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State of the Art Technology for Decontamination and Dismantling of Nuclear Facilities

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1999

STATE OF THE ART TECHNOLOGY FOR DECONTAMINATION AND DISMANTLING OF NUCLEAR FACILITIES

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FOREWORD

The decommissioning of nuclear facilities is a topic of great interest to many Member States of the IAEA as a result of the large number of older nuclear facilities which are or soon will be retired from service. The first IAEA document in the field of decommissioning was published in 1975. Since then, some 30 technical documents, conference proceedings, technical reports and safety series documents have been published, covering specific aspects of decommissioning such as technologies, safety and environmental protection, national policies and regulations, characterization of shut down facilities, and design and construction features to facilitate decommissioning. The majority of reports addressing decommissioning technologies were prepared in the early or mid-1990s and mainly reflected experiences on small research reactors or pilot facilities.

After more than a decade of major decommissioning activity, technology has advanced considerably and has benefited from parallel development in other industrial fields such as electronics, robotics and computing. New decommissioning technologies have emerged and are ready to face the challenge of the year 2000 and beyond, when a number of large commercial facilities will reach the end of their operational lifetime and become candidates for decommissioning.

This report is a review of the current state of the art in decontamination and dismantling technology, including waste management and remote systems technology. International input was mainly provided at a Technical Committee Meeting held on 10–14 November 1997 with the participation of eighteen experts from twelve Member States and one international organization. Further information was made available by consultants who met in 1997, 1998 and 1999. The Scientific Secretary throughout the preparation of the report was M. Laraia, Division of Nuclear Fuel Cycle and Waste Technology.

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1. INTRODUCTION

The first IAEA document in the field of decommissioning of nuclear facilities was published in 1975 [1]. Since then, some 30 technical documents, conference proceedings, reports and safety series documents have been published, covering specific aspects of decommissioning such as technologies, safety and environmental protection, national policies and regulations, monitoring programmes, characterization of shutdown facilities, and design and construction features to facilitate decommissioning. A selection of such publications is given in Refs [2–15]. Other reports have focused on the decommissioning of specific types of nuclear facility, such as research reactors, uranium mining and milling facilities and non-reactor nuclear facilities, e.g. Refs [16–18]. Several technical documents have described on-going research and development activities in the field of decommissioning, e.g. Refs [19, 20]. The majority of technical reports addressing decommissioning technologies, and in particular decontamination and disassembly techniques and the management of resulting wastes [4–7], were prepared in the early or mid-1980s and mainly reflected decommissioning experience gained on relatively small research reactors or prototype facilities. At that time, only feasibility studies or preliminary plans to decommission larger nuclear facilities were generally available.

Experience gained on the decommissioning of larger nuclear facilities, which has become available over the last 10–15 years, has somehow altered the picture. In many industrialized countries, the total dismantling of major prototype facilities such as Kernkraftwerk Niederaichbach (KKN) in Germany, Tunney's Pasture in Canada, Shippingport NPP in the United States of America and the Japan power demonstration reactor (JPDR) has been viewed by the operators and the government decision makers as an opportunity to demonstrate to the public that the decommissioning of major nuclear facilities can be conducted in a safe and cost effective manner. Equally importantly, these decommissioning efforts also served to test and optimize decontamination and disassembly techniques and to create a 'decommissioning market' including specialized suppliers and contractors.

Over a decade of major decommissioning activity, technology has advanced considerably and has benefited from parallel development in other industrial fields such as electronics, robotics and computing. New decommissioning techniques have emerged and are ready to face the challenges of the year 2000 and beyond, when a number of large commercial facilities will reach the end of their operational lifetime and become candidates for decommissioning (Figs 1, 2).

As a result of the time which has elapsed since the publication of preliminary IAEA reports in the field of decommissioning technologies and the implementation

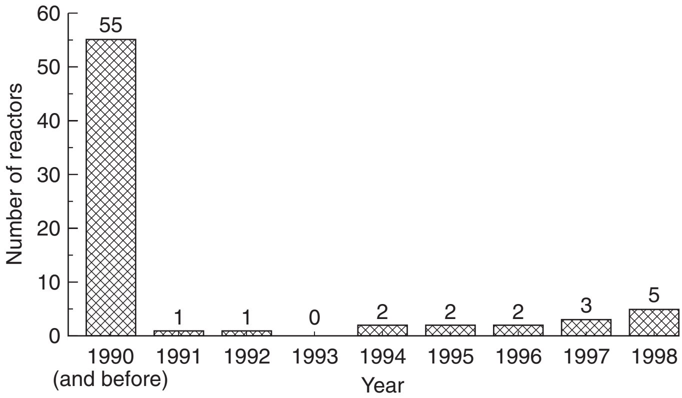

FIG. 1. Integrated number of shutdown nuclear power plants in a given year (IAEA elaboration).

of numerous large scale decommissioning projects since then, the time is now right to review the experiences gained and the trends that are forecast. The data in this report represent information collected up to the end of 1998.

