magnesium should also be avoided owing to the risk of dust explosions. It is most effective on flat surfaces, and because the abrasive is sprayed, it can also be used on ‘hard to reach’ areas. Nonetheless, materials such as oil and grease, or obstructions close to or bolted to components, must be removed before application, and precautions should be taken to stabilize, neutralize, or remove combustible contaminants because certain abrasives can cause some materials to detonate or can cause dust explosions.

Static electricity may be generated during the blasting process and, therefore, the component being cleaned, or the installation itself, should be earthed. Industrial, remotely operated units are available.

I.3.2.2. Abrasive media used

Depending on the application, a variety of materials can be used as abrasive media:

- Minerals (e.g. magnetite, sand);
- Steel pellets, aluminium oxide;
- Glass beads/glass frit, silicon carbide, ceramics;
- Plastic pellets;
- Natural organic products (e.g. rice hulls, ground nut shells);
- CO_2 (dry ice, for ‘cold’ oxides, painted surfaces, etc.).

Although silica has been used as an abrasive, its use is not recommended as it can form a highly irritating dust which is moderately toxic and 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.

I.3.2.3. Secondary waste generation

As indicated before, abrasives may be applied under either wet or dry conditions. Under dry conditions, dust control measures may be needed to control dusts and/or airborne contamination. This problem can be reduced by using filtered vacuum systems in the work area.

When water is used to apply the abrasive, large volumes of waste are produced including waste water, abrasive and removed debris. These wastes must be properly treated and/or disposed of. Recirculation of abrasives and recycling of the waste water (treated or not before reuse) allows a significant reduction to be achieved in the amount of secondary wastes generated.

I.3.2.4. Guidelines for selecting appropriate abrasive blasting decontamination techniques

When selecting a suitable abrasive decontamination process, criteria must again be considered in a detailed analysis based on site specific conditions. These criteria are very similar to the criteria mentioned in Sections 3.3 and I.1.3, and take into account the specific characteristics of the abrasive blasting decontamination process.

I.3.2.5. Advantages

There are several advantages to using this method:

- Generally, abrasive blasting techniques have proven themselves to be effective. In many cases, the equipment is well developed and commercially available. Industrial equipment is also available for remote operation.
- Several methods are able to remove strongly adhering material, including corrosion layers. Special tools for cleaning the insides of tanks and pipes are also available.
- The abrasive blasting technique gives results within a relatively short time-span.

I.3.2.6. Disadvantages

There are also several drawbacks to using this method:

- Abrasive blasting techniques generally produce a large amount of waste if recirculation and/or recycling of abrasives and/or water is not possible. In some cases, it is difficult to control the amount of metal substrate removed. In dry abrasive systems, dust control measures may be needed to control dusts and/or airborne contamination. Wet abrasive systems also produce a mixture of dust and water droplets that might be difficult to treat.
- Care must be taken not to introduce contamination into the material surface (the so-called ‘hammering’ effect), which could compromise the ability to meet clearance levels.

I.4. MECHANICAL TECHNIQUES FOR DECONTAMINATING BUILDINGS

The following mechanical decontamination techniques are most commonly used for decontaminating building surfaces. Before any surface cleaning or surface removal activity is conducted, surface preparation and safety precautions are required. Surfaces to be treated must be free from obstructions (e.g. piping and supports should be dismantled or segmented) and should be vacuumed in order to minimize any release of airborne contamination during application of the surface removal technique. Moreover, precautions are needed to prevent explosions from occurring when treating an area containing combustibles. In this instance, all combustibles should be neutralized, stabilized or removed. Due consideration should be given to the industrial hazards associated with the use of these techniques and the unacceptable damage that can be caused.

I.4.1. Scarifying

Scarifiers physically abrade both coated and uncoated concrete and steel surfaces. The scarification process removes the top layers of a contaminated surface down to the depth of the sound, uncontaminated surface. A decade ago, concrete scarifying was considered an unreliable approach to decontamination owing to the poor performance of the tools and their inability to provide a uniform surface profile during removal of the contaminants. The refined scarifiers of the present-day are not only very reliable tools, but also provide the desired profile for new coating systems in the event that the facility is to be released for unrestricted use.

I.4.2. Needle scaling

Needle scalers are usually pneumatically driven and use uniform sets of 2, 3, or 4 mm needles to obtain the desired profile and performance. Needle sets use a reciprocating action to chip contamination from a surface. Most of the tools have specialized shrouding and vacuum attachments to collect dust and debris produced during needle scaling which results in no detectable activity concentrations above background levels being achieved.

Needle scalers are exceptionally useful tools when used in tight, hard to access areas, as well as for wall and ceiling surface decontamination. This technique is a dry decontamination process which does not introduce water, chemicals or abrasives into the waste stream. Only the removed debris is collected for treatment and disposal. Production rates vary depending on the desired surface profile.

I.4.3. Scabbling

Scabbling is a scarification process used to remove concrete surfaces. Scabbling tools typically incorporate several pneumatically operated piston heads to strike (i.e. chip) a concrete surface. Available scabblers range from one to three headed hand-held scabblers to remotely operated scabblers, with the most common versions incorporating three to seven scabbling pistons mounted on a wheeled chassis. Scabbling bits have tungsten carbide cutters, the bits having an operating life of about 100 hours under normal conditions of use. Both electrically and pneumatically driven machines are available. As scabbling can pose a cross-contamination hazard, vacuum attachments and shrouding configurations have been incorporated in order that it can be done without causing any detectable increase in airborne exposures above background levels.

Before scabbling, combustibles must be stabilized, neutralized and/or removed. In practice, floor scabblers can only be moved to within some 5 cm of a wall. Consequently, other hand-held scabbling tools are needed to remove the remaining 5 cm of concrete flooring immediately adjacent to a wall, as well as to remove surface concrete on walls and ceilings.

This technique is a dry decontamination method; no water, chemicals or abrasives being required. The waste stream produced is only the removed debris. Work rates are not easy to predict owing to the variety of concrete compositions and characteristics and to the different types of bit that can be used.

Scabblers are best suited to removing thin layers (up to 25 mm thick) of contaminated concrete (including concrete block) or plastered brick. The method is recommended for use in instances where:

- No airborne contamination can occur,
- 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 treating both large open areas and small areas.

I.4.4. Concrete shaving

A floor shaver has been developed as an alternative to floor scabbling. This machine is similar to a normal floor scabbling unit and has a quick change diamond tipped rotary cutting head designed to give a smooth surface finish, which is easier to measure and ready for painting. It is capable of cutting through bolts and metal objects, an act which would damage the head of a traditional scabbler. Actual cutting performance results in:

- A threefold increase in mean working rate for floor decontamination compared with scabbling;
- A 30–45% reduction in waste production compared with scabbling and with a comparable level of decontamination efficiency;
- Much less physical load being placed on the operators owing to the absence of machine vibration;
- End products (concrete dust) that, when combined with suitable additives, can be incorporated in a cement matrix.

On the basis of the positive experience gained with the floor shaver, a remote controlled diamond wall shaving system has been developed as a solution to the decontamination of larger concrete surfaces. The machine consists of :

- A remote controlled power pack for the remote controlled shaving unit;
- Vacuum systems to temporarily fix vacuum pads for 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 mm and 15 mm per pass, and produces a smooth surface finish. The cutting head is designed to follow the contours of the surface being removed, and depth adjustments can be set manually in increments of 1 mm in order to minimize waste generation. With 300 mm wide and 150 mm wide shaving heads, both large areas and ‘awkward’ corners can be accessed. When the vertical rail is fitted to the wall with the cutting head shaving, the horizontal rail can 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. The ‘lifetime’ of a shaving head equates to 2000 m^2 of surface treated.

I.4.5. Hydraulic/pneumatic hammering

The cutting and decontamination of concrete structures can be carried out with hydraulic or pneumatic hammers, either hands-on or by using an electrically powered, hydraulically controlled robot. The latter can be equipped with a hydraulic hammer, an excavator bracket, or other tools, and is well suited for decontaminating floors and walls. A mini-electrohydraulic hammering unit (weighing 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 work load of the operators.

I.4.6. Dust collection

For the dustless decontamination of concrete, scabblers, scarifiers and shavers may be integrated into a system of remotely and manually operated dust collection equipment. With these systems, dust and debris are captured at the cutting tool surface, which minimizes cross-contamination. For hand-held scabblers and smaller systems, dust evacuation is carried out using industrial vacuum cleaners with capacities of up to 500 m^3/h, and which are equipped with absolute filtering systems at the outlet.

Larger scabbling or shaving machines are connected to vacuum systems with capacities of up to 2500 m^3/h or greater. They incorporate a cyclone to evacuate larger concrete particles, a filtering system with cleanable prefilters and an absolute filter, and a vacuum pump. The cleanable filtering system incorporates a fill-seal drum changeout method that allows the operator to fill, seal, remove and replace the waste drum under controlled conditions. The unit can accommodate different drum sizes and serve several scabblers/shavers/needle scalers operating at greater distances.

I.5. DECONTAMINATION BY MELTING

I.5.1. General considerations

Specifically during the decommissioning of nuclear plants, large quantities of slightly contaminated metallic scrap are generated. This scrap can also result from maintenance and from the replacement of equipment. Much of this waste consists of bulky equipment (e.g. heat exchangers, moisture separators, steam generators) that, if disposed of in appropriate repositories, would occupy considerable volumes of the available space. Moreover, in many cases, this equipment contains valuable material that can be recycled, including pressure vessel steels, stainless steels and Inconel. By melting slightly contaminated scrap, it is possible to recover much of these valuable metals while simultaneously conserving valuable space at final disposal facilities. The pieces of equipment considered frequently also have complex geometries, making the determination of the exact location and level of radioactivity on the internal surfaces extremely difficult, time consuming and expensive tasks. After melting, however, the radioactivity can be precisely determined by sampling each ingot. Moreover, an ingot can be released for restricted or unrestricted reuse, or stored for decay to appropriate limits.

Melting completely destroys components and as a decontamination technique is effective only for contaminants that are volatile or that concentrate in the slag or dross (e.g. plutonium) rather than in the molten metal. The decontamination efficiency varies widely, depending on the radioisotope present. The radionuclides remaining in the molten material are distributed homogeneously and thereby effectively immobilized, thus reducing the possibility of spreading the contamination. In some cases, when ingots are found to be so active that they must be sent to a final repository, melting will have achieved significant volume reduction and will thus have preserved valuable repository capacity. As an alternative, some ingots with activity levels higher than freely releasable can be remelted to make shielding blocks or cold-rolled to fabricate containers for radioactive waste, and can, therefore, be recycled within the nuclear industry.

A particularly advantageous consequence of melting is its ‘decontaminating’ effect on ^{137}Cs, a volatile element that has a half-life of 30 years. During melting, ^{137}Cs accumulates in the dust collected by ventilation filters; the dominant nuclide remaining in the ingots (for most reactor scrap) being ^{60}Co. This element has a half-life of only 5.3 years. Other nuclides remaining have even shorter half-lives. Consequently, ingots with reasonably low activity concentrations can be stored for release in the foreseeable future. Moreover, radiation exposure of foundry workers during the subsequent remelting of ingots is drastically reduced as a result of the removal of ^{137}Cs. The secondary waste consists of the slag from segmenting and melting, as well as dust from the ventilation filters. This secondary waste only comprises 1–4 wt% of the melted scrap.

I.5.2. Current melting practices

Only limited quantities of metallic scrap have thus far been released from nuclear facilities for melting at conventional facilities. These releases have been permitted on a case by case basis and the qualifying release limits for activity vary from country to country. The practices and conditions prevailing at these conventional foundries during the direct melting of contaminated scrap have previously provided the basis for calculating the exposure of workers and the public.

However, within the last five years, the melting of contaminated steel in special purpose plants for recycling has developed as a new industry. Established techniques are being utilized for minimizing the quantity of active metallic waste. A number of plants are, or have been, melting contaminated metals on an industrial scale, including:

- CARLA Plant, Siempelkamp, Germany (start 1989);
- STUDSVIK Melting Facility, Sweden (start 1987);

- INFANTE Plant, Marcoule, France (start 1992);
- Scientific Ecology Group Plant, Oak Ridge, USA (start 1992);
- Manufacturing Sciences Corporation, Oak Ridge, USA (start 1996).

At the STUDSVIK Melting Facility, the ingots are stored, if necessary, to permit the activity to decay to a level at which they can be released for remelting in commercial foundries. Prior to release, the material is certified by the appropriate radiation protection authorities. After remelting, the materials can be used without radiological restrictions. Several unique advantages result from remelting in this fashion:

- Volatile nuclides such as ^{137}Cs will have been removed in the first melt. Consequently, dust is no longer a radiological problem.
- There is no surface contamination. As a result, there is no need for further segmentation.
- The slag has been removed as radioactive waste.

I.5.3. Advantages of melting as a decontamination technique

Melting presents the particular advantage of redistributing a number of radionuclides among the ingots, slag and filter dust resulting from the melting process, thereby decontaminating the primary material.

Melting may provide an essential step when releasing components with complex geometries; simplifying monitoring procedures for radioactive metal characterization. In addition to its decontaminating effects, the problem of inaccessible surfaces is eliminated and the remaining radioactivity is homogenized throughout the total mass of the ingot. Melting, therefore, can be a last step in the decontamination and release of components with complex geometries after these pieces have been decontaminated by, for example, chemical methods, which remove radionuclides such as ^{60}Co.

I.6. OTHER DECONTAMINATION TECHNIQUES

In special cases, other decontamination techniques (e.g. ultrasonics, high pressure water jetting or steam spraying, thermal erosion, application of pastes, gels and foams) have also been used in decommissioning. Some of them, however, require more or less complex application procedures or require still more development in order to allow their industrial application.

An overview of the characteristics and applications of the common techniques used for the decontamination of metal and concrete is shown in Table VIII.

TABLE VIII. OTHER DECONTAMINATION TECHNIQUES FOR METAL AND CONCRETE

Technique/equipment	Fields of application*	Advantages**	Limitations***	Remarks
Vacuum cleaning	a, b, c, d	1, 2, 3, 4, 5, 6	A, B, C	Widely used alone and with destructive decontamination methods to collect dust, fumes, etc. Good for gloveboxes and cells.
Brushing, washing and scrubbing	a, b, c, d, e, f, g	1, 2, 4, 5	A, B, C, D, E	Widely used. Solvents, detergents and chemical cleaning agents can be used for dirty/oily surfaces,or abrasive pads and aggressive chemicals for corrosion layers and embedded material.
High pressure water/steam lance	a, b, c, d, e, f	1, 2, 4, 5, 6, 7	B, D, E, F	Very versatile. Chemicals or abrasives can be added. Pressures up to 70 Mpa; flows about 1–4 l/s. For good cleaning, steam must be wet or saturated. High pressure is a potential hazard.
Abrasive blasting	a, b, c, d, e, f	2, 6, 8	B, D, F, G	Efficient decontamination method. Variety of abrasives (sand, alumina, boron oxide, metal oxides) carried in high velocity fluid (air, water or steam) used to remove layer. Care needed to balance feed of abrasives and control dust and aerosol generation.
Ultrasonic cleaning	a, c, d, g	1, 2, 3, 4, 5, 7		Good for small reusable pieces of equipment and precision components.
Scarifying	b	1, 2, 3, 5, 6	B, C	Suitable for shallow contamination. Uses air operated piston with 5–9 bits to chip thin layer (up to 2.5 cm) of concrete. Floor and wall models are available. Surface suitable for putting on new layer. Removal rate about 4 m^2/h per piston.