2. PURPOSE AND SCOPE

The objective of this report is to identify and describe state of the art technology for the decommissioning of nuclear facilities, including decontamination, dismantling and management of the resulting waste streams. This information is intended to provide consolidated experience and guidance to those planning, managing and performing the decommissioning of NPPs, research reactors, reprocessing plants and other nuclear facilities. The report may also be of use to those involved in the nuclear regulatory field, when reviewing plans, carrying out inspection activities and confirming satisfactory completion of decommissioning. It will also be helpful to those carrying out refurbishment or large scale maintenance activities on operational nuclear installations.

This report is not intended to be a decommissioning handbook (although it takes a significant amount of information from existing handbooks), but reflects upon the experience gained over the last 10–15 years in the practical decommissioning field. Technical details are given to a limited extent, while the reader is directed to more detail in the quoted literature.

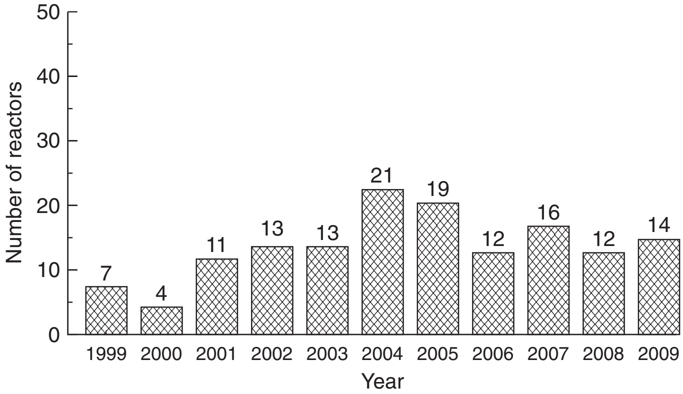

FIG. 2. Nuclear power plants reaching 30 years of age in a given year (IAEA elaboration). Note: 18 UK generating NPPs were over 30 years old in 1997 and have not been included: Bradwell A, B; Calder Hall A, B, C, D; Chapelcross A, B, C, D; Dungeness-A A, B; Hinkley Point-A A, B; Oldbury-A A, B; and Sizewell-A A, B.

The focus of this report is on decommissioning technologies, particularly decontamination and dismantling. However, the management of materials/waste is also an essential part of decommissioning and hence has also been addressed.

Less emphasis has been given to other aspects of decommissioning such as planning/organization and regulations. However, the impact of these on technology and related technical decisions should not be ignored. Also, a few detailed aspects such as radiological characterization and decommissioning techniques for specific types of nuclear installation (e.g. research reactors) are only reviewed briefly as they have already been covered in recent IAEA publications [15, 16].

In principle, the technologies described in this report are independent of the specific plant or plant type in question. However, in practice, most technologies have to be tailored to the specific needs of the facilities being decommissioned, and this is reflected in the information presented. It is uncommon, except for very simple technologies, for any technology to be used on a specific facility without consideration of the features of that facility. Therefore, the reader is advised not to extrapolate conclusions on the performance of a given technology without consideration of the specific features of the facility for which that technology was developed (e.g. contamination levels, structural materials, radioactive deposit composition).

Another focus of this report is research and development (R&D) on emerging technologies in the decommissioning field. To achieve technological maturity, an R&D programme is nearly always compulsory. In one sense, R&D implemented in the 1980s is one of the bases on which current state of the art technology stands. Current R&D represents the limit of this report and will form the basis from which the next decade's technology will develop.

3. STRUCTURE

This publication initially discusses those factors important in the selection of a decommissioning strategy and which have an impact on planning and implementing decommissioning technologies (Section 4). These factors include national policies and regulations, cost estimation and funding, planning and management of a decommissioning project, radioactive waste classification and facilitation techniques for decommissioning. Section 5 discusses the impact that safety and radiation protection requirements have on the planning and implementation of decommissioning technologies. Methods and technologies for decommissioning, including decontamination, dismantling, waste management, robotics and remote operation, long term integrity of buildings and systems and other miscellaneous aspects, are described in detail in Section 6. Also, the reader is given a general orientation on where to find descriptions of techniques matching specific applications. Section 7 describes the general lessons learned from decommissioning experience worldwide. Conclusions are given in Section 8. In the Appendix to the report, case histories and specific lessons learned are provided. The report is complemented with an extensive set of references.

4. FACTORS TO BE CONSIDERED IN THE SELECTION AND IMPLEMENTATION OF A DECOMMISSIONING STRATEGY

This section is intended to describe the conditions affecting the selection of a decommissioning strategy and their implications for the development of decommissioning technologies. Some of these factors, having either a national or an international nature, will foster further R&D and will ultimately result in optimized techniques and methods; others may hinder or reduce further R&D activities in this field. Enhancing or hindering work on decommissioning technology development may be the result of a conscious decision or may derive from a lack of infrastructure needed to support these activities. Examples of this are provided in this section.

4.1. NATIONAL POLICIES AND REGULATIONS

4.1.1. National regulations and international harmonization efforts

There are several examples of national regulations which have an impact on decommissioning technologies, for example Ref. [21], which specifically addresses European Union (EU) countries. Another example is Japan, where the national policy prescribes immediate dismantling after final shutdown. In the light of this policy and the large number of operating nuclear reactors in Japan, it is easy to understand why R&D work on decommissioning technologies has been, and currently is being, carried out in Japan with such great intensity [22–24]. The entire JPDR decommissioning project was conducted as an integrated test and optimization of available decontamination and decommissioning (D&D) technologies and included the development of several new technologies [25]. In the Russian Federation, there are numerous regulations directly or indirectly connected with decommissioning activities [26–33].