Shaving, grinding	b	1, 2, 3, 5, 6	B, C	Suitable for removal of thin layers (1–3 cm). Heavy duty floor and hand grinders. Dust extraction with vacuum systems and HEPA filters. A 30–50% reduction in secondary waste production compared with normal scabbling.
Drilling and spalling	b	3, 6	B	An expandable bit is inserted into a drilled hole to spall away concrete. Fog sprays and air cleaning systems can be used to reduce contamination spread and dust/aerosol levels.
High pressure jet spalling	b	3, 5	C	Two types: glycerine gun uses gunpowder to fire solidified glycerine capsules at high velocity to spall craters (2 cm deep, 10 cm diameter); water cannon uses compressed gas to drive piston and eject water at high velocity. Water cannon slower than glycerine gun. Water cannon usually mounted on backhoe machine; glycerine gun is hand-held.
Hydraulic hammering	b	1, 2, 7	B, C, D Impractical for large areas	Used to remove small surface areas that are not accessible to large pieces of equipment. A hardened bit is driven against the floor or wall to chip away material. Also used for cutting and demolishing small structures.
Melting	h	6		

* a: loose particulate contamination; b: bare and painted concrete walls, floors and ceilings; c: metal surfaces; d: components of all sizes; e: pipe and tank internals; f: embedded material and some oxide surfaces; g: small items such as tools; h: metal.

** 1: relatively cheap, easy to apply; 2: readily available equipment; 3: easy waste handling/disposal; 4: little or no surface damage; 5: easy to train operators; 6: remote operation possible or available; 7: can penetrate crevices; 8: can be applied wet or dry.

*** A: difficult to remove contamination from crevices; B: spread of contamination possible; C: personnel exposure could be high; D: labour intensive; E: solvents and detergents could complicate waste management; F: could produce increased volumes of waste unless recirculation possible; G: possibility of excessive erosion or surface roughening.

Appendix II

DISMANTLING TECHNIQUES FOR DECOMMISSIONING

The dismantling of nuclear reactors and other facilities contaminated with radioactivity generally involves the segmentation of metal items: reactor vessels, tanks, piping and other components. Also, in most facilities to be decommissioned, the cutting and demolition of concrete components is required, often preceded by scarification of the surface in order to remove contaminated areas. A wide variety of processes for the demolition and segmentation of metal and concrete structures has been used and new processes and techniques are continually being developed.

Different amounts of wastes, mainly in the form of dust, sludges, metal scrap, concrete, filters and some liquids, etc., may be generated during the application of dismantling techniques. The amount and character of this waste material depends on the type and scale of the dismantling method. The selection of dismantling techniques is mainly defined by the nature of the work to be carried out. However, the generation, collection and adequate treatment of associated waste materials should be carefully considered within the selection process.

More detailed information about demolition and segmentation techniques can be found in Refs 12, 18, 20, 21, 95 and 96, and in the references cited in the following sections.

II.1. CUTTING AND DEMOLITION TECHNIQUES FOR CONCRETE

Almost every large decommissioning project will have to contend with the cutting and demolition of concrete structures such as:

- Heavily reinforced, massive concrete used to construct the biological shields in a reactor, the walls of hot cells, foundations and walls;
- Massive, heavy concrete (metal or magnetite aggregate) with little or no reinforcement, used for certain biological shields;
- Lightly reinforced or non-reinforced floors and walls;
- Prestressed reactor vessels and reactor buildings.

The demolition of such concrete structures is not unique to nuclear plants and many of the techniques are modified versions of those used in the non-nuclear industry. However, such demolition is still a difficult task because of the reinforcement, the volume of concrete and, in the nuclear industry, the radioactivity. Often, the demolition equipment used for nuclear facilities is operated remotely.

Some of these concrete structures become radioactive during plant operation. In reactors, concrete adjacent to the core becomes activated as a result of neutron leakage from the core. This is usually the most difficult removal job because of the relatively high radiation dose rates and poor accessibility for equipment.

The cutting and demolition techniques recommended for various applications in the nuclear industry are summarized in Table IX and described in more detail in the following sections.

II.1.1. Controlled blasting

Controlled blasting is generally recommended for the demolition of massive, heavily reinforced concrete sections. The process consists of drilling holes in the concrete, loading them with explosives and detonating them using a 1–3 ms delayed firing technique. The delayed firing increases fragmentation and controls the direction of material movement. Delayed firing also reduces the vibration impact on adjacent structures. Each borehole fractures radially during the detonation; the radial fractures in adjacent boreholes forming a fracture plane. The detonation wave separates the fractured surfaces and moves the material towards the structure's free face.

The selection of the best type of explosive requires an evaluation of the properties of the explosive and the concrete. A blasting expert should be employed to select the best explosive for the purpose. Typical types of explosive used for concrete removal include: pentaerythritol tetranitrate (PETN), 85% high velocity gelatine dynamite, cast TNT (high detonation pressure primers), products based on ammonium nitrate, and water gel explosives.

A blasting mat (varying from automobile tyres tied together for large pieces, to rubber mats for smaller debris and filter mats to retain fine dust) can be placed over the blast area. Continuous fog sprays of water should be used before, during and after the blast in order to suppress dust. The exposed reinforcing bar may then be cut using an oxyacetylene torch or bolt cutters.

II.1.2. Wrecking ball or slab

The wrecking ball or slab is only recommended for use on non-radioactive concrete structures. It is not practical to contain the dust which arises from the use of this type of demolition technique because of the amount of space required by the crane to swing or drop the ball/slab.

The wrecking ball/slab is used for the demolition of non-reinforced or lightly reinforced concrete structures less than 1 m thick. The equipment consists of a 2–5 Mg ball or flat slab suspended from a crane boom.

TABLE IX. CUTTING AND DEMOLITION TECHNIQUES FOR CONCRETE STRUCTURES

Technique/equipment	Recommended fields of application	Cutting rate for concrete	Limitations	Remarks
Controlled blasting	a, b, c, d	High	Reinforcing bars must be cut after fracture. Metal aggregate in heavy concrete slows drilling speed.	Shock/noise levels can be moderated with controls. Contamination control with blasting mats and fog spray.
Wrecking ball or slab	c	Medium	Relatively slow. Not recommended for radioactive structures.	Suitable for low structures and for breaking rubble.
Backhoe mounted ram (hydraulic or pneumatic)	c, d	Medium	Cannot reach structures over about 6–7 m in height. Limited to thicknesses of about 0.6 m.	Dust contamination control with fog spray. Exposed reinforcing bars must be cut by other methods.
Flame cutting	a, b, c	Low	Large amounts of smoke produced.	Reinforcing bars speed cutting. Used when vibration to surroundings must be minimized or when thickness to be cut exceeds capability of other methods.
Thermite reaction lance	e	Low	Large amounts of smoke produced.	Requires an efficient exhaust system.
Rock splitter	b, c	High	Not recommended for thick reinforced concrete. Limited to thicknesses of about 0.6 m.	Used when noise and vibration must be controlled or when access is limited. Reinforcing bars must be cut after fracture. Backhoe required to separate rubble.
Demolition compounts	b, c	Medium	Not recommended for thick reinforced concrete.	As for rock splitter.

Circular diamond or carbide saws	c, d	Medium	Slow in cutting reinforcing bars. Maximum thickness cut is equal to 40% of blade diameter.	For removal of entire wall or floor sections. Dust controlled by water spray and envelope. Concrete 1 m thick has been cut.
Core stitch drilling	b	Low	Rock splitter and reinforcing bar cutter required.	Used when surroundings must not be disturbed or when access is limited. A series of close spaced holes are drilled on the breaking plane of the concrete, force being applied to break the remaining concrete.
Core drilling	a, c, e	Medium		Used when geometry of object is too complex for other methods or where several cuts must be made at the same time, e.g. for removal of reinforced concrete beam. Precision cutting, using shaped explosive cores.
Laser cutting	Under development	Low	Fairly costly; large equipment.	Development of lasers for cutting and drilling concrete still requires development work.
Abrasive water jet	a, b, c	Medium		Method to be evaluated.
Wire cutting	a, b, c, d	Medium		Diamond wire or plain wire and abrasive slurry have been used to cut large concrete blocks. Promising technique.

Note: a: Cutting and demolition of heavily reinforced, massive concrete (> 0.6 m);
b: Cutting and demolition of non-reinforced, massive concrete (≤ 0.6 m);
c: Cutting and demolition of non-radioactive, lightly reinforced or non-reinforced floors and walls (≤ 0.6 m);
d: Demolition of lightly reinforced concrete;
e: Cutting holes or slits in any material in a nuclear facility.

The ball may be used by either of two techniques used for demolishing structures. The preferred method is to raise the ball with a crane 3–6 m above the structure and release the cable brake, allowing the ball to drop onto the target surface. The second method is to swing the ball into the structure, using a suck line for recovery after impact.

The maximum height of structure that can be tackled using this technique is limited to about 15 m because of crane instability during the swing and after impact. This method is not recommended for use in confined areas because the target area could be more difficult to hit and the ball could ricochet off the target and damage adjacent structures, while putting side loads on the crane boom.

The flat slab may only be used in the vertical drop mode but offers the advantage of being able to shear through steel reinforcing rods as well as concrete.

II.1.3. Backhoe mounted ram

Backhoe mounted pavement breakers are used for demolishing lightly reinforced concrete structures less than 0.6 m thick. The equipment consists of an air operated or hydraulically operated impact ram with chisel points mounted on a backhoe arm. The equipment should be used in conjunction with a fine spray of water in order to minimize dust. However, the spray should be synchronized with the ram head in order to avoid excessive use of water. With the ram head mounted on a backhoe, the operator has a reach of about 7 m and the ability to position the ram in limited access structures.

II.1.4. Flame cutting

Flame cutting can be used when vibration of the adjacent area is not permissible and when the concrete to be cut is thicker than that which can be cut using other methods, such as diamond sawing. Flame cutting of concrete is effected by a thermite reaction process whereby a powdered mixture of iron and aluminium oxidizes in a pure oxygen jet. The temperature in the jet is in the range of 2000–5000°C, which causes rapid decomposition of the concrete in contact with the jet. The mass flow rate of the reactants through the flame cutting nozzle clears away the decomposed concrete and leaves a clean kerf. Reinforcing rods in the concrete add iron, sustaining the flame and assisting the reaction. Flame cutters can cut through concrete with or without reinforcement (Table IX).

Prior to cutting, a hole is cut through the slab to prevent torch damage from blowback of material. The torch is then moved along the workface by the operator using a variable speed electric motor mounted on a metal frame which covers the area being cut. The rate of cutting depends on the depth of concrete being cut.

During flame cutting, large amounts of dust, smoke and heat are produced. These can be removed using an exhaust system that includes a flexible duct, prefilters and, if the material is active, HEPA filters. However, the effluent gas must be cooled to prevent damage to the HEPA filters. Also, the system should be designed to enable the prefilters to be changed easily.

II.1.5. Thermite reaction lance

The thermite reaction lance can cut almost any material encountered in a nuclear facility and is suitable for use on irregular surfaces. This equipment consists of a combination of steel, aluminium and magnesium wires packed inside an iron pipe through which a flow of oxygen gas is maintained [97]. Typical lances are 3 m in length and 6–10 mm in diameter.

The lance is ignited in air by a high temperature source such as an electric arc or an oxygen burning torch. During operation, the thermite reaction at the tip completely consumes the constituents of the lance and causes the temperature to reach 2200–5000°C, depending on the environment.

The thermite reaction lance can be used in air or under water. The operational procedure is the same in both cases, except that the lance must always be ignited in air and the incident angle relative to an underwater workpiece must be carefully controlled in order to preserve visibility, since many bubbles are formed during the process. In metal cutting, the procedure has been reported as generating an approximately 2.5 cm diameter hole at the rate of 30 cm depth per minute, provided that the molten metal is free to flow away from the kerf. A 3 m lance will burn for about 6 minutes.

During cutting, the lance must be hand-held and the operator must be equipped with fireproof protective clothing and a mask. The smoke and dust problems arising from the use of this equipment are similar to those experienced with flame cutting. Since the process generates considerable smoke, a control envelope and ventilation must be provided, particularly if the component being cut is radioactive.

In some specific applications, 50% more person-hours were required to dismantle reinforced concrete structures using a thermal lance than by using blasting techniques [98]. However, lance cutting causes less damage to secondary structures.

II.1.6. Rock splitter

The rock splitter is ideal for fracturing concrete in limited access areas where large air rams cannot operate. The process is relatively quiet except for hole drilling and is used extensively for demolition near densely populated areas. Application of the technique is limited by the amount of reinforcing bars in the structure and limited to use on walls with thicknesses of up to 60 cm.

The rock splitter fractures concrete by hydraulically expanding a wedge inserted into a drilled hole until the tensile stresses become great enough to cause fracture. In order to deal with long sections of concrete, multiple splitters are used along the desired fracture line. The tool consists of a hydraulic cylinder that drives a wedge shaped plug between two expandable guides (termed ‘feathers’) inserted into the drilled holes. The rock splitter unit is powered by a hydraulic supply system which operates at 50 MPa. The hydraulic unit may be powered by air pressure, petrol engine or electric motor sources.

Units are available to develop splitting forces approaching 3.2 MN. The maximum lateral expansion of the feathers is approximately 2 cm. Concrete may be separated at a fracture line using a backhoe mounted ram or similar equipment. The reinforcing rod in reinforced concrete must be cut before separation is possible. Additional holes and fractures would be necessary in order to expose the rod in heavily reinforced concrete.

Removal rates of up to 200 m^3/d for non-radioactive concrete have been achieved.

II.1.7. Demolition compounds

Demolition compounds are only effective with non-reinforced or lightly reinforced concrete. The proprietary compounds consist of limestone, a siliceous material, gypsum and slag. The powder is mixed with water and then packed into holes drilled into the concrete along a fracture line of predetermined burden, spacing and depth. No hole caps are required if the hole depth is at least six times the hole diameter. Pressure in excess of 30 MPa, well above the tensile strength of concrete, will develop within 20 hours. Cracks will form and propagate along the fracture line. The fractured burden may then be removed with a pavement breaker, backhoe or bucket loader. If a reinforcing rod is encountered, it must be cut separately.

The compound is not classified as a hazardous substance and can easily be stored and handled. There is no noise or vibration (except when drilling holes), and no flyrock, dust or gas release. Contamination control is only required during drilling and waste removal.

II.1.8. Circular diamond or carbide saws

Large diamond or carbide tipped saws are being developed for cutting thick concrete walls and floors. This technique is generally used when disturbance of the surrounding material must be kept to a minimum. These saws can cut through reinforcing rods, although the rods tend to break off diamonds from the blade. The blade is rotated by an air or hydraulic motor. For most applications the saw will be mounted on a guide that also supports its weight. The dust produced by the abrasive cutting is controlled by using a water spray; the spray should be contained in order to prevent the spread of contamination. The abrasive blade produces no vibration, shock, smoke, sparks or slag and is relatively quiet during operation.

Thicknesses of up to 1 m have been cut with concrete saws; the maximum thickness of cut being equal to approximately 40% of the blade diameter. The saw cuts approximately 0.2 m^2/min of surface. Cutting can be controlled either manually or remotely, depending on the size of the saw.

The choice of material for the tip of the saw and the of choice binding agent are strongly influenced by the type of aggregate present in the concrete. Specific tests are required for each new application.