Release criteria for solid materials is another important factor affecting the development of D&D technologies. Examples of criteria and practices for the unrestricted release of materials and components, and their recycling and reuse, during the last 15 years can be found in Refs [9, 10, 34–44]. However, at present, few Member States have issued firm criteria for recycling and reuse of material, even though it may be an attractive alternative to radioactive waste disposal.

The IAEA has proposed unconditional clearance levels [45] and the European Commission (EC) has proposed nuclide specific clearance levels for the direct reuse of metals and recycling of metal scrap [46]. While the IAEA proposal is intended to provide clearance (unconditional release) criteria, other recycle technologies could be developed which allow restricted release mechanisms. One such approach, which considers not only the risks from radiation but also major non-radiological risks, was developed by the OECD Nuclear Energy Agency (OECD/NEA) [47]. Examples of proposed release criteria and practices for the USA and Spain are given in Refs [43, 48–51].

A significant example of how national policies/regulations directly affect D&D technologies can be found in Germany, where the Atomic Energy Act favoured recycling of dismantled radioactive components unless this was opposed for major technical, economic or safety reasons [52]. This situation entailed on the one side the development of a coherent and comprehensive set of regulations for the restricted/unrestricted release of radioactively contaminated materials (clearance levels) [10, 52, 53], and on the other side the establishment of industrial infrastructures, e.g. melting facilities to meet regulatory criteria [54–56]. Therefore, in Germany, the criteria for recycling and reuse cover a wide range of options, i.e. unconditional clearance, clearance of metal scrap, clearance of material for conventional disposal and clearance of buildings [53, 57–60].

4.1.2. Land reuse, waste disposal and other technical factors affecting the choice of a decommissioning strategy

There is no general worldwide trend in selecting a decommissioning strategy (basically, this comprises either immediate or delayed dismantling after final shutdown). National regulations may prescribe the decommissioning strategy, as is the case in Japan where the selected immediate dismantling strategy reflects the scarcity and limited size of sites suitable for the construction of new NPPs (see Section 4.1.1). In most countries, both immediate and delayed dismantling are pursued for different facilities. The short term availability of disposal sites and escalating disposal costs have convinced several US utilities to opt for immediate dismantling [61–65]. A deferred dismantling strategy (up to 135 years' delay) is currently in place for the United Kingdom's Magnox reactors and is based mainly on radiation protection and financial considerations [66]. In Germany, the Lingen NPP is being kept under safe enclosure conditions for a number of years [13], while KKN was the first NPP in Europe to reach the goal of unrestricted site release [67]. What the trend will be over the next 10–15 years remains uncertain, as several factors interacting in a complex manner are involved.

The decommissioning strategy is an important element in determining the need for developing decommissioning technologies. Activities aimed at achieving a long term safe enclosure condition do not usually require sophisticated D&D methods and techniques. Exceptions may include the construction of long term containment barriers, on-site (e.g. for corrosion effects) and off-site monitoring, and the predictive modelling of structure and equipment deterioration. The risk of not developing dismantling technologies for facilities being kept under long term safe enclosure is that dismantling at a later stage might be more complex and expensive. An opposite consideration is that developing technologies at a later stage would benefit from overall technological progress. A mixed approach seems to prevail in several countries. This consists of using one or two shutdown facilities for the purpose of developing decommissioning technologies while leaving the other facilities under safe enclosure conditions for a stipulated period of time.

It is recognized that immediate dismantling is the most challenging decommissioning strategy. For instance, owing to higher radiation levels, the use of remotely operated equipment may be required during the dismantling of an NPP or large research reactor. In general, provisions to minimize doses to the decommissioning workforce are more stringent in the case of immediate dismantling and entail extensive use of decontamination, shielding and remote tooling. Some of these provisions may require advanced technology and ancillary equipment, e.g. underwater cutting of reactor internals in the Fort St. Vrain (FSV) gas cooled reactor required the implementation of an ad hoc water purification method [68].

It should be noted that for some non-reactor nuclear fuel cycle facilities the radiological benefits from delayed dismantling are limited. Therefore, the strategy selected is often immediate dismantling. A 1998 IAEA technical report deals with current decontamination and dismantling technologies in non-reactor nuclear facilities [18].

The selection of a decommissioning strategy is to a large extent based on the availability of waste disposal facilities. Existing facilities might have to be extended or new facilities built in order to cope with the large volumes of waste from decommissioning operations. Whether and to what extent existing facilities will be used for waste resulting from the decommissioning of large nuclear facilities still remains to be seen. Considerable progress has been achieved over the last 10–15 years, resulting in the establishment of new disposal facilities in countries such as the Czech Republic, France, Japan and Spain. In Italy, however, the lack of waste disposal sites has, so far, forced plant operators into a delayed dismantling strategy [69]. A decision to defer dismantling should be taken as the result of an optimization process and not because other alternatives are precluded by the unavailability of disposal sites. If disposal sites are not available, interim storage of decommissioning waste could be considered.

The waste management and disposal issue may affect the development of decommissioning technologies in other ways. Firstly, the increasing disposal costs may foster the development of technologies to minimize the volumes of radioactive waste [70, 71]. Examples in this regard are recycling/reuse technologies, such as the melting of radioactive scrap or decontamination. This is the case in the USA, where the need for new disposal sites is recognized and enforced by law but where little practical progress has been achieved. In such a situation, recycling/reuse practices may help reduce the amount of radioactive waste for disposal [72, 73]. Recycling/reuse can also be part of national environmental policy, as is the case in Germany (see Sections 4.1.1 and 6.4.1). Additional waste minimization methods may include segregation, reuse of buildings and equipment, compaction, liquid waste concentration, use of contaminated materials as waste container void filler, and various decontamination techniques [70, 74–77].

A second important aspect of waste management that may affect decommissioning technologies is related to the radiological and industrial specifications of waste containers and packages for storage, transportation or disposal. For instance, component segmenting activities should be aimed at optimizing further steps in waste management including decontamination (if required), conditioning, packaging, transportation, storage and/or disposal. Development of technologies in any of these fields will depend on available waste management infrastructures, e.g. the capability to produce containers of the required size and weight [70, 75]. One example is the categorization of radioactive waste containers for the Morsleben repository in Germany [78] (see Section 4.5).

A special problem in the context of waste disposal and its effects on decommissioning technologies is posed by some decommissioning waste which could require special disposal provisions, e.g. some reactor internals are not acceptable for routine near surface disposal under current US regulations [79]. Also, within the UK and Germany, the accepted national policies are that all intermediate and high level wastes be disposed of in an underground repository. Thus, the disposal of intermediate level waste from decommissioning activities in the UK will have to wait until a repository is available in the next century [80].

Similar to waste management, spent fuel storage and/or disposal capacity is a major factor in deciding a national approach to decommissioning, including technologies. Spent fuel requires special storage in spent fuel ponds, dry storage casks, or other specialist facilities. These may be at the reactor site or at a centralized facility away from the reactor. If at-reactor spent fuel ponds are used, large dismantling operations will generally be deferred until the spent fuel can be transferred to other storage facilities or shipped for reprocessing or disposal. Spent fuel management is a field where significant progress has been achieved in many countries over the last 10–15 years. In particular, the technology of dry storage has been fully developed in countries such as Canada [13], USA [81] and Germany [82]. In contrast, difficulties emerged in many countries in securing the availability of a spent fuel repository, a significant example being the Yucca Mountain project in the USA [83]. Also, in some Eastern European countries, the practice of returning spent fuel to the manufacturer has become difficult for political and economic reasons [84, 85]. A recent development in this context is that the US Department of Energy (USDOE) has agreed to take back and manage certain foreign research reactor spent fuel that contains uranium enriched in the USA [86].

4.1.3. R&D considerations

The driving force behind technology development is its applicability to specific industrial projects. New technologies for decommissioning generally improve safety, reduce waste generation or increase productivity, thereby reducing overall costs. Generally, the larger a national decommissioning or environmental restoration programme is, the greater the probability that a large R&D programme on decommissioning technologies can be justified and carried out. This is the case in the USA or a community of countries such as the EU and the Commonwealth of Independent States (CIS), where it is expected that dozens of large nuclear facilities will be decommissioned over the next 10–20 years [87–91]. A country with a small number of operational nuclear facilities is often more reluctant to embark on significant R&D work on decommissioning technologies and may prefer to use or adapt technologies available in the commercial sector. This choice may also be driven by the perceived applicability of the decommissioning technologies currently being tested or optimized. It will also depend on the timing of decommissioning, i.e. if it is envisaged that decommissioning will take place in the near future or in the longer term.

4.1.4. Social considerations and public involvement

Social considerations are likely to affect national decommissioning strategies, including technology development, in several ways. For example, the extensive workforce at a nuclear facility will become redundant soon after shutdown unless immediate dismantling is selected. This would have an obvious effect on the local economy. On the other hand a dismantling strategy could actually attract labour and investment to the area.

Public concern about the effect of nuclear facilities on the health and welfare of the population is growing. The scope of this concern varies from country to country but normally has a significant effect on national nuclear policy and hence on the timing of decommissioning activities and the extent to which they are progressed. In some countries, the public may demand that the dismantling work be done immediately after shutdown with existing, proven technology, rather than waiting for an improved technology to be developed. As a different example, at the Trawsfynydd power station in the UK [92], it was decided to consult the staff and the local community on the three main options available for decommissioning: early site clearance, ‘safestore’ — early or deferred — and mounding — early or deferred. Finally, the utility owner modified its corporate strategy from deferred safestore to early safe storage in response to public opinion and the views of local government bodies.

In the EU, the situation differs from one country to another. The regulatory approaches in the field of decommissioning nuclear installations do not cover all the aspects of a decommissioning process [21]. However, in a recent Council Directive [93], the EC has foreseen that decommissioning of nuclear installations will be an integral part of a compulsory environmental impact assessment of industrial activities. Countries need to take the measures necessary to ensure that the authorities likely to be concerned with the project, in view of their specific environmental responsibilities, are given the opportunity to express their opinion on the information supplied by the developer. These requests are made available to the public within a reasonable time-scale in order to provide them with an opportunity to express their opinion before consent is granted.