II.1.9. Core stitch drilling

Core stitch drilling is recommended for use on non-reinforced concrete, especially when the surroundings are not to be disturbed. The technique consists of the drilling of closely spaced holes in concrete using a diamond or carbide tipped drill bit inserted in an electric or fluid driven rotary drill. The centres of the holes are aligned to correspond to the desired breaking plane in the concrete. The hole spacing is such that there is very little concrete left between adjoining holes (less than half the radius of the holes). When a line of holes has been drilled along the breaking plane, bars are inserted into the holes and force applied to the free end of the bars in a line perpendicular to the breaking plane in order to shear the remaining concrete. Alternatively, a wrecking ball may be dropped onto the piece to be removed, shearing the remaining concrete.

A variation of this method reduces the spacing between the holes until the holes intersect. In this case, no force is required to separate the concrete.

This is a fairly slow process but it could be improved by the use of multiple drilling heads.

II.1.10. Core drilling

Core drilling can be used to remove cylindrical sections from all types of concrete. The drill consists of a hollow cylindrical pipe equipped with a water cooled, diamond tipped cutting edge. Cylindrical blocks up to 1 m in diameter can be sectioned using this technique. Also, the blocks can be sized to fit into a 200 L drum.

II.1.11. Explosive cutting

Explosive cutting is normally used either when the geometry of an object being cut is too complex to employ other methods or when several cuts must be made simultaneously, e.g. when making two simultaneous cuts in a large concrete beam in the case where it is not practical to provide temporary support to the ends. It is suited to cutting concentric pipes and felling large chimneys.

An explosive cutter consists of an explosive core, such as cyclotrimethylenetrinitramine (RDX) or PETN, surrounded by a casing of lead, aluminium, copper or silver. Hard plastic casings are also being developed. The cutter is chevron shaped, with the apex pointing away from the material to be cut, and acts as a hollow charge. When detonated, the explosive core generates a shock wave that fractures the casing inside the chevron and propels the molten casing into the material to be cut. Cutting is accomplished by a high explosive jet of detonation products and molten casing metal. The small quantity of explosive used usually does not give rise to large volumes of gas or aerosols. However, fragile equipment nearby should be protected from possible projectiles coming from the casing or from the piece being cut.

Normally, the charge is placed on the equipment fairly quickly in which case the workers do not receive a large radiation dose, even in high radiation zones. Remote placement of the charge is also possible.

II.1.12. Laser cutting

Laser cutting has been applied to the cutting of both metal and concrete structures. A high power gas laser generates infrared radiation which can be focused using water cooled reflective optics to produce a beam with power densities capable of cutting steel or concrete. However, the cutting can only be carried out in air, since water would diffuse the laser beam excessively. The laser gas can be inert (CO_2, He, N_2) or reactive (O_2, air).

A CO_2 laser uses an inert gas as the lasing medium, with a typical gas composition of about 78% He, 18% N_2 and 4% CO_2. The laser beam melts and vaporizes the material being cut and removes it from the cutting area by means of a high velocity gas jet. Lasers with power ratings in the range of 1–15 kW can be used to cut concrete or steel.

A CO_2 laser cutting system consists of a laser beam generator and associated controls, high voltage electricity and gas supplies, beam handling and focusing optics, a cooling system and a nozzle assembly.

High power laser cutting systems tend to be relatively expensive and require large spaces in which to operate. However, it may be possible to mount such systems on skids or trailers, or to direct the laser beam with mirrors and focusing lenses in order to bring the beam to the piece being cut, instead of moving the laser source.

Although progress has been made in using laser technology to assist decommissioning, it would appear that much more work is required before it becomes a viable option for cutting or drilling massive concrete.

II.1.13. Abrasive water jet

In the abrasive water jet process, a small diameter, high velocity water jet and a stream of solid abrasives are introduced from separate feed ports into a specially shaped abrasive jet nozzle. At this point, part of the water jet’s momentum is transferred to the abrasives, whose velocity increases rapidly. The abrasive water jet can be used to cut reinforced concrete and metal structures. As an example, an abrasive water jet tool can use water at a pressure of 410 MPa and employ a sapphire nozzle to form the coherent high velocity jet [99].

A deep kerf tool has been developed to cut concrete up to 1.5 m thick from one side using a rotary nozzle that makes a slot in the concrete wide enough to accommodate the cutting tool as it advances [100]. A shroud and vacuum system is used to contain the wastes with over 99% efficiency. Garnet sand is the abrasive most commonly used for cutting, although steel grit is also being investigated since it can be separated magnetically and reused.

The wide application of this technique for dismantling large reinforced concrete structures in reactors will be limited since the process results in large volumes of dirty and contaminated water and is relatively slow.

II.1.14. Wire cutting

A process using diamond wire to cut massive blocks of reinforced concrete has been developed and is being used at nuclear power plants and at other facilities. To make such a cut, holes are drilled through the floor at the four corners of the block to be removed. The diamond wire is fed down through one hole and back up an adjacent hole, joined together to make a loop, and then tensioned to make the cut. The cutting rate is about 2 m^2/h. This process is fairly well developed and has been used in non-nuclear applications.

The advantages of this process include the capability of making precise cuts, the very low amounts of debris created, the relatively high cutting rates, the relatively low levels of noise and vibration, and the capability of cutting thin blocks. Also, the amounts of water required for cooling and dust control are small and the water can be recycled.

II.2. SEGMENTING METAL COMPONENTS

During the decommissioning of nuclear facilities, a wide range of metal structures and components needs to be segmented for easy removal and disposal. This includes large items such as reactor vessels, pressure tubes, large and small tanks, and all types of piping and ancillary components. Cutting methods used for highly radioactive components, such as pressure vessels or certain reprocessing plant equipment, must provide for remote operation.

In this section, segmenting processes for all thicknesses of metal components are briefly reviewed (Table X) in order to assist users in the selection of the cutting methods most suitable for their needs.

II.2.1. Arc saw cutting

The arc saw is a circular, toothless metallic blade which can be used to cut any conductive metal without contacting the workpiece. The cutting action is obtained by means of a high current electric arc created between the rotating blade and the material being cut. The blade can be made from any electrically conductive material (e.g. tool steel, mild steel or copper) and used with equal success. Blade rotation, which can range from 300 rev./min to 1800 rev./min according to the diameter, assists in the cooling of the blade and the removal of the molten metal from the kerf of the cutting zone. On being expelled, the molten material solidifies in the form of highly oxidized pellets.

Although the arc saw can be operated in air or water, underwater operation provides a smoother cut and suppresses the smoke, dust and noise better than is possible in air. However, during underwater cutting, the water can become clouded, impairing visibility. For ‘in air’ operation, localized containment and absolute filtration of the resulting vapour would be required.

The depth of cut is determined by the diameter of the blade. For example, a 30 cm thick pressure vessel can be cut using a 100 cm diameter blade. The arc saw also permits the cutting of components which are not solid, for example, a heat exchanger where voids alternate with the metal tubes.

Cutting rates for the arc saw are much faster than for torch cutting and range from 1750 cm^2/min for steels up to 5000 cm^2/min for aluminium. Carbon steel cuts are the most difficult since slag buildup in the kerf reduces the cutting rate. Although the arc saw is a potential candidate for use in segmenting reactor vessels, practical problems include access and positioning difficulties resulting from the large blade which is needed and the large capacity containment envelopes required for cutting such structures in air.

II.2.2. Thermal cutting techniques

II.2.2.1. Oxygen burning

The oxygen burning technique for the cutting of metals uses a torch assembly carrying a flowing mixture of fuel gas and oxygen which is ignited at the nozzle of the torch. The cutting process depends on the rapid exothermic oxidation of the metal being cut. The fuel gas can be acetylene, propane or hydrogen. The cutting tip of the torch consists of a main oxygen jet orifice surrounded by a ring of preheater jets which exothermically oxidize the fuel gas. When the metal to be cut reaches a temperature of about 800°C, the main oxygen jet is turned on and the heated metal is burned away, leaving a reasonably clean cut surface.

Since oxidation of the metal being cut is required, only ferrous metals which oxidize readily, such as mild steel, can be cut using this process. Stainless steel, aluminium and other non-ferrous metals cannot usually be cut using this process, owing to the formation of refractory oxides with melting points higher than the torch temperature. However, iron or iron–aluminium powder in a flowing mixture can be introduced at the torch nozzle to increase the flame temperature (through the thermite reaction) sufficiently to melt the refractory oxides and permit the cutting of non-ferrous metals.

For mild steel in the 30–100 cm thickness range, cutting speeds are 5–15 cm/min. Normally, the cutting is done in air. However, some underwater cutting has also been done. The equipment is light enough to allow its easy adaptation for remote operation.

Since the process gives rise to dust and aerosols, suitable ventilation, filtering and operator protection are required.

Oxygen cutting is widely used in industry, and therefore skilled operatives and good, inexpensive equipment are readily available. The equipment is also easy to set up.

A modified oxygen burning torch system has been developed for cutting reactor pressure vessels that consist of stainless steel clad low alloy steel [101]. In this process, which is carried out under water in order to reduce dust and radiation exposure, an arc gouging torch is used to cut through the stainless steel, followed by a conventional torch which is used to cut through the low alloy steel. Cutting speeds of up to 3 cm/s are possible with 40 cm thick material.

II.2.2.2. Plasma arc torch

A plasma arc torch can be used for the rapid cutting of all conductive metals. The process is based on the establishment of a direct current arc between a tungsten electrode and the metal to be cut. The arc is first established between the electrode and the gas nozzle and then carried to the workpiece by the flow of gas. The constricting effect of the orifice on both the gas and the arc results in very high current densities and temperatures (10 000–24 000°C) in the stream. The high temperature breaks the gas molecules into a high velocity plasma of positively charged ions and free electrons which, in conjunction with the arc, melts the metal being cut and disperses the vapours.

Different types of gas can be used depending on the results required. Hydrogen gas gives the highest temperature and a reducing atmosphere. Argon is generally used, but other gases such as nitrogen or air can also be employed.

TABLE X. SEGMENTING TECHNIQUES FOR METAL PRESSURE VESSELS, PIPES, TANKS AND MISCELLANEOUS COMPONENTS

Technique/ equipment	Pressure vessels, thick plates, etc.		Pipes	Tanks	Miscellaneous: bar stock, angle iron, I-beams, channel iron	General data					
	Metal type[a]	Thickness (cm)				Cutting environment[b]	Feasibility of remote operation	Cost	Cutting rate	Limitations	Remarks
Arc saw cutting	(R)[c] CS, SS, Al (R) Zr (R) In	≤100 ≤30 ≤10	All metals; diameter limited to 0.33 saw blade diameter	As for pipes	As for pipes	A, W A, W A, W	Excellent	High	High	Space needed for blade diameter	Some development required for large scale operation
Oxygen burning	(R) CS (R) CS	≤100 >100	All diameters	Only CS	Any shape	A, W A, W	Excellent	Low	High	Good only for CS	Equipment and operators readily available
Plasma arc torch	(R) CS, SS, Al (R) CS, SS, Al, Zr, In	≤17 ≤10	All diameters	All diameters	Any shape; cutter to follow shape of component	A A, W A, W	Excellent	High	High	Space needed behind workpiece to accept flow of molten metal	
Thermite reaction lance	(F)[d] CS, SS, Al (F) CS (F) Zr	≤100 >100 ≤30	All metals, thickness >7 cm	All diameters	For gross cutting, especially of reinforcing bars	A, W A, W A, W	Poor	Low	High	Can only be hand held; extensive ventilation required	
Explosive cutting	(F) CS, SS, Al, Zr, In	≤15	All metals, diameter ≤2 m	Under development		A	Good	Medium	High		Used if other methods not practical (concrete beams)
Laser cutting Zr, In	(F) CS, SS, Al,	≤11				A	Good high	Very	Medium equipment	Relatively large	Under development
Mechanical nibbler	(R) CS, SS, Al, Zr, In	≤0.6				A, W	Good	Low	Medium		
Shears	(R) All metals	≤0.6				A, W	Good	Low	Medium		

Circular cutting machines	(R) All metals	<7	All metals; diameter ≤6 m	As for pipes	Not applicable	A, W	Good	Low	Medium	Items must have circular cross-sections	Large circular cutting machines being developed
Abrasive cutters	(F) All metals	<15	All diameters	All diameters	Any shape	A, W	Good	Low	Medium	Produces sparks and dust	
Hacksaw, guillotine saw	(R) All metals		Diameter limited by length of blade	Not practical	Any shape	A, W	Good	Low	Medium		
Abrasive water jet	(F) All metals		All diameters	All diameters	Any shape	A	Good	Medium	Medium	Short nozzle life	Under development
Fissuration cutting	(F) All metals	<10	All diameters	Under development	Any shape	A, W	Good	Low	Medium		Under development

[a] CS: carbon steel; SS: stainless steel; Al: aluminium alloys; Zr: zirconium alloys; In: Inconel.
[b] A: air; W: water.
[c] (R): recommended field of application.
[d] (F): feasible field of application.

Even higher temperatures can be achieved by directing a radial jet of water onto the plasma stream near the torch nozzle which further constricts the plasma stream and creates higher current densities. This results in reduced smoke, a higher quality cut surface and a narrower kerf.

This process produces large quantities of aerosol, smoke and dust with a large number of particles of less than 3 µm in size. If the process is carried out in air, the working place must be well ventilated and exhaust air filtered using prefilters to prevent the rapid ‘blinding’of the HEPA filters. During underwater cutting, the water must be filtered to keep it clear for viewing.

II.2.3. Thermite reaction lance

The thermite reaction lance described in Section II.1.5 can also be used to cut through most kinds of metal.

II.2.4. Explosive cutting

The explosive cutting process is the same as that described in Section II.1.11 and is only used in special cases. Only a few grams of explosive located every 10 cm are required to cut 6 mm thick steel. Explosive cutting can be used to cut pipes from the outside as well as from the inside using shaped charges.

II.2.5. Laser cutting

The process for the laser cutting of metals is the same as that described in Section II.1.12.

II.2.6. Mechanical cutting devices

II.2.6.1. Mechanical nibbler

A mechanical nibbler is a punch and die cutting tool which can be used to cut plates and tanks. Normally, the punch reciprocates rapidly against the die, ‘nibbling’ a small amount of the thin sheet metal workpiece with each stroke. The nibbler can be operated electrically or pneumatically for dry or underwater applications. The machines are light and can be remotely operated. Typical heavy duty nibblers can cut 5 mm thick stainless steel at a speed of 1 m/min. This process could give rise to small amounts of aerosols coming from loose contamination. The debris can easily be picked up by vacuum cleaning.

II.2.6.2. Shears

A shear is a two blade or two cutter tool that operates on the same principle as a conventional pair of scissors. It can be used to cut sheet metal, pipes and small rods and bars. Shears actuated by high hydraulic pressure have been developed which can cut piping of up to 300 mm diameter and 5 mm wall thickness. These tools are light enough to be handled remotely. Shears only give rise to large debris, with no dust or smoke, and only very small quantities of aerosols.

II.2.6.3. Circular cutting machines

Circular cutting machines are used to cut cylindrical components. They are usually self-propelled saws, blades or grinders that cut as they move on a track around the outside of a cylindrical workpiece. The machine may be powered pneumatically, hydraulically or electrically and is held to the outside of the pipe, tank or component by a guide chain that is sized to fit the outside diameter. Small machines are relatively inexpensive and easy to use.

The number of hardened steel cutter blades may be varied in order to change the thickness of the cut. The maximum cutting depth in carbon steel is limited to 2 cm per pass. Wall thicknesses of up to 7 cm may be cut using multiple passes on pipes up to 6 m in diameter.

Contamination control is normally maintained by vacuuming the chips from the cut and by collecting, filtering and recycling lubricants if they are used.

A plumber’s pipe cutter is another inexpensive type of circular cutting machine. It consists of three or four wheels, including a hardened cutting wheel mounted on a frame. The cutter is slipped over the pipe, clamped and rotated around the pipe until the cut is complete. No cutting wastes are produced. Although this machine is normally operated manually, it could be operated remotely.

II.2.7. Abrasive cutters

An abrasive cutter is an electrically, hydraulically or pneumatically powered wheel formed of resin bonded particles of aluminium oxide or silicon carbide. Such cutters can be used to segment all types of component. Usually, the wheel is reinforced with fibreglass matting for strength. It cuts through the workpiece by grinding the metal away, leaving a clear kerf. Since the cutting process generates a continuous stream of sparks, it is unsuitable for use near combustible materials.

Abrasive cutters can be used as portable machines or as part of a stationary workstation. Hand-held abrasive cutters are relatively slow, demand continuous operator attention and are tiring to the operator. Contamination control is a significant problem since the swarf comes off as very small particles. In order to limit the spread of contamination, cutters may be fitted with a swarf containment system and use water lubricants. In most cases, the operator would have to work within a contamination control envelope and wear protective clothing and respiratory protection apparatus.

In a stationary set-up, more powerful machines can be used to cut sections of pipe or solid rod into convenient lengths. Units are available that can cut 15 cm diameter solid stock in two minutes and at a much lower cost than with a hacksaw employing a similar cutting speed. Contamination control is much easier with a properly designed stationary unit than with hand-held cutters.

II.2.8. Hacksaw and guillotine saw

Hacksaws and guillotine saws are relatively inexpensive and common industrial tools used to cut all types of metal pieces with a hardened steel reciprocating saw blade. Since these saws use mechanical methods to cut the metal, fire hazards are reduced and contamination control is easier. These tools have low operating costs and high cutting speeds and can be used as either portable or stationary units. Some types can also be operated remotely.

Portable power hacksaws weighing about 6 kg can be clamped with a chain to a pipe in such a position that the blade contacts the underside of the pipe. This allows the weight of the motor to advance the blade into the workpiece about the chain mounted pivot point. The operator can increase the feed pressure manually by applying downward force on the motor body or by suspending weights from the body. In general, blade lubrication is not necessary. Portable hacksaws can cut piping 20 cm in diameter and 0.9 cm thick in about eight minutes.

A portable guillotine saw is also clamped by chain to a pipe but in this case the saw and motor are mounted above the cut, allowing the weight of the unit to advance the saw into the workpiece. In general, blade lubrication is not necessary. Air or electric motors may be used for both types of portable saw.

The set-up time for both types of portable saw is relatively short. Also, once in place, the saws operate without needing any further action to be taken on the part of the operator, thus reducing occupational exposures.

Large stationary hacksaws weighing up to 5 Mg can be effectively used in decommissioning since they can cut metal as thick as 60 cm. Cutting rates of about 100 cm^2/min make these machines very suitable for segmenting large quantities of material. Locating a facility of this type near decommissioning activities will reduce the costs and exposures associated with handling long sections of pipe. The cost–benefit analysis of such a stationary facility will depend on factors such as the cost of equipment and labour, the amount of material to be cut, the activity levels on the pieces to be cut and the man-sievert worth.

II.2.9. Abrasive water jet

The abrasive water jet technique described in Section II.1.13 can also be used to cut metals.

II.2.10. Fissuration cutting

Fissuration cutting is being developed for cutting metal components without producing secondary waste [102]. Pieces up to 10 cm thick have been cut using this technique.

In this method, the addition of molten material produces a controlled intergranular fissure in the heated area of the piece being cut, giving rise to the formation of brittle components. Tension stress created by the thermal gradient induced during local heating causes brittle failure of the component. The heating device used for this technique can be adapted for remote handling.

Owing to the relatively low temperature of this process (800°C) and the intergranular nature of the failure, the production of aerosols and smoke is very low.

II.3. PRECAUTIONS REQUIRED WHEN APPLYING CUTTING TECHNIQUES

The cutting of concrete and metallic components can produce debris, dust, smoke and aerosols whose composition and particle size depend on the type of process employed. In addition to the surface contamination released during cutting, beta emitting radionuclides from the interior of activated metals can be released as a result of cutting the material.

The workers involved in these operations must be protected against the inhalation of such products. When the parts to be cut are contaminated, the environment must also be protected from the spread of contamination by employment of a suitable containment and ventilation system. Even if the materials are not contaminated, a ventilation system can be useful when cutting indoors.

Typically, mechanical cutting processes, with the exception of abrasive cutting, produce large sized debris and very few aerosols. Filtering or collecting the debris can be done using ordinary HEPA filters and vacuum cleaning. Thermal processes, on the contrary, produce fine debris and large amounts of hot particles, dust and aerosols. The ventilation system must pick these up close to the source. In order to prevent the filters from becoming very quickly saturated, prefiltering devices must be installed. Also, the ventilation system must be designed to allow easy replacement of filters and be shielded against radiation derived from the buildup of active particles in the filters. Research in this field is aimed at characterizing both the size of the particles and the aerosols for each process in order that the most suitable prefiltering system can be designed [103].

It has been demonstrated that underwater cutting reduces by at least a hundredfold the dust and aerosol emissions resulting from cutting in air [103]. However, it is necessary to pump and filter the water in order keep it clean, thereby permitting observation of the ongoing work and preventing upwelling, which would bring the active particles to the surface and cause worker exposure.

For remote handling, cutting tools must be modified or designed to allow easy decontamination and maintenance and to facilitate remote replacement of worn components. In certain cases, it may be possible to install protective devices such as sleeves to protect cutting machines and manipulator arms.

Appendix III

MEASUREMENT TECHNIQUES FOR DECOMMISSIONING

Waste minimization of materials resulting from decommissioning operations requires characterization and segregation. Characterization develops a complete understanding of the physical, chemical and radiological characteristics of the materials, which allows them to be segregated and sent for selected processing and/or disposition.

Characterization begins with the acquisition of knowledge of the radiological state of an installation, both before and during dismantling. A number of techniques are available to measure the radioactivity of materials generated in decommissioning operations [21]. In general, these techniques can be organized into three categories: direct measurement, indirect measurement and measurement by sampling.

Three kinds of measurement can be carried out: dose rate measurement, total radioactivity measurement and spectrometry. The choice of the appropriate dosimeters, detectors or spectrometers depends on the type, energy and level of radiation.

For the purpose of decommissioning, two categories of techniques and instrumentation are important:

- Techniques for the initial characterization of equipment and facilities to be decontaminated and decommissioned, including characterization of the associated radioactive waste;
- Techniques for measuring very low levels of radioactivity after decontamination, in order to prove compliance with the requirements for conditional or unconditional release.

The following information presented on the different measuring techniques is related to, and important for, the management of materials arising during D&D. The basic principles of the techniques applied for measuring and quantifying the different radiation types are presented and discussed in order to provide a basis for deciding which technique should be selected as the means of achieving the identified goal. Particular commercial instruments based on the specific techniques are not discussed because of the wide variety available. The selection of any particular instrument may be site, project or task specific. However, general information presented may facilitate the selection process, including:

- A description of the basic techniques and characteristics of the detector types available for the measurements that are needed.

- Consideration of the factors, parameters and utilization conditions relevant to the selection of instrumentation types for the measurements that are needed.
- Additional information on some specialized equipment where this is directly relevant to the waste minimization strategy described in the report.
- Descriptions of relevant measurement techniques needed to meet characterization requirements for the decommissioning and waste management processes. Other techniques used in the early stages of characterization, such as neutron measurements, are noted but not described.
- Information on the essential supporting laboratory measurement requirements, covering sampling strategies, equipment and procedures which complement the direct measurement systems.
- An overview of quality assurance aspects, including documentary records forming part of the total system requirements.

Table XI provides a ready reference on the applicability of the different techniques described, as well as noting some relevant experience gained in their use.

III.1. AVAILABILITY OF INSTRUMENTATION AND PROCEDURES

III.1.1. Radiation detection devices

Radiation detection devices may be grouped into four categories: gas filled ionization detectors, scintillation detectors, semiconductor devices and solid state detectors [29].

III.1.1.1. Gas filled radiation detectors

The three main types of this class of detector are the ionization chamber, proportional counter and Geiger–Müller (GM) counter [29]. The names of these detectors are derived from the regions of the ionization curve over which they operate. The most widely used geometry comprises a sealed outer cylindrical chamber which is filled with counting gas and which acts as the cathode; a coaxial fine wire serving as the anode.

In the ionization chamber region, the total charge collected is equal to the total charge carried by the ion pairs produced. Ionization chamber instruments used for survey purposes have wide measurement ranges and, therefore, have a great number of applications.

Proportional counters operate in a higher voltage region where the quantity of charge collected for a given amount of radiation is larger than, but proportional to, the original amount of ionization. They therefore offer the possibility of working as spectrometric devices. Proportional counters have a very short dead time (of the order of microseconds) and therefore very high counting rates are possible. They are able to distinguish between alpha and beta particles and between high and low energy beta particles. Proportional counters are therefore often used in contamination monitors and laboratory equipment for detecting simultaneous alpha and beta contamination. Usually, this type of instrument has a sealed volume filled with gas, or it can be of the gas flow probe type where the gas is continuously replaced.

The GM detector operates without any spectrometric capability in the GM region, where there is saturated charge amplification and where little, if any, external amplification is required. The pulse height is independent of the number of ions created by the primary ionization. GM detectors are used for particle detection but are unable to measure the energy of the particles themselves. With few exceptions, they measure only beta and gamma radiation. GM counters have an efficiency of almost 100% for charged particles that penetrate the sensitive volume. The total efficiency of beta radiation detection is reduced by the absorption of some of the beta particles in the detector walls. In the case of gamma rays, efficiency depends on particle interaction with the walls and is very poor, about 1% for 1 MeV photons.

GM counters have a relatively long dead time (some 100 microseconds), which limits high counting rate measurements. Many contamination monitors are equipped with GM tubes which have end windows made of a thin metal foil that allows even low energy beta particles to be monitored.

III.1.1.2. Scintillation detectors

A scintillator is a crystal, glass, liquid organic or plastic organic phosphor which will emit a light pulse, the intensity of which is proportional to the energy of the individual alpha particle, beta particle or photon responsible for the pulse. Scintillation counters are spectrometers which can be used to determine both the energy and the number of excited particles and photons [29].

The detector device consists of a scintillator, optically coupled to a photomultiplier tube, which converts the light into electrical pulses which are amplified and registered. In survey instruments, only the total number of pulses is indicated. In a spectrometer, the amplified pulse heights are analysed by a single or multichannel analyser to give the energy spectrum. Some characteristics of the different types of detector and the practical experience gained with regard to their measurement capabilities are given in Table XII.

The main advantages of scintillation counting are:

- High efficiency, since the ionizing medium has a relatively high density and large masses of phosphor can be used if necessary;

TABLE XI. APPLICABILITY OF RADIOLOGICAL MEASUREMENT TECHNIQUES IN DECOMMISSIONING

Measurement technique	Applicability			Application	Examples
	In situ	On-site	Laboratory		
Direct measurements:					
• Gas filled detectors	×	×		Surface measurements (alpha, beta, gamma)	Release of metal components and buildings
• Scintillation detectors	×	×		Release measurements in facilities	Release of thin plates, insulation, cables, etc., packaged in boxes, drums, etc.
• Semiconductor detectors	×	×	×	In situ gamma scanning	Release of buildings (replacement or reduction of hand monitor measurements) and ‘green’areas (classified), soils, etc.
• Solid state detectors	×	×		Surface measurements (alpha emitters)	Release of metal components, buildings
Indirect measurements:					
• Sampling	×			Radiological characterization of systems and buildings	Radiological characterization of vessels, pipes, floors, walls, soils, etc.
• Alpha measurements	×	×		Surveillance of working areas	Measurements from ducts and collection filters
• Beta–alpha measurements	×	×		Surveillance of working areas	Determination of the relevant radionuclides in order to define a release nuclide vector
					Release measurement of green areas, soils, etc.

• Gamma spectrometry			×	Measurement of samples	Determination of the relevant radionuclides in order to define a release nuclide vector Release measurement of green areas, soils, etc.
• Alpha spectrometry			×	Measurement of samples	Determination of the relevant radionuclides in order to define a release nuclide vector Release measurement of green areas, soils, etc.
• Radiochemical analysis			×	Measurement of samples	Determination of the relevant radionuclides in order to define a release nuclide vector Release measurement of green areas, soils, etc.
• Smear tests	×	×	×	Prevention of contamination spread	Recontamination control programme

- High precision and counting rates, which are possible since the light pulses have a very short duration (of the order of 1 μsec).

A common crystal scintillator is thallium activated sodium iodide, NaI(Tl), which is used in gamma survey instruments and also in certain spectrometers. The detector has a short time constant which allows the instrument to measure a wide range of activities from natural background intensities upwards. The size of the crystal is important; too large a crystal increases the background, whereas too small a crystal reduces counting efficiency and decreases spectrometric capability. Typically, the crystal diameter in a probe is about 2 cm with thicknesses of about 0.3 cm for lower energy gamma radiation and 2 cm for higher energy.

Anthracene is an organic crystal scintillator which is used in beta detectors and which is suitable for low energy beta emitters such as ^{14}C as well as high energy beta emitters. Anthracene crystals of about 20 cm^2 are available, as well as anthracene coated on Perspex detectors with sensitive areas of up to 100 cm^2.

Plastic scintillators are very versatile and come in a wide variety of shapes ranging from sheets up to 3.5 m long to cylinders over 1 m in diameter. They have high count rate performance and good mechanical stability, and are relatively low cost and easy to handle.

Scintillation detectors for alpha particles are usually made of ZnS(Ag) luminescent powder coatings that are fixed on a transparent disc such as Plexiglas. The sensitive areas of these probes are typically 50 cm^2 and 100 cm^2. The scintillator thickness should correspond to the range (path length) of alpha particles in order that the beta and gamma sensitivities are very low. As an example, the optimum thickness for 5 MeV alpha particles results in a layer with a total weight of 9 mg/cm^2. The ZnS(Ag) detectors have a very low background and a wide measurement range and are used in portable contamination monitors and also in laboratory equipment to measure alpha activity on solid samples, wipe samples, etc.

A popular combination consists of a plastic scintillator disc or sheet with a thin coating of ZnS(Ag), a so-called ‘dual phosphor’, for the simultaneous counting of alpha and beta particles. Pulse height selection is used to discriminate between the particles.

Liquid scintillators are only used in laboratory instruments, mainly for the measurement of low energy beta emitters such as ^{14}C and ^{3}H. The material to be measured is added in suitable solution form to the liquid scintillator. Liquid scintillation analysers have a low background.

III.1.1.3. Semiconductor devices

Semiconductor devices use very pure single crystals of semiconductor material to measure the ionization charge [29]. In these crystals, electron hole pairs created by ionization are mobile and can be collected under the influence of an applied electric field before they can recombine. Unlike positive ions in gas ionization chambers, the positive electron holes are highly mobile and both positive and negative charges can be gathered quickly. The short pulse signal is proportional to the energy absorbed, giving these devices an excellent spectrometric capability.

The most common crystal materials used in these devices are silicon, which may be used at normal ambient temperature, and germanium which must normally be cooled to the temperature of liquid nitrogen in order to reduce thermally generated conduction currents to acceptable levels.

Semiconductor devices, as with other solid state detectors, absorb much more incident radiation than gas detectors because of their higher density. In addition, the small ionization energy or band gap in semiconductors leads to the production of many charge carriers with low statistical uncertainty. As a result, the efficiency in the identification of radionuclides and the accuracy in measuring gamma and X ray radiations have been significantly improved. Thus, these devices have the ability to identify and measure, separately, radiations with small energy differences.