In the USA, at those USDOE sites with ongoing environmental cleanup programmes, separate site technology co-ordination groups (STCG) have been established for each site. At these sites, the STCG has representatives of the general public as well as the site management to provide the overall perspective on the acceptability of the technologies selected to be used in particular decommissioning projects [94]. At commercial NPPs in the USA, recent regulatory changes now require a formal public briefing on plans for the decommissioning of an NPP prior to starting the removal of any component from the facility [95].

4.1.5. R&D priorities

The technology currently available is generally adequate to cover most decommissioning tasks. The dismantling of complex, highly activated or contaminated facilities can, however, still require the development of special techniques. Sometimes a trade-off strategy is needed. For example, it has been suggested that in the case of Rancho Seco it might be more cost effective to use the results obtained from other ongoing decommissioning and research activities, rather than conduct a research programme at Rancho Seco [96]. Extensive R&D work may result in the testing of new equipment, training of personnel, expenditure of time and money and possible delays in completing decommissioning. A country's attitude to these issues will be affected by its willingness to launch ambitious R&D programmes and is influenced by factors such as the number and age of its nuclear facilities, whether ownership is private or public, and the expected impact on other industrial sectors. 'Spin offs' from nuclear decommissioning technologies are expected in industries dealing with operation in a hostile environment and with the management of hazardous, toxic materials. Examples of countries where comprehensive R&D programmes on decommissioning yielded technological results are Belgium [97], France [98], Japan [23, 99], and the UK [100, 101].

As part of the USDOE's Office of Science and Technology, the D&D Focus Area has been effectively demonstrating and deploying more than 50 innovative D&D technologies through its large scale demonstration projects (Chicago pile reactor no. 5 (CP-5), Hanford C reactor, Fernald Plant 1 and others) [102]. Emphasis in new technologies is generally focused on costs, waste minimization, exposure reduction, staff reduction and the general ease in applying a technology to perform a task [103]. A sample of the technologies being tested or demonstrated within the USDOE programme is given in Ref. [104].

4.2. COST ESTIMATION AND FUNDING

4.2.1. Cost estimation

The cost of decommissioning a nuclear facility is affected by many factors which are either related to engineering problems such as waste disposal practices

[105] and dismantling options, to financial issues such as inflation, discount rates and currency fluctuations, or to sociopolitical issues. It is obvious that an accurate estimate of costs is essential to the development and optimization of decommissioning technologies. This refers not only to the implementation costs of D&D technologies, including staffing and the cost of secondary waste management, but to related costs such as R&D.

In the field of decommissioning cost assessment, considerable progress has been achieved over the last 20 years. International and national organizations have provided studies estimating decommissioning costs, highlighting the most important parameters [106–109]. It has been estimated that decommissioning costs in the USA for commercial size PWRs and BWRs (1000 MW(e)) are between US$300 million and US$400 million (in 1994 US$) [110–112]. Cost estimates in Germany, as indicated in Ref. [113], are of the same order. Uncertainty in low level and high level waste disposal costs, and in environmental standards for cleanup of sites, has caused considerable concern. A comparison of decommissioning costs in Sweden, Germany and the USA appears in Refs [114–116]. The costing issue may be such that several countries would opt for delayed dismantling in order to accrue additional funds. Further progress in cost estimation is expected when large commercial facilities with a significant radioactive inventory have been dismantled. A comprehensive description of decommissioning cost items and their impact on the overall decommissioning cost is given in Ref. [117]. Computer codes for estimating decommissioning costs are now widely available [118–121].

4.2.2. Funding provisions

Descriptions of funding schemes for decommissioning in several countries can be found in Refs [107, 108]. The size of the annual contribution to a decommissioning fund is usually based on current cost estimates, and these need to correspond as closely as possible to the actual final costs. Governments and/or utilities (depending on national policy) contribute to these funds on the basis of these cost estimates [12, 108, 122, 123]. Most operating nuclear facilities have prepared decommissioning plans, including cost estimates. However, these should be reviewed on a regular basis to take advantage of advances in technology and changes in regulatory framework.

For NPPs, decommissioning normally amounts to a few per cent of the total electricity costs which are levied from consumers over the lifetime of the plant [124, 125]. In the case of other operating nuclear facilities, the costs are recovered from the customer as part of the charge for the services, e.g. the thermal oxide reprocessing plant in the UK [126]. For historic liabilities, it is often the case that no decommissioning fund exists. In these cases funding is usually provided directly from the State budget.

4.3. PLANNING AND MANAGEMENT

Although planning and management aspects of a decommissioning project are not the focus of this report, they affect, or are affected by, decommissioning technologies either currently available or yet to be developed. Examples of this interactive process are described in the following sections.