Germanium used as the basic material in gamma ray spectrometers can either be substituted by lithium (Ge(Li)) or by a high purity form (HPGe). They are available as small, thin planar detectors for taking low energy measurements or as large coaxial detectors with volumes in excess of 200 cm^3. The Ge detectors are less efficient than NaI(Tl) detectors of the same size.

As an illustration of the excellent energy resolution of semiconductor devices, the full width at half maximum (FWHM) energy resolution of Ge detectors is less than 0.2% for ^{137}Cs radiation compared with 7% for NaI(Tl) detectors.

Silicon semiconductors are used as detectors in alpha particle spectrometers. The sensitive volume is matched to the range of the alpha particle in order to minimize background interference and the silicon must, therefore, be very thin (typically less than 100 µm). The entrance window is typically 1–10 cm^2 with an energy resolution for a 5 MeV alpha particle of about 20 keV (FWHM). With a low background, this results in a very low limit for the detection of specific radionuclides.

III.1.1.4. Solid state detectors

Chemical or physicochemical processes may be used to detect radiation by integrating the phenomena over the exposure time. The four main classes of detector are: photographic emulsion, track etch detectors, absolute chemical dosimeters and solid detectors based on thermoluminescence, radiophotoluminescence or stimulated exoelectron emission. Two of these detectors (thermoluminescent dosimeters [104] and track etch detectors) may be used for taking dose measurements or for radionuclide characterization in decommissioning.

TABLE XII. CHARACTERISTICS OF DIFFERENT TYPES OF HAND-HELD DETECTOR AND MEASUREMENT CAPABILITY EXPERIENCED[a]

Type of detector	Nuclide (radiation) measurement efficiency (%) (4 π)	Detectable activity from experience (Bq/cm^2)
Bell type organic GM	C-14 (beta) 20%	0.24
Cylindrical halogen GM Ø = 35 mm, L = 190 mm	Sr-90 + Y-90 (beta) 8%	0.33
Air filled counter	U-235 (alpha) 13%	0.03
	Pu-239 (alpha) 9%	0.05
Gas flow counter	Am-241 (alpha) (HV = 750 V) 21%	0.04
	Tl-204 (beta) (HV = 1700 V) 31%	0.04
Fluorescent plastic scintillator 70 mm × 3 mm	Sr-90 + Y-90 (beta) 14%	0.12
Fluorescent plastic scintillator 40 mm × 40 mm	Co-60 (gamma) 5%	2.6
NaI(Tl) crystal 32 mm × 25 mm	Co-60 (gamma) 5%	10.0
NaI(Tl) crystal 32 mm × 5 mm	Fe-55, Pu-238, Pu-239 (X) 25%	1.0

[a] Demonstrating residual contamination on surfaces that have been decontaminated requires a minimum measurement time of 6–10 seconds per 50 cm^2.

(a) Radiothermoluminescent (RTL) dosimeters

Some previously irradiated crystals produce, when heated, a light emission which is proportional to the absorbed dose [27]. The thermoluminescence curve (glow curve), which gives the light flux as a function of temperature, shows several peaks, the locations of which depend on the substance. In order to avoid the loss of dosimetric information (or fading), only the higher temperature peaks are used for dosimetry purposes.

The RTL materials that are mostly used are calcium sulphate activated with dysprosium ($CaSO_4$, Dy), which is by far the most sensitive, lithium fluoride (LiF), which is widely used, and lithium tetraborate activated with copper ($Li_2B_4O_7$, Cu). These are used as a powder or as sintered pellets in a waterproof and opaque packaging. The response to dose is linear over a large range from the reading threshold up to 100 Gy or more, depending on the specific dosimeter material used. The lower limits for measurable cumulative doses are:

• $CaSO_4$, Dy:	$1–5 \times 10^{-5}$ Gy ± 30%
• LiF:	$1–2.5 \times 10^{-4}$ Gy ± 30%
• $Li_2B_4O_7$, Cu:	$1–2.5 \times 10^{-4}$ Gy ± 15%.

The stability of the response at normal temperatures is good. For a delayed reading taken 3–6 months after the irradiation, the fading does not exceed 10% of the result.

When this kind of dosimeter is used for taking decommissioning measurements, the process must be automated, i.e. delivery and withdrawal of the dosimeters, reading (including dose or activity results), identification, localization map drawing.

(b) Track etch detectors for alpha particle measurement

The passage of alpha particles through polymers creates irreversible damage along their paths which can be increased by etching [27]. This is only possible if the energy loss per unit length is higher than a threshold value specific for the material and etching conditions. With cellulose nitrate, alpha particles with energies between a few hundred keV and four MeV can be detected. These detectors are insensitive to both beta and gamma radiations and to light and are only slightly affected by dampness. The detection material is manufactured on an industrial scale and detectors and etching solutions are inexpensive. The measurement consists of numbering the tracks and this can be carried out by:

- Microscope counting with an image analyser,
- Electrical discharge,

- Electrochemical etching which leads to larger holes and allows counting by light scanning,
- Densitometry in which light reflection or diffusion are used for high track density.

Depending on the counting method employed, activities ranging from 3×10^{-2} Bq/cm^2 up to 10^6 Bq/cm^2 can be measured with an exposure duration of 10 minutes.

These detectors are able to render visible alpha particles' paths through a thin polymer film. This property can provide information on the spatial distribution of alpha emitters on a sample.

III.1.1.5. Selection of instrumentation

The selection of suitable instrumentation must take into account many factors, parameters and utilization conditions:

- Dose rate or radioactivity measurements.
- Alpha, beta or gamma emissions.
- Counting or spectrometry.
- Expected accuracy.
- Measured dose or radioactivity level compatible with the minimum detection level of the device and its maximum range.
- Variations in radioactivity criteria, e.g. total radioactivity per package (Bq) or in concentration unit (Bq/g) or in surface radioactivity unit (Bq/cm^2). These criteria may apply to a single radionuclide (e.g. ^{60}Co or ^{137}Cs) or to a class of radionuclide (e.g. alpha emitters) or to the total radioactivity of the material.
- In situ or laboratory measurements.

Theoretically, the instrumentation must be capable of measuring all isotopes relevant to decommissioning. In practice, two kinds of measurement are taken: in situ measurement of dose rate and gross counting in order to detect high energy emitters, and laboratory analysis and spectrometry conducted in order to determine the radionuclide composition. By checking the constancy of the radionuclide spectrum, it is then possible to evaluate the entire spectrum from gross counting. For low energy beta and X ray emitters, such as ^{63}Ni and ^{3}H, there are no portable instruments able to measure the mass specific activity. For these isotopes, laboratory analysis is required.

Instruments have to be calibrated in order to accommodate a wide range of sample geometries, measured both in the laboratory and in situ. In selecting suitable instrumentation, it is necessary to define the minimum detectable activity (MDA) for a particular instrument and to compare the MDA with the required criteria. Choosing instrumentation with a low MDA is an important factor in the selection process [105].

The MDA corresponds to the measured value for which the relative uncertainty equals ±100% at the 95% probability level. If the number of pulses is larger than ten and if the background and the signal are measured during the same duration (t), then the MDA is equal to 2.8 $\sqrt{B/t}$, where B is the background counting rate. If R is the detector efficiency, then the activity threshold is expressed as:

$$\mathrm{MDA(Bq)} = \frac{2.8}{R}\sqrt{\frac{B}{t}}$$

In some cases, the MDA is given for a probability level other than 95%.

The MDA levels will be significantly lower than those measured during normal operation and the threshold levels corresponding to release criteria are generally very small. Measurements designed to validate the required MDA criteria should be undertaken in an area where the background level is sufficiently low. This concept means that it may be necessary to create a restricted area in the plant with a low background.

Measurement techniques may include high resolution alpha and gamma spectrometry and also radiochemical analysis to separate elements for the measurement of low energy beta and X rays.

(a) Measurement of alpha emitters

Gross alpha measurements taken on samples can be made with alpha scintillation detectors, proportional counters or semiconductor detectors. These instruments may be equally capable of detecting any activity present in the sample and therefore the choice between them may be more a question of which type is available.

Since the alpha particle range is short, the samples should be very thin in order to keep alpha particle self-absorption as low as possible. For liquid samples, this will be accomplished simply by evaporating the liquid directly onto the measurement plate or by electrodeposition, in order to concentrate the radioactivity sufficiently and thereby exceed the detection limit of the instrument.

Thin solid samples are difficult to prepare. However, a thick but homogeneous sample has a well-defined measurement geometry that will be useful. If the sample has a thickness greater than the alpha particle range, the effective sample is defined by that range. Measurement of such a sample will always yield the same sample mass. The counting efficiency dependence on the energy of the average particle is not very strong.

It is impractical to carry out direct alpha measurements on rough or uneven surfaces such as debris or soil since it is difficult to place the detector near to the source. The detector windows are very thin (about 0.7 mg/cm^2) and can be easily damaged.

Alpha spectrometry is carried out in the laboratory by using grid ionization chambers filled with argon and pressurized to 0.15–0.2 MPa. The counting geometry is 2π. Between 4 and 6 MeV, the detection threshold is very low and the background is less than two pulses per hour. Semiconductors with silicon surface barriers are also used for alpha spectrometry. The crystal thickness (100–200 μm) reduces interference with the gamma and beta radiations. The deposited layer on the detector is extremely fragile and must be protected against the effects of friction. This detector is used at ambient temperature, although the background noise can be reduced by cooling the detector. Measurements are carried out under vacuum conditions.

The efficiency calibration of alpha monitors is carried out by means of specially prepared standard reference sources containing natural uranium or ^{241}Am.

Owing to the very short range of alpha particles, alpha emitters can only be measured for their alpha emission if they occur as accessible surface contamination. When the radionuclides are inside the materials (e.g. the inner parts of pipes or apparatus, waste in drums), it is sometimes possible to detect X or gamma rays associated with the alpha emission, and to detect the neutrons from fissile elements.

Passive methods (high resolution gamma spectrometry and neutron counting) are based on the measurement of spontaneous gamma rays and neutrons emitted by the fissile nucleus. Active neutron interrogation techniques are based on the detection of delayed gamma rays and neutrons emitted when fission events are induced in the fissile material by an auxiliary neutron source. This can be a ^{252}Cf source or a neutron generator.

Spontaneous or induced neutrons are measured using ^{3}He detectors and gamma rays are measured using scintillators. In some cases, gamma spectrometry is performed in order to measure gamma emitters in the waste. The sensitivity depends on the drum volume, the matrix nature and the measuring time.

(b) Measurement of beta emitters

Beta radiation in solid and evaporated samples on plates is easily measured using GM detectors, proportional counters or organic scintillators. Measurements are less sensitive to sample thickness than are alpha measurements. Nevertheless, calibration of the detectors has to be made with standard reference sources such as ^{204}Tl or ^{90}Sr which have a geometry similar to that of the sample. Attention has to be paid to the choice of detector and its probe window in the case of low energy beta emitters. If only high energy beta emitters are of interest, covering the sample with an absorber can mask the low energy beta emissions.

Since beta detectors are also sensitive to background and gamma radiations, it is normal practice to provide a substantial lead shield around both detector and sample. A special ‘anticoincidence’ technique may be used to obtain a low background for measuring low level samples in the laboratory.

The measurement of very low energy beta emitters may require special calibration with reference solutions containing the radionuclide in question. On the other hand, there may be situations where only the high energy beta emitters are of interest. Covering the sample with an absorber will, in this case, discriminate against low energy beta emissions which are very sensitive to absorption within the sample.

Liquid scintillation analysis is a very good alternative for liquid samples containing beta emitters. If the sample contains low energy beta emitters such as ^{3}H, ^{14}C or ^{63}Ni, the liquid scintillation measurement technique will be the easiest and most viable method to use. In this case, a chemical and/or a physical extraction of the radionuclide must be achieved in order to obtain a solution. The solution is mixed with the organic liquid scintillator which will result in a high counting efficiency. Modern liquid scintillators have a low background which makes this technique a valuable alternative to other beta measurement techniques.

In liquid scintillators, some smear papers can become transparent to scintillation light and this provides a simple method for measuring non-fixed contamination.

(c) Measurement of gamma emitters

Gamma radiation is usually measured with scintillation devices using a NaI(Tl) scintillator. Rate meters with a simple channel pulse height analysis function are available. The first step taken to improve the measuring instrumentation is the incorporation of spectrometry technology for the identification of different radionuclides and for the quantitative measurement of their individual concentrations.

A scintillation crystal used as a radiation detector is relatively inexpensive and provides good results for the identification of specific gamma emitters. The NaI(Tl) scintillation detectors described in Section III.1.1.2 have good efficiencies but poor resolution, for example, only 10% of the measured radiation energy (e.g. 60 keV for ^{137}Cs and 130 keV for ^{60}Co).

Moreover, it is impossible to identify radionuclides with closely separated energy rays. In this situation, the background activity is important.

For gamma spectrometry, the most sophisticated instrumentation uses a high resolution semiconductor device. The usual gamma ray spectrometer has a Ge detector connected to a computer based multichannel analyser which both collects and analyses the data. The high energy resolution of Ge detectors makes them superior to other detectors for gamma ray spectrometry. Automatic peak finding software is used to locate the photopeaks, identify them and calculate the proportion of the corresponding radionuclide present in the sample.

This instrumentation is substantially more expensive and complex than the simpler NaI(Tl) scintillator spectrometer. A Ge device requires relatively sophisticated electronics, including multichannel pulse height analysers. In addition, the apparatus operates at very low temperatures and requires a constant supply of liquid nitrogen (–196°C) to act as a coolant. At such temperatures, the background noise is very low. Recently, HPGe detectors have been improved. The detector, as well as its preamplifier, must also be cooled in order to reduce background noise. Recent developments include the replacement of liquid nitrogen by thermoelectric or thermomechanical cooling.

III.1.2. Special equipment

III.1.2.1. Soil and floor measurements

This category of portable instrument includes devices too large or too heavy to be carried by hand but normally not requiring self-contained motorized power. Existing wheeled ground monitors are supplied with large window gas flow counters. They are also provided with a switch for beta–gamma or alpha measurements on even ground, e.g. roads, car parks.

As an example, a road contamination monitor has been developed which consists of a large area gas flow proportional counter mounted on a ‘tractor’. The contamination monitor measures alpha and beta–gamma contamination simultaneously over a large area. The unit has a built-in beta–gamma background compensation function and separate visible and audible alarms for the alpha and beta–gamma channels. The large area gas flow proportional counters (700 mm × 850 mm) are filled with argon–methane [21]. The detector’s position can be adjusted from 4 mm to 30 mm above the floor. Detection characteristics are as follows:

- Efficiency of large area detectors in contact:
  beta ^{147}Pm > 30%,
  beta ^{204}Tl > 33%,
  alpha ^{241}Am ≅ 25%.
- Beta–gamma background: 50 cps in a 0.1 μGy/h field.

In general, for this type of detector, the 2π efficiency for alpha ranges between 30% and 40%. For beta, it ranges between 10% and 70%, depending on the beta energy. The efficiency for gamma is less than 1%.

Many companies produce similar devices equipped with proportional counters, plastic scintillation detectors or NaI(Tl) crystals [29]. Recently, a method was proposed for analysing the small peaks in gamma ray spectra and one which is adapted to a moving array detector system [106, 107].

III.1.2.2. Other techniques for measurement and characterization

A knowledge of the radioactive inventory and the characterization of the facility to be decommissioned are important for decision making and planning.

Characterization may be undertaken by calculation, as in the case of the inventory of reactors which is derived from activation calculations and from the extrapolation of measurements to the entire facility. This involves neutron activation calculations applied to the core, concrete structures, steels and graphite [108–115].

In non-reactor facilities, in addition to the standard alpha, beta and gamma radiation surveys, characterization may also involve the use of gamma counters and gamma spectrometers or the use of neutron measurements for uranium and transuranics. Characterization can be used both for inventory checking before dismantling and for the subsequent monitoring of drummed dismantling waste [116–118]. During dismantling work, gamma cameras can be used to represent visually the radiation fields on TV pictures of the working areas as an aid to work planning and dose control [119, 120].

III.2. CHARACTERIZATION BY MEASUREMENT

III.2.1. Reference spectra

Contamination comprises the presence of many radionuclides and its composition varies and depends on many factors, including:

- Type of nuclear installation;
- Duration of operation and delay after shutdown;
- Incidents or accidents occurring during the operational period;
- Nature of the contaminant fluid, e.g. water, CO_2, aerosols;
- Contamination conditions, e.g. temperature, routine or accidental;
- Nature of the support, e.g. steel, concrete.

Typical radionuclide spectra may be defined for each main part or for each waste category in order that contamination may be characterized by the radioactivity of one nuclide and its associated spectrum.

This method is particularly useful when there is one main radionuclide which is easy to detect, has a rather long half-life, and which has a significant impact, either as a result of its radiotoxicity or its external exposure rate, or as a result of its importance to the considered disposal criteria [121, 122]. Owing to variation of the spectra over time, the date of their assessment is important. For example, Table XIII shows how a spectrum changes with the delay after shutdown [16]. Radionuclide compositions may also be assessed from the spectra measured on operational waste [122].

TABLE XIII. EVOLUTION OF A CONTAMINATION SPECTRUM [16]

Radionuclide	Proportion of radionuclide in the spectrum (%)		
	Delay after shutdown		
	5 y	25 y	100 y
^{55}Fe	6.6		
^{60}Co	66.0	39.1	
^{59}Ni	≅0.0	≅0.0	0.4
^{63}Ni	1.3	9.2	36.6
^{90}Sr	3.3	16.8	17.6
^{125}Sb	6.6		
^{134}Cs	2.6		
^{137}Cs	6.6	34.2	40.0
^{147}Pm	6.6		
Gross alpha	0.1	0.9	5.0

III.2.2. In situ measurements

A knowledge of the processes that give rise to contamination in the measured area, confirmed by sample analysis, generally helps in assessing the total activity from the beta and gamma measurements performed. The in situ, direct measurement of low energy beta radiation, as well as low energy X and gamma radiations, is as difficult to perform as alpha particle measurement.

In general, over limited areas, the activation or contamination corresponds to a specified mixture of radionuclides. Therefore, alpha emitters and low energy beta or gamma emitters are often associated with high beta and gamma radiations. A radiochemical or alpha spectrometric analysis carried out on a sample in a laboratory may help in defining the composition of the mixture.

III.2.2.1. Alpha, beta and gamma measurements

For in situ measurement, simple hand-held survey instruments are suitable. Depending on the radiation to be measured, these instruments use GM counters, ionization chambers, proportional counters, scintillation detectors or semiconductor detectors. The possibility of measuring low energy beta emitters and X rays depends on the thickness of the window.

As an example, an ionization chamber with a volume of 515 cm^3 can be used as a linear dosimeter which enables absorbed dose to be measured with a tissue equivalence under 7 mg/cm^2 or 300 mg/cm^2 over an energy range of 8 keV to 2 MeV. An ergonomic shape which incorporates a pistol type grip makes it easy to use and because of its excellent polar response, it allows accurate measurement of direct and scattered X and gamma radiations. The maximum sensitivity corresponds to 5×10^{-12} A/mGy/h and the response time is less than 7 s for ranges of 10 and 100 µGy/h and less than 3 s for all other dose ranges. The accuracy is better than 10% for the lowest dose range and better than 7% for higher dose ranges.

Many constructors offer multiprobe rate meters, one example of which is able to measure alpha and beta rays. This instrument is well suited for rugged multi-user operation. It can also be used with different probes. It consists of two components: the waterproof monitor, which can be decontaminated by water spraying, and the power unit which is equipped with 10 rechargeable batteries. Made of moulded plastic, it contains surface mounted electronics and a microprocessor which controls and processes the display. The monitor has either one or two probe inputs in order to receive a large range of different probes. There is also a switch which can be connected to a loudspeaker in order to deliver an audible signal proportional to the measured activity. Its characteristics are:

- Measuring range: 0–9999 c/s.
- Accuracy: ±10%.

The monitor is associated with an alpha–beta dual probe which gives the operator on-site the capability to detect alpha and/or beta contamination with only one probe. The dual probe is equipped with a double scintillator. Electronic discrimination between alpha and beta particles is dependent on the pulse width and it allows excellent separation between the two channels. A switch located on the probe allows solely alpha or beta, or both alpha and beta together to be measured.

III.2.2.2. Gamma spectrometry

In situ gamma spectrometry is useful for the identification of radioactive materials and for waste control. A wide range of spectrometry technology is available, including:

- A scintillation device that uses a NaI(Tl) scintillator and which is well adapted for routine field spectroscopy, such as the SM 512 spectrometer which comprises a portable 512 channel analyser with linear or logarithmic scales that have a zoom option. The memory can store data on up to 60 spectra. Data collection and routine analyses are possible. The device is battery powered and weighs 7 kg.

- A mobile HPGe type detector, specifically for measuring the activity deposited on the internal walls of pipes which have been used to transport radioactive fluids. It uses a combination of dB GAMMA analysis conceived software. The HPGe detector, which is especially selected for high counting rate performance, is used for high activity applications.

Optionally, a tungsten collimator may be fitted in order to minimize the effects of ambient background. The electronics and the personal computer used for acquisition display and analysis are mounted on a trolley.

Recently, a portable spectroscopy workstation has been marketed which can be easily used to carry out a laboratory grade analysis anywhere. It consists of a portable Ge detector with analysis software; data collection and routine analysis being reduced to a few keystrokes. Even personnel with no experience in spectroscopy can operate the system. This device combines electronics and a display in a simple unit and provides a computer based analysis.

III.2.3. Laboratory measurements

III.2.3.1. Sampling strategies

A technique may be classified as a sampling technique if the samples are collected at points on a sampling grid covering the site, and if the samples are subsequently analysed for their radionuclide content off-site in the laboratory [106]. Measurements conducted on the materials or liquids giving rise to the contamination can be used to assess the composition. The main problem with sampling techniques is that they assume a uniform distribution of contamination. This may not be the case and a localized source of activity could be overlooked.

The definition of a localized activity source depends on the dimensions of the sampling grid. If it were possible to collect samples at all points on a very closely spaced sampling grid and at a reasonable cost, then only sampling techniques would be needed for activity distribution assessment. Obviously, sampling of all material, if the quantities are very large, is very expensive and it is extremely unlikely that this would be justified. The percentage of material sampled and the techniques used must be considered against the costs incurred and the hazards posed.

Whilst sampling has an important role to play in activity distribution assessment, additional measurement techniques are required, such as survey techniques. A technique can be classified as a survey technique if measurements of radionuclide activity are made at a number of locations on a survey grid, covering the site, by an instrument located on the site. In principle, survey techniques can be used to detect the penetrating emissions from active material located anywhere on the site. Survey techniques can readily identify gamma emitters and are probably the best methods to use in situations where contamination is not uniform. Pure alpha and beta emitters, however, cannot always be identified by survey alone and need to be assessed by establishing a ratio of alpha/beta to gamma emitters by radiochemical analysis of representative samples. This ratio can then be applied to the gamma emitters' survey in order to infer alpha and beta activities.

In general, if contamination is thought to be uniform, then sampling is probably the best technique to use. If the contamination is not thought to be uniform and localized activity may be present, then survey methods are probably the best ones to employ.

Application of a sampling method depends on the quality of information required, on the type and degree of contamination, and on the variation of the radionuclide content as a function of depth from the surface. This is particularly relevant in the case of soil and concrete sampling. The number of samples necessary should be evaluated very carefully, preferably on a statistical basis. If there are any doubts, additional samples should be taken. In order to avoid unnecessary sampling and analysis, all data from the plant's history should be taken into account.

As many of the samples can be analytically investigated, the cost of the analysis depends on the number of samples, the radionuclides that are to be analysed and the required accuracy of the analytical procedures. Sample analysis for a single radionuclide may present little difficulty, but analysis of the same sample for a wide spectrum of radionuclides may be more difficult. In addition, some isotopes are much easier to quantify than others. Analysis may require chemical preparations that are, in general, expensive because of the trained staff and the analytical equipment necessary. The cost of instrument calibration and the cost of verifying the accuracy of the measurement results should also be evaluated [105].

III.2.3.2. Sample preparation

Collected samples must be representative of the plant or the site from which they were taken. The sample size must be based on the radioactivity concentration and on the detection limit. Several samples may be taken from the same area in order to obtain a reliable average value.

Some analyses can be performed directly on the sample material while others require preparation of the samples before the analytical procedure can be applied. Gross alpha and beta measurements, gamma spectrometric and sometimes alpha spectrometric analyses on fine granular material may be possible without any pretreatment of the samples. Liquid samples, on the other hand, may require evaporation on plates before measurement. For the analysis of transuranics and ^{90}Sr, it may be necessary to dissolve the samples and separate the radioactive elements by chemical methods.

Soil and sediment sample preparation includes removal of sticks, vegetation, rocks exceeding about 0.6 cm in diameter and foreign objects. If non-volatile elements are the only contaminants of concern, the samples can be dried. Volatile radionuclides (^{3}H, ^{99}Tc and iodides) must be separated from the sample before drying in order to avoid loss of the radionuclides of interest. Dried samples can be homogenized by the use of pestle and mortar, jaw crushers, ball mills, parallel plate grinders, blenders or a combination of these techniques, and sieved to obtain a uniform sample [123].

Liquid samples are usually prepared by filtration of the suspended material using 0.45 µm filters and acidification with nitric or hydrochloric acid to produce a pH of less than 2. This permits separate analyses of suspended and dissolved fractions to be conducted and, if preparation is not performed promptly following collection, prevents loss of dissolved radionuclides through deposition on container surfaces.

III.2.3.3. Equipment used in laboratory measurements

Samples collected during surveys undertaken for decommissioning purposes should be analysed and/or measured using appropriate equipment and procedures in a well-established laboratory. The most commonly used radiation detection measuring equipment for field survey applications has already been described in this appendix. Many of these general types of device are also used for laboratory analysis and/or measurement, but usually under more controlled conditions which allow lower detection limits to be achieved and allow greater discrimination to be made between radionuclides.

Often, laboratory methods also involve the combined use of both chemical and instrumental techniques to quantify the low levels expected to be present in samples taken from facilities being decommissioned. A knowledge of the radionuclides present, along with a knowledge of their chemical and physical forms and their relative abundance, is a prerequisite to selecting the appropriate laboratory methods. Those responsible for the survey should be aware that chemical analyses require lead times which will vary according to the nature and complexity of the request. For example, a laboratory may provide fairly quick turnaround for gamma spectrometry analysis because computer based systems are available for the interpretation of gamma spectra. On the other hand, soil samples that must be dried and homogenized require a longer turnaround time.

Analytical and/or measurement methods should be capable of measuring levels below those of the established criteria.

III.2.3.4. Specific procedures for analysis of samples — Pure beta and K capture emitters

Analysis of samples containing pure beta emitters such as ^{90}Sr, ^{90}Y, ^{99}Tc and ^{63}Ni, requires the use of wet chemistry separation followed by counting. Strontium-90 and ^{90}Y radioactivity levels can, in many cases, be inferred from the accompanying concentration of ^{137}Cs. A rough estimate of ^{90}Sr can be made from direct high energy ^{90}Y beta measurement on solid samples, and liquid scintillation measurements with pulse height discrimination are often used in the case of liquid samples. If lower detection limits are required, a radiochemical ^{90}Sr analysis may be performed.

The liquid scintillation spectrometer is a well adapted method of counting both ^{14}C and ^{3}H and the sample can be mixed directly into a scintillation mixture and counted.

Extraction of ^{55}Fe and nickel from chemical solutions has been described [124, 125]. The extraction of ^{59}Ni and ^{63}Ni can be carried out with chloroform to produce a dimethylglyoxime–nickel complex.

For alpha emitters, normally, the most popular method of laboratory analysis is to count both alpha and beta in a low background proportional counter system. Such systems have low background, relatively good detection sensitivity and the capability of processing large quantities of samples in a short time.

III.3. OTHER ASPECTS

III.3.1. Quality assurance

A definition of quality assurance (QA) is given by the American National Standards Institute (ANSI) [126]. QA comprises the planned and systematic actions necessary to provide adequate confidence that a structure, system or component will perform satisfactorily in service [127].

Any reputable organization or professional person has always practised QA to a degree, but the increasing complexities of large engineering programmes in the space and energy industries require that nothing be left to chance. The objective of a QA programme on monitoring for compliance with decommissioning criteria is to ensure confidence in the sampling, analysis, interpretation and use of data generated for this purpose, on a cost effective basis that will not compromise public health. Such QA must start with the original programme design and be maintained at each significant step up to the point where the final decision is taken on whether to release the site totally, or in part, for unrestricted or restricted use. A good proportion of common sense, aided by a manual of standard procedures and confirmed by a final survey, will meet the objective. A basic document for the nuclear industry has been published by ANSI [128] from which Table XIV has been adapted, listing 14 essential elements.

Depending on the size of the company or its nuclear operations, responsibility for the QA of company activities and products should rest on one person or office with direct access to higher management. In addition, a very large organization might have one person concerned, at least part of the time, with QA for its building, department or plant. No single set of QA requirements can be entirely applicable to every specific site or programme. The intensity of QA effort should be commensurate with the seriousness of breakdown in quality of a given step.

Many elaborate QA manuals are in use by large organizations in the nuclear industry and a QA programme leading to eventual or immediate decommissioning of a nuclear facility should be an integral part of any large programme, all of which should be compatible, for the sake of simplicity and cost effectiveness. Hence, a QA co-ordinating office or officer is required.

TABLE XIV. ESSENTIAL ELEMENTS OF A QA PROGRAMME ON MONITORING FOR COMPLIANCE WITH DECOMMISSIONING CRITERIA [127]

1	An identifiable QA programme
2	Design control of the monitoring programme
3	Instructions, procedures, drawings, computer files, etc.
4	Document control
5	Identification and control of component parts of the monitoring system[a]
6	Control of special processes (e.g. sampling procedures, statistical models)[a]
7	Control of measuring and test equipment[a]
8	Handling, storage, shipment and preservation of field samples and records[a]
9	Timeliness
10	QA records (as controls on other records)
11	Audits
12	Non-conforming items (samples, sample analyses)[a]
13	Corrective action[a]
14	Health and safety QA for decommissioning personnel

[a] Since monitoring requires hardware (analytical equipment, calibration standards, supplies, etc.), in contrast to services (computer programming, data storage and analysis routines, interpretation, etc.), the footnoted items (5, 6, 7, 8, 12 and 13) may not apply if the physical aspects of the monitoring programme are contracted out to a specialized company. The QA of these categories then becomes the primary responsibility of the contractor or subcontractor. However, the site owner is jointly responsible for QA on the final results, namely, compliance with the decommissioning criteria.

III.3.2. Recording

Documentation is a major part of any QA programme. Proper and accurate documentation forms the main basis by which a regulatory authority is able to verify the results obtained by the licensee or its contractors. Documentation should include an accurate mapping of the survey site, a material history and a record of important events (original location, decontamination, monitoring, etc.). This documentation should be retained for a defined period of time.