4.3.1. Preparation of a decommissioning plan

Future decommissioning should be taken into account at the facility design and construction stage [14]. This also implies that preliminary decommissioning plans should be prepared at an early stage in the plant life-cycle, e.g. preferably before operations begin [3]. They should be based on state of the art technology at the time and experience in the decommissioning of similar installations. Decommissioning plans should be reviewed/revised periodically in the course of a plant’s lifetime, or at times of significant plant modifications, incidents or cost saving technology improvements, as prescribed by the national regulatory body. Eventually, decommissioning plans should be finalized before a plant’s final shutdown in order to optimize decommissioning investments by taking advantage of the availability of personnel familiar with the plant and utilizing existing facilities. This is the phase when the most important decisions on the technologies to be employed during decommissioning should be made.

4.3.2. Project management

Besides preparing a decommissioning plan and obtaining regulatory body approval where appropriate, it is necessary to define and implement a suitable management structure for the project. Technology related aspects of the project management include [127]:

- *Specification of work packages.* The decommissioning plan will identify and specify the principal decommissioning work packages. However, before work commences, these packages should be analysed in sufficient detail to allow the decommissioning team to understand them clearly in order to execute the work. The work packages [18, 128] should be planned at an early stage, e.g. because such planning greatly assists in the identification of any required specialist support and equipment that may be needed.

- *Permits/regulatory reviews.* The project may require review and approval of the approach taken to decommission the facility. Additionally, regulators may need to amend or issue air/water discharge permits, shipping package certificates (a significant example would be one-piece reactor vessel removal), and other review documents/permits.

- *Qualifications and training of staff to perform work.* To execute the job safely and efficiently, it will be necessary to ensure that all persons involved in the decommissioning project are qualified for the tasks they have to perform. In many cases, training programmes should be established to ensure that staff meet these requirements. Also, training of dismantling staff on mock-ups will assist in reducing occupational exposures [129]. Use of mock-ups during the BR3 decommissioning project in Belgium is described in Refs [130, 131] (see Section 6.6.7). Training on new equipment is essential in this regard. Specialists in the use of such equipment may be contracted as needed.

- *Selection and acquisition of equipment.* Technical management staff must ensure that special equipment (e.g. instrumentation, decontamination units, transport containers, dismantling tools) has been identified in advance and procured in time to suit the planned sequence of decommissioning activities.

When it is planned to use a new technology, an important consideration would be the provision of a backup technique, in case problems are encountered. Also, provisions should be made for the setting up, testing and de-bugging of 'one of a kind' tooling.

4.3.3. Data management and return of experience

An essential aspect of decommissioning technology development is the acquisition and management of decommissioning data. A few examples are given below.

4.3.3.1. Example 1

A code system for the management of a decommissioning project has been developed in Japan [132–134] and various data about the JPDR dismantling have been accumulated in a database. These data are being used for: (1) managing ongoing dismantling activities, (2) verifying the predictive code system for management of reactor decommissioning (COSMARD), and (3) planning future decommissioning of commercial nuclear power reactors [25, 135]. The components that make up the database are: activity dependent data, period dependent data and collateral data.

4.3.3.2. Example 2

A data management system capable of processing working hours, production factors, budgeting data for personal performance, etc. [136], was set up at the main process building of the Eurochemic reprocessing plant in Belgium. Other examples of such systems have been used at C reactor, Hanford, USA [137] and at Brennilis, France [138].

4.3.3.3. Example 3

The databases EC DB TOOL and EC DB COST are under development within the framework of the EC's 1994–98 nuclear fission safety programme on decommissioning of nuclear installations [139]. EC DB TOOL contains mainly technological data, e.g. on dismantling tooling and associated filtration techniques, and EC DB COST contains data for cost estimations and dose uptakes for unit operations. Developments are currently being implemented for the use of both databases throughout the EU. Public network access and security issues of data transmission are being assessed, as well as the user interface and the recommended system requirements.

4.3.3.4. Example 4

At the Greifswald NPP (KGR) site in Germany, a data management system, called the project information system, has been set up to control the world's largest ongoing decommissioning project [140]. This information system comprises about 500 work units, their required specifications and costs, masses to be handled and radiological data. It assists in optimizing the process flow and ensures optimum use of resources. A PC program, ReVK, has also been developed to represent material and waste flow, to exercise data control within administrative constraints, to maintain bookkeeping, to generate reports and to manage transportation and storage requirements. With respect to radioactive wastes and final disposal aspects, ReVK includes two other PC programs: AVK and AVK-ELA. The first is used to control radioactive waste flow, the second is used for assisting final disposal [141, 142].

Other software tools have been developed for the assessment of the required volumes and related costs of the disposal of decommissioning waste. For the calculations, these tools take into account the proposed dismantling technique, the masses involved, the disposal containers available, etc. [143, 144]. A new development towards a more general management support system is given in Ref. [145].

4.3.4. Pre-decommissioning refurbishment

Pre-decommissioning refurbishment may be needed to bring all systems/equipment necessary for decommissioning up to satisfactory levels of operability. Pre-decommissioning activities are described in Refs [146–148]. Examples of such activities are:

- Installation of new auxiliary ventilation plant,
- Servicing of manipulators and cranes,
- Installation of modular containment systems,
- Laundering [149] and secondary waste treatment facilities,
- Construction of interim storage facilities,
- Implementation of new (remote) monitoring systems for the site.