Instrumental measurements and analytical results should include the following information:

- Identification of the component, material or site.
- Details of the location where the sample or measurement was taken.
- Sample collection and measurement dates.
- Instrument specifications: background, efficiency, calibration, detection limit.
- Dose rate, surface contamination, mass activity results.
- Error at the required confidence limit.
- Name of surveyor, sampler, analyst, verifier.

The primary data obtained from field measurements and laboratory analyses must be interpreted, organized and summarized into a report on the work and survey operations. This secondary documentation may consist of master plans with survey readings added, as well as tables and computer files. The most usual methods are tabulation and mapping, which are undertaken in order to ensure that:

- The radiological condition of the entire site is completely and accurately depicted;
- The regulatory and surveying staffs can ascertain the radiological condition of the components without further analysis and evaluation of the data;
- The inspectors or other surveyors can readily ascertain the types and location of conditions exceeding the release criteria.

For all waste packages and materials, the following information should be reported:

- Identification;
- Mass;
- Physical and chemical characteristics;
- Radioactivity, including information on the spectrum;
- Destination and date of consignment.

Appendix IV

SUMMARY OF APPROACH TO IMPLEMENTING A WASTE MINIMIZATION STRATEGY FOR THE D&D OF NUCLEAR FACILITIES

It was indicated in Section 1 that the scope of this report includes the minimization of wastes arising from all non-fuel radioactive materials resulting from D&D activities across the entire nuclear industry. This covers materials which have been activated by neutron irradiation as well as materials contaminated as a result of contact with radioactive substances.

In Section 2, the strategic, tactical and technical issues are identified in relation to D&D, and the sources and characteristics of materials that may arise during these activities are described. In Section 3, an overview of, and general considerations on, techniques for the decontamination and dismantling of nuclear facilities are given. In Section 4, the principles of waste minimization and their implementation are described. Section 5 addresses factors that are relevant to the consideration of waste minimization options in decommissioning, as well as their implications for achieving the objective of recycle or release of the materials from decommissioning. Taking into account the strategic, technical, political, regulatory, economic and other constraining factors identified in the previous sections, Section 6 describes possible future trends in materials selection, decontamination and dismantling methods, and regulatory approaches taken in support of waste minimization. In addition, Appendices I, II and III include technical information on the decontamination, dismantling and radioactive characterization of materials arising from decommissioning operations.

In Section 1, it was also stressed that the aim of this report is to aid, rather than be prescriptive to, the decision making process for the incorporation of waste minimization as an inherent part of a total decommissioning strategy. Therefore, in this appendix, a summary of the approach to implementing a waste minimization strategy for the D&D of nuclear facilities is given, based on considerations throughout the full life-cycle of the facilities, including waste minimization during:

- Design of installations (Fig. 4),
- Construction of installations (Fig. 5),
- Operation of installations (Fig. 6),
- Post-operation and decommissioning of installations (Fig. 7).

Detailed information about the terms ‘prevention’, ‘containment’, ‘reutilization’ and ‘consolidation’ is given in Section 4, which addresses fundamental principles of waste minimization.

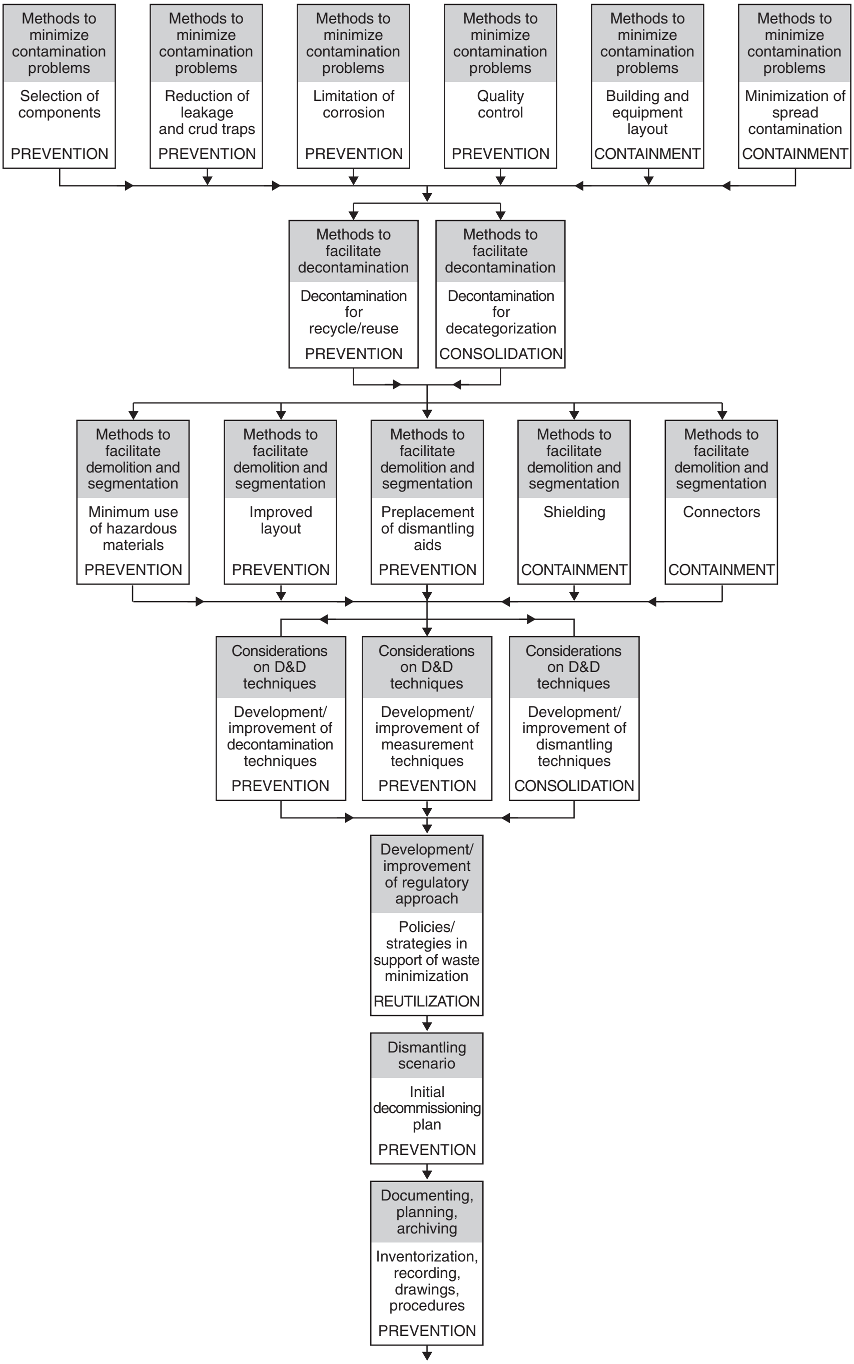


FIG. 4. Waste minimization during design of installations.

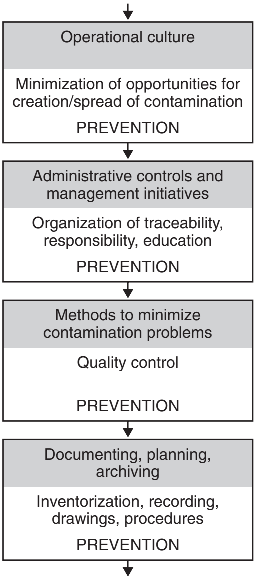


FIG. 5. Waste minimization during construction of installations.

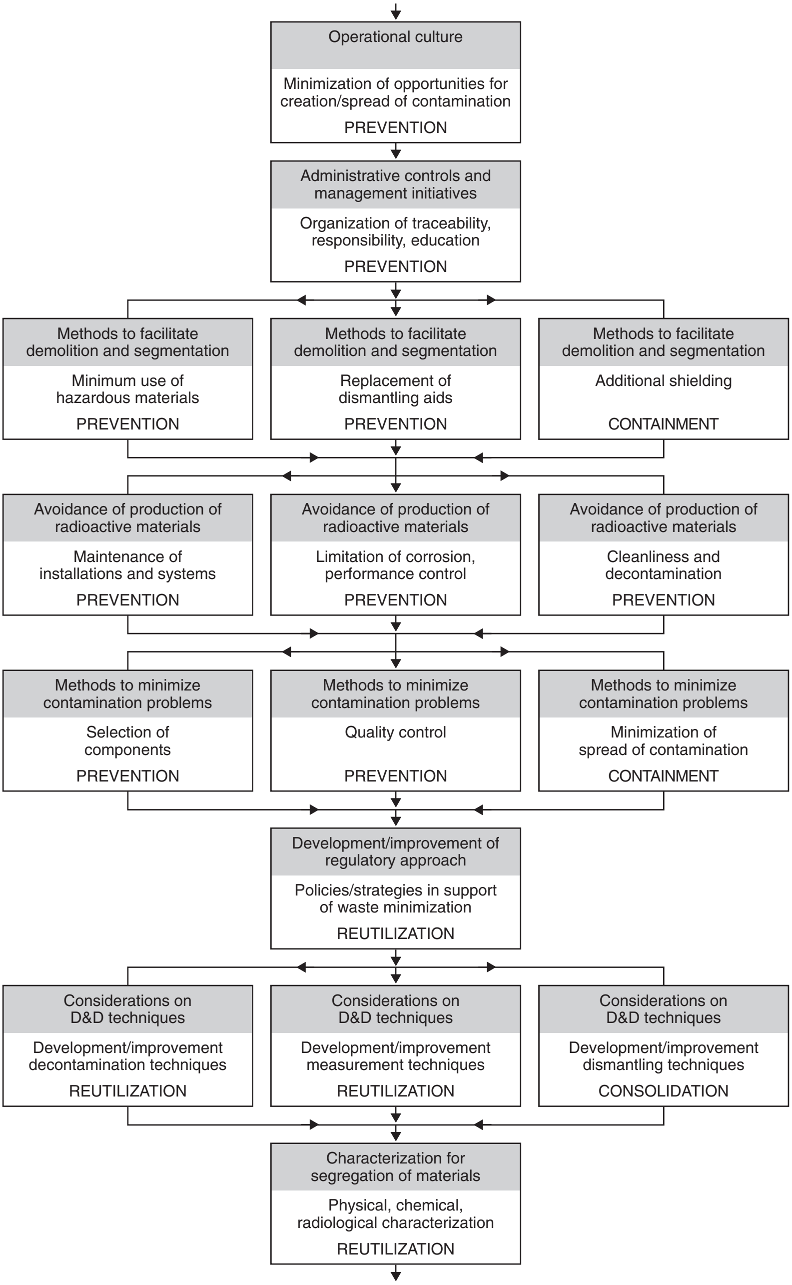
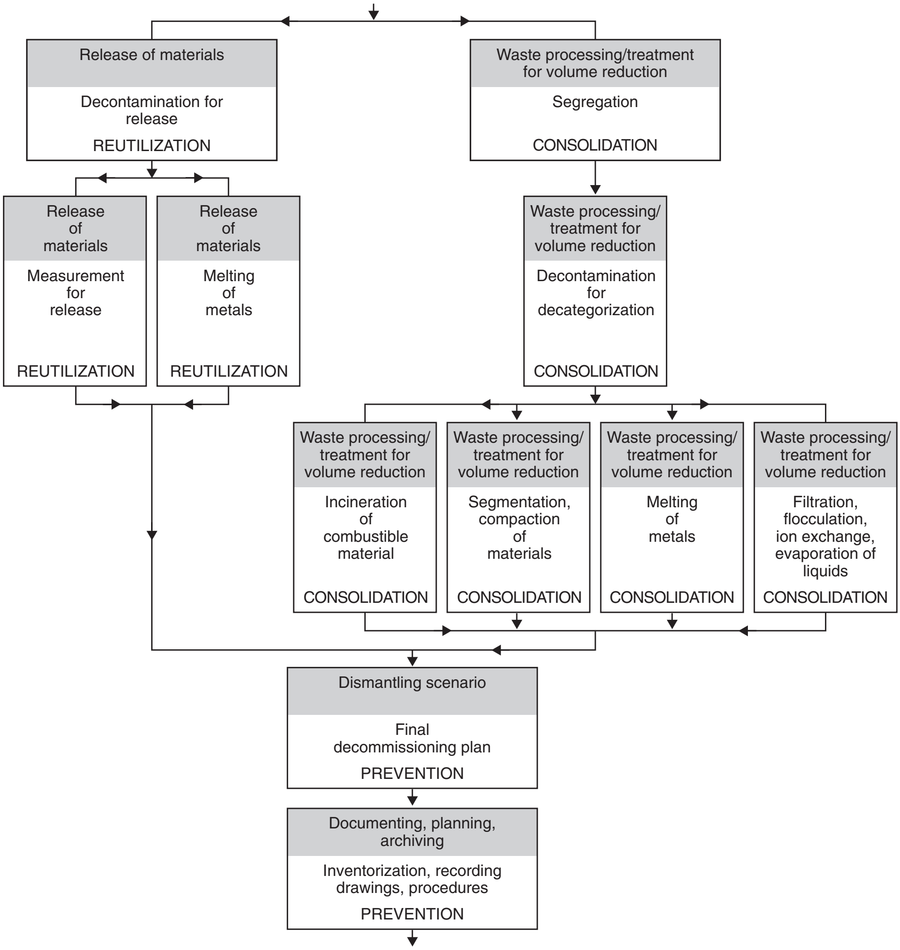


FIG. 6. Waste minimization during operation of installations (continued overleaf).


Release of materials
Decontamination for release
REUTILIZATION
Waste processing/treatment for volume reduction
Segregation
CONSOLIDATION
Release of materials
Measurement for release
REUTILIZATION
Release of materials
Melting of metals
REUTILIZATION
Waste processing/treatment for volume reduction
Decontamination for decategorization
CONSOLIDATION
Waste processing/treatment for volume reduction
Incineration of combustible material
CONSOLIDATION
Waste processing/treatment for volume reduction
Segmentation, compaction of materials
CONSOLIDATION
Waste processing/treatment for volume reduction
Melting of metals
CONSOLIDATION
Waste processing/treatment for volume reduction
Filtration, flocculation, ion exchange, evaporation of liquids
CONSOLIDATION
Dismantling scenario
Final decommissioning plan
PREVENTION
Documenting, planning, archiving
Inventorization, recording drawings, procedures
PREVENTION

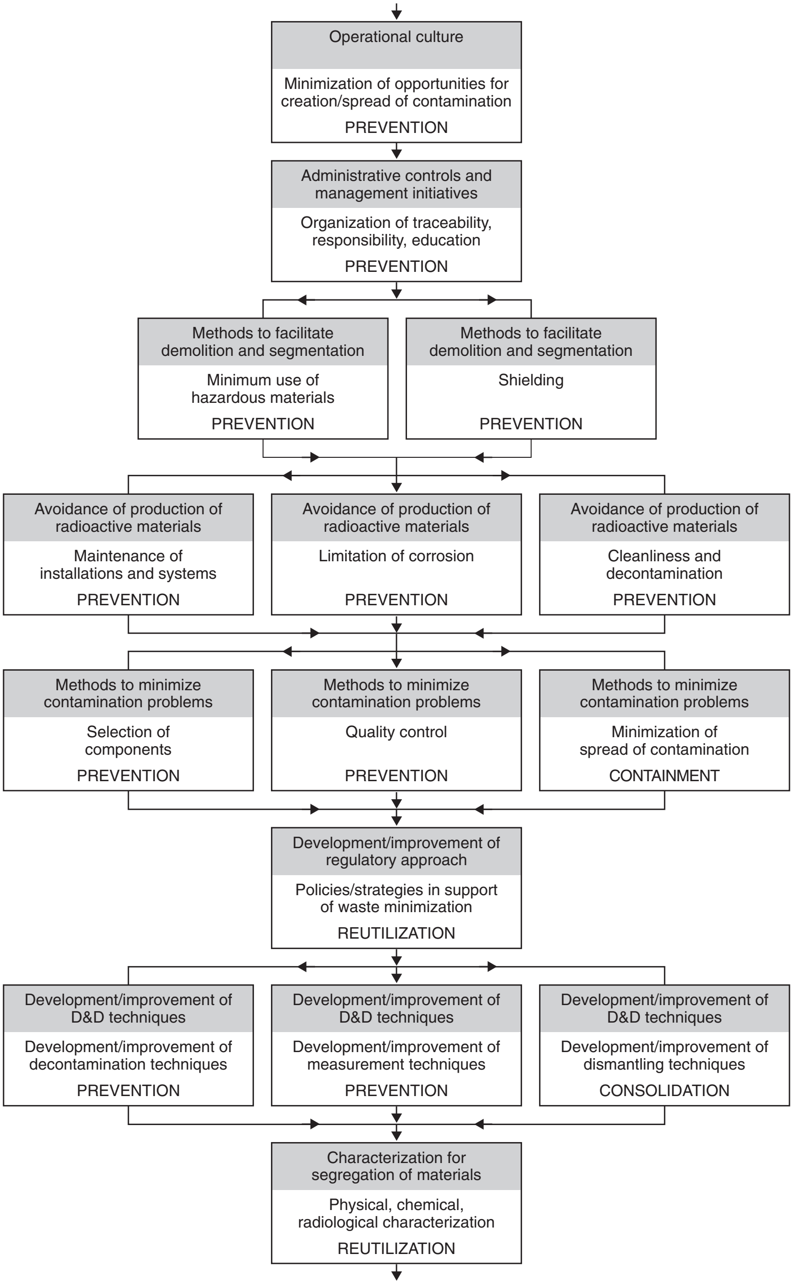
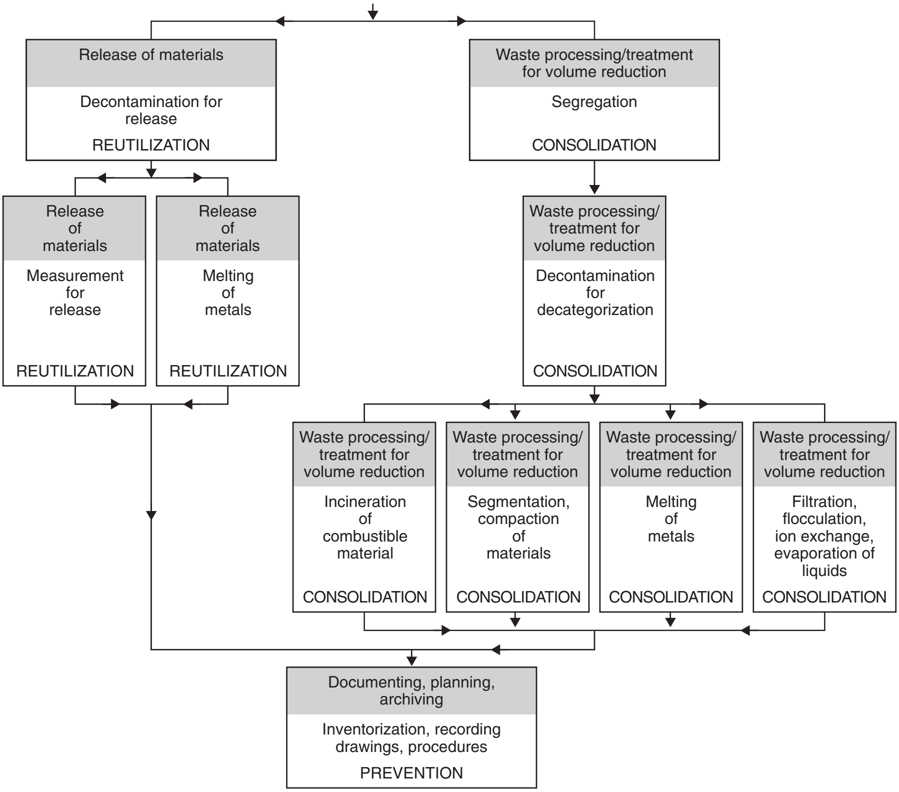


FIG. 7. Waste minimization during post-operation and decommissioning of installations (continued overleaf).


Release of materials
Decontamination for release
REUTILIZATION
Waste processing/treatment for volume reduction
Segregation
CONSOLIDATION
Release of materials
Measurement for release
REUTILIZATION
Release of materials
Melting of metals
REUTILIZATION
Waste processing/ treatment for volume reduction
Decontamination for decategorization
CONSOLIDATION
Waste processing/ treatment for volume reduction
Incineration of combustible material
CONSOLIDATION
Waste processing/ treatment for volume reduction
Segmentation, compaction of materials
CONSOLIDATION
Waste processing/ treatment for volume reduction
Melting of metals
CONSOLIDATION
Waste processing/ treatment for volume reduction
Filtration, flocculation, ion exchange, evaporation of liquids
CONSOLIDATION
Documenting, planning, archiving
Inventorization, recording drawings, procedures
PREVENTION

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GLOSSARY

The Radioactive Waste Management Glossary published by the IAEA in 1993 serves as a source for the terms used in this report. Interpretation of these terms is provided below. Interpretation of some other terms which are not included in the published IAEA Glossary but which are used in this report is also provided. These new or modified terms are indicated with an asterisk, thus*.

ALARA. An acronym for ‘as low as reasonably achievable’, a concept meaning that the design and use of **nuclear facilities**, and the practices associated with them, should be such as to ensure that exposures are kept as low as reasonably practicable, with technical, economic and social factors being taken into account. (See also **optimization**.)

analysis, cost–benefit. A systematic economic evaluation of the positive effects (benefits) and negative effects of undertaking an action. **Cost–benefit analysis** may be used for **optimization** studies in radiation protection evaluations.

analysis, safety. The evaluation of the potential hazards associated with the implementation of a proposed activity.

authorization. The granting by a **regulatory body** of written permission for an operator to perform specified activities. An **authorization** may be more informal or temporary than a **licence**.

clearance.* Removal of radioactive materials or radioactive objects within authorized practices from any further (radiological) control by the **regulatory body**.

clearance levels. A set of values, established by the **regulatory body** in a country or State, expressed in terms of activity concentrations and/or total activities, at or below which **sources** of radiation can be released from nuclear regulatory control. (See also **exemption**.)

contamination. The presence of radioactive substances in or on a material or in the human body or other place where they are undesirable or could be harmful.

criteria. Conditions on which a decision or judgement can be based. They may be qualitative or quantitative and should result from established principles and standards. In **radioactive waste management**, **criteria** and **requirements** are set by a **regulatory body** and may result from specific application of a more general principle.

decommissioning.* Administrative and technical actions to take a **nuclear facility** out of service with removal of the facility and the site from regulatory controls.

decontamination. The removal or reduction of radioactive **contamination**, for example, by a physical and/or chemical process. (See also **contamination**.)

discharge, **routine**. A planned and controlled release of **radionuclides** to the environment. Such releases should meet all restrictions imposed by the appropriate **regulatory body**. (See also **effluent**.)

dismantling. The disassembly and removal of any structure, system or component during **decommissioning**. **Dismantling** may be performed immediately after permanent retirement of a **nuclear facility** or may be deferred.

disposal. The emplacement of waste in an approved, specified facility (e.g. near surface or geological repository) without the intention of retrieval. **Disposal** may also include the approved direct discharge of **effluents** (e.g. liquid and gaseous wastes) into the environment with subsequent dispersion. (See also **discharge**, **routine**).

effluent. Gaseous or liquid radioactive materials which are discharged into the environment. (See also **discharge**, **routine**.)

environmental impact.* The physical, ecological, cultural and socio-economic effects of an installation, facility or technology on the existing natural and social environment.

exclusion (from regulatory control). A designation, by the **regulatory body** in a country or State, of **sources** of radiation that are not subject to nuclear regulatory control because they are not amenable to control (e.g. cosmic rays and ^{40}K (potassium) in the human body). They are said to be excluded from the regulatory process. (See also **exemption**.)

exemption or **exempt**. A designation, by the **regulatory body** in a country or State, of **sources** of radiation that are not subject to nuclear regulatory control because they present such a low radiological hazard (principles for **exemption** are presented in IAEA Safety Series No. 89). Under this designation, a distinction can be made between **sources** which never enter the regulatory control regime (control is not imposed) and **sources** which are released from regulatory control (control is removed), in both cases because the associated radiological hazards are negligible. The latter is especially pertinent to **radioactive waste management**, where **sources** of radiation are released from nuclear regulatory control in accordance with established **clearance levels**. (See also **clearance levels**, **exclusion**.)

licence. A formal, legally prescribed document issued to the applicant (i.e. operating organization) by the **regulatory body** to perform specified activities related to the siting, design, construction, commissioning, operation, **decommissioning** of a **nuclear facility**, closure of a disposal facility, closeout of a mining and mill tailings site, or institutional control. (See also **authorization**.)

minimization. A concept which embodies the reduction of waste with regard to its quantity and activity to a level as low as reasonably achievable (**ALARA**). Waste **minimization** begins with **nuclear facility** design and ends with **decommissioning**. **Minimization** as a practice includes **source** reduction, **recycling** and **reuse**, and **treatment** with due consideration for secondary as well as primary waste materials.

monitoring. The measurement of radiological or non-radiological parameters for reasons related to the assessment or control of exposure and the interpretation of such measurements. **Monitoring** can be continuous or non-continuous.

nuclear facility. A facility and its associated land, buildings and equipment in which radioactive materials are produced, processed, used, handled, stored or disposed of (e.g. repository) on such a scale that consideration of safety is required.

optimization. As used in radiation protection practice, the process of reducing the expected detriment of radiation exposures to humans, through use of protective measures, to as low as reasonably achievable (**ALARA**), taking into account the technical, economic and social factors.

quality. The totality of features and characteristics of an item, process or service that bears on its ability to satisfy a given **requirement**.

quality assurance. All those planned and systematic actions necessary to provide adequate confidence that an item, process or service will satisfy given **requirements** for **quality**, for example, those specified in a **licence**.

quality control. Action which provides means to control and measure the characteristics of an item, process, facility or person in accordance with **quality assurance requirements**.

radioactivity. Property of certain nuclides to undergo spontaneous disintegration in which energy is liberated, generally resulting in the formation of new nuclides. The process is accompanied by the emission of one or more types of radiation, such as alpha particles, beta particles and gamma rays.

radionuclide. A nucleus (of an atom) that possesses properties of spontaneous disintegration (**radioactivity**). Nuclei are distinguished by their mass and atomic number.

records. A set of documents, including instrument charts, certificates, log books, computer printouts and magnetic tapes kept at each **nuclear facility** and organized in such a way that they provide a complete and objective past and present representation of facility operations and activities including all phases from design through closure and **decommissioning** (if the facility has been **decommissioned**). **Records** are an essential part of **quality assurance**.

recycling.* The reutilization of materials and equipment for their original purpose in the original form or after being treated or reworked.

regulatory body. An authority or a system of authorities designated by the government of a country or State as having legal authority for conducting the licensing process, for issuing **licences** and thereby for regulating the siting, design, construction, commissioning, operation, closure, closeout, **decommissioning** and, if required, subsequent institutional control of the **nuclear facilities** (e.g. near surface repository) or specific aspects thereof. This authority could be a body (existing or to be established) in the field of nuclear related health and safety, mining safety or environmental protection vested and empowered with such legal authority.

release or **use**, **conditional**.* A designation, by the **regulatory body** in a country or State, to restrict the **release** or **use** of equipment, materials, buildings or the **site** because of its potential radiological hazards. The **release** may be constrained in some way, usually because the fate of the material being considered is known, so that only a limited number of reasonably possible exposure routes have to be considered in deriving the **conditional release** levels. The **release** may then be granted with certain conditions, e.g. it may prescribe a definite fate for the material being considered.

release or **use**, **unconditional**.* A designation, by the **regulatory body** in a country or State, that enables the **release** or **use** of equipment, materials, buildings or the **site** without radiological restriction. The full and complete **unconditional release** of a material requires that all reasonably possible exposure routes be examined and taken into account in the derivation of the **unconditional release** levels, irrespective of how that material is used and to where it may be directed.

requirement. A condition defined as necessary to be met by a product, material or process. (See also **criteria**.)

reuse.* The reutilization of materials and equipment in their original form or after being treated or reworked for purposes different to their original use.

risk. The following alternative definitions may be relevant in the field of radioactive waste management:

- In general, **risk** is the probability or likelihood of a specified event occurring within a specified period or in specified conditions.
- In the safety assessment of radioactive waste repositories, **risk** may be used as a measure of safety. In this context it is defined as the product of the probability that an individual is exposed to a particular radiation dose and the probability of a health effect arising from that dose.

segregation. An activity where waste or materials (radioactive and **exempt**) are separated or are kept separate according to radiological, chemical and/or physical properties which will facilitate waste handling and/or processing. It may be possible to **segregate** radioactive from **exempt** material and thus reduce the waste volume.

site. The area containing, or under investigation for its suitability to construct, a **nuclear facility** (e.g. repository). It is defined by a boundary and is under effective control of the operating organization.

source. Any physical entity that may cause radiation exposure, for example, by emitting ionizing radiation or releasing radioactive material.

source reduction.* A prominent component of a waste minimization strategy, involving plant and equipment design and process control, and aiming at minimizing amounts of wastes generated during facility operation.

specific activity. Includes: (a) The activity of a radioisotope per unit mass of a material in which the radioisotope occurs. (b) The activity of a radioisotope per unit mass of a material consisting of only that isotope.

storage (interim). The placement of waste in a **nuclear facility** where isolation, environmental protection and human control (e.g. **monitoring**) are provided with the intent that the waste will be retrieved for **exemption** or processing and/or **disposal** at a later time.

treatment. Operations intended to benefit safety and/or economy by changing the characteristics of the waste. Three basic treatment objectives are:

- — Volume reduction,
- — Removal of **radionuclides** from the waste,
- — Change of composition.

After **treatment**, the waste may or may not be immobilized to achieve an appropriate waste form.

waste, **radioactive**. For legal and regulatory purposes, **radioactive waste** may be defined as material that contains or is contaminated with **radionuclides** at concentrations or activities greater than **clearance levels** as established by the **regulatory body**, and for which no use is foreseen. (It should be recognized that this definition is purely for regulatory purposes and that material with activity concentrations equal to, or less than, **clearance levels** is radioactive from a physical viewpoint — although the associated radiological hazards are considered negligible.)

waste, **secondary**. A form and **quality** of waste that results as a by-product from processing of waste.

waste arisings. The quantity of waste generated by any stage in the nuclear fuel cycle, by research reactors and by the production and utilization of radioisotopes.

waste characterization. The determination of the physical, chemical and radiological properties of the waste to establish the need for further adjustment, **treatment**, conditioning, or its suitability for further handling, processing, **storage** or **disposal**.

waste management, **radioactive**. All activities, administrative and operational, that are involved in the handling, pre-treatment, **treatment**, conditioning, **storage** and **disposal** of waste from a **nuclear facility**. Transportation is taken into account.

waste package. The product of conditioning that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and liner), as prepared in accordance with **requirements** for handling, transportation, **storage** and/or **disposal**.

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