At many of the USDOE sites, there are numerous shutdown nuclear research facilities which have required refurbishment in order to prepare them for decommissioning. For the experimental BWR (EBWR) at Argonne National Laboratory (ANL) this included the installation of a new high efficiency particulate air filtration system [150]. Also at ANL, a modular containment was built for the size reduction of 61 plutonium contaminated gloveboxes. This was an especially sensitive operation since non-radioactive research work continued in laboratories in close proximity to the D&D site [151].

In Germany, the construction of the Zentrallager Nord interim storage facility at KGR for the purpose of facilitating decommissioning of the five blocks of KGR and allowing the segmenting of larger components ex situ can be regarded as another example of pre-decommissioning refurbishment [140].

4.3.5. Final survey plan

When physical dismantling has been completed, a final radiological survey will have to be conducted to demonstrate that the site of the nuclear facility and any remaining buildings can be released for restricted or unrestricted use. Detailed reviews of the survey requirements and the equipment and methods of monitoring for compliance with release criteria are provided in Refs [10, 152, 153].

Steps taken to ensure that the decommissioned facility and site comply with release criteria include:

- Identification, provision and calibration of suitable instruments and laboratory facilities;

— Direct measurements to determine residual radioactivity;
— Collection of samples for laboratory analysis and their archiving;
— Statistical evaluation of data to demonstrate compliance with release criteria;
— Proper, detailed documentation of every aspect of the compliance survey.

It should be demonstrated that the D&D technologies applied are adequate to achieve the objective of final site release. For instance, decontamination of building concrete surfaces should reduce residual contamination levels to below release criteria [154, 155]. Also, D&D techniques should never complicate the achievement and demonstration of compliance with release criteria, e.g. the application of the D&D technique must not redistribute contamination to previously uncontaminated areas.

4.4. LONG TERM INTEGRITY OF BUILDINGS AND SYSTEMS

Some of the decommissioning strategies involve the long term safe enclosure of shutdown facilities for reasons such as radioactive decay and the need to accumulate adequate decommissioning funds. The development of any D&D technologies should take into account at what point such technologies will be employed. Ideally technologies should be considered for immediate application, as a long period of safe enclosure may render them obsolete. A long period of safe enclosure may be a critical issue for a different reason, i.e. the potential degradation of buildings and systems. Technologies developed for immediate application to a newly shut down plant may not be applicable to the same plant after a few decades owing to factors such as reduced containment or weakened structural supports. This point is of a particular concern owing to the large number of shutdown facilities having been in a dormant condition for a number of years.

Measures required for maintaining shutdown facilities in a safe condition to enable deferred decommissioning are described in Ref. [13] and were also studied within the EC R&D programme [88]. Within the EC programme, a programme to substantiate and refine predictive models of the mode and pace of deterioration of NPP structures, and to predict the level of nitric acid which will form as a result of radiolysis in these installations prior to being dismantled is reported Ref. [156]. A study of the parameters of a pre-stressed concrete vessel has been made and recommendations for monitoring requirements of these structures prepared. Corrosion and atmospheric monitoring systems have been installed at Berkeley power station in the UK, at Lingen in Germany and at other NPPs [157].

A computational fluid dynamics model of the UK's Hunterston–A power station has been developed to allow a validated assessment to be made of the structural integrity and preservation requirements of components which will undergo long term storage [158].

4.5. WASTE CLASSIFICATION

Another important segment of national legislation and regulations is the classification of waste in relation to the availability of suitable, operating disposal sites. This aspect is particularly relevant to decommissioning as it is estimated that many thousands of tonnes of waste are generated during the dismantling of a facility, e.g. a commercial NPP. National regulations commonly prescribe waste acceptance criteria, including parameters such as radioactive concentrations and dose rates for the disposal of radioactive waste in licensed repositories. Radioactive inventories allowed in waste containers depend in general on disposal site characteristics, e.g. near surface or underground repository, as well as on transport regulations. The existence of waste disposal criteria is essential (see Section 4.1.2) for the planning of decommissioning activities, including cost estimates and the selection of decontamination and dismantling techniques. A 1994 IAEA publication [159] is intended to promote the harmonization of national criteria and practices in this field. An overview of national waste classification schemes in Europe is given in Ref. [160].

National regulations may also prescribe criteria for the release into the public domain of materials/waste arising from decommissioning. The availability of such criteria is essential for the cost effective implementation of decommissioning, as large amounts of decommissioning materials/waste have very low contamination levels and may be eligible for release as non-radioactive. More details on this subject are given in Sections 4.1.1, 5.2.1 and 6.4.1.

4.6. FACILITATION OF DECOMMISSIONING

Planning decommissioning during the design, construction and operation phases, as well as during the shut down of the facility, will make decommissioning easier. For example, maintaining records of all phases of plant life is vital to this end. Other facilitation techniques are facility specific and depend on the expected benefits in terms of dose and cost reduction. A comprehensive description of design and construction features to facilitate decommissioning is given in a recently published IAEA technical report [14]. National policies vary widely, but more and more States are realizing the importance of planning now rather than later for the future decommissioning of facilities currently being designed and constructed. The use of novel software techniques is invaluable in the archiving and use of data relevant to decommissioning. Examples include the maintenance of ‘as built’ documentation

(Fig. 3) and the system for tracking remediation exposure, activities and materials [137].

In principle, facilitation techniques at the design and construction stage should simplify decommissioning, for example hands-on dismantling could become possible instead of the use of remotely operated equipment and avoiding the use of certain construction materials in NPPs should decrease the inventory of ^{60}Co in the primary loop. In this way there would be less need for the application of sophisticated decommissioning technology. However, in practice there are limitations to what can be achieved at the design and construction stage, for example limitations imposed by cost. Also, most nuclear facilities currently operating have been designed and constructed with little consideration having been given to decommissioning. For example, the inadequacy of records such as as built drawings may require the development of robotic equipment for working in an environment which is not completely known.

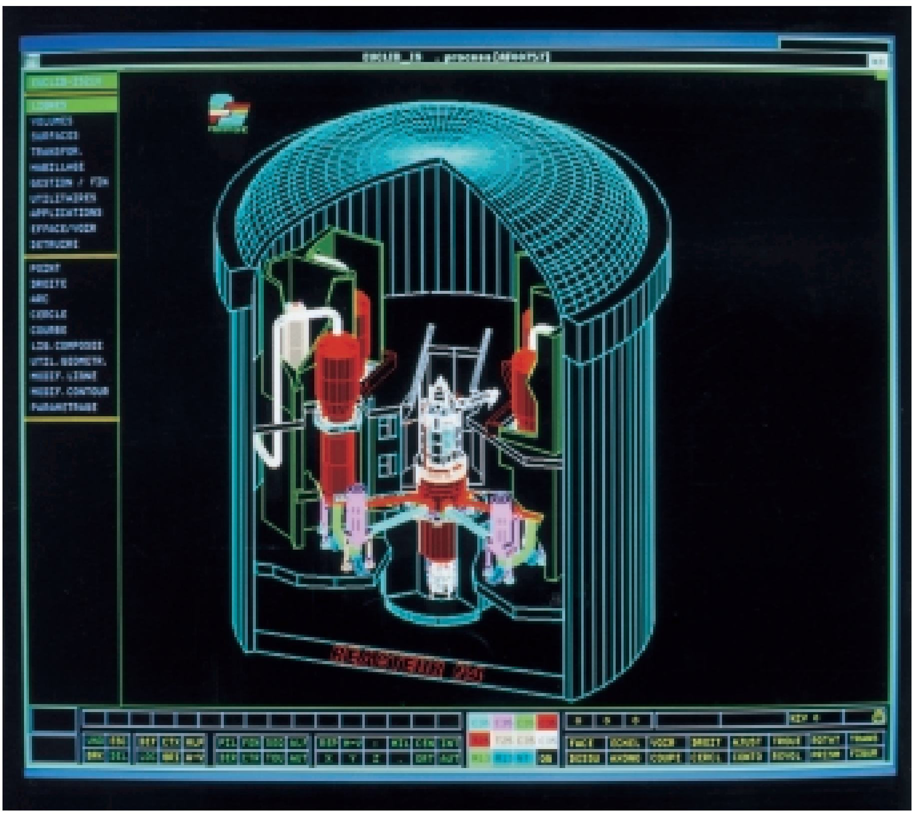

FIG. 3. CAD view of the reactor at the new N4 plant in France.

5. SAFETY AND RADIATION PROTECTION

This section is intended to describe how safety and radiation protection requirements should be taken into account in the planning and implementation of decommissioning activities. Examples are provided to show how such requirements may affect the development and optimization of D&D technologies.

5.1. INTERNATIONAL RECOMMENDATIONS

The conceptual framework of the 1990 International Commission on Radiological Protection (ICRP) recommendations [161] as regards ‘practices’ (as distinct from ‘interventions’, i.e. remedial actions) is based on the following general principles:

- *Justification of a practice.* No practice involving exposures to radiation should be adopted unless it produces sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes. It should be noted that decommissioning is only the inevitable terminal phase of a practice. The benefit required for justification of the practice is to be found in the previous exploitation of the installation.
- *Optimization of protection.* In relation to any particular source within a practice, the magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures where these are not certain to be received, should all be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account. This procedure should be constrained by restrictions on the doses to individuals, or the risks to individuals in the case of potential exposures.
- *Limitation of individual doses and risks.* The exposure of individuals resulting from the combination of all relevant practices should be subject to dose limits, or to some control of risks in the case of potential exposures. These are aimed at ensuring that no individual is exposed to radiation risks that are judged to be unacceptable in any normal circumstances.

The dose limits recommended by the ICRP [161] and promoted by the International Basic Safety Standards (BSS) [162] and the Euratom BSS [163] are as follows:

- For workers, the limits of effective dose are 20 mSv per year averaged over five consecutive years and 50 mSv in any single year. There is a trend in some Member States to reduce these limits even further.
- For members of the public, the limit is 1 mSv in a year; in special circumstances a higher effective dose of up to 5 mSv could be allowed in a single year, provided that the average over five years does not exceed 1 mSv/year. In addition to these limits of effective dose, limits of equivalent dose are set for certain organs (lens of the eye, skin, extremities).

It should be stressed that the 1990 ICRP recommendations as endorsed by the BSS contain more restrictive dose limits for both workers and the population than pre-1990 limits. For decommissioning workers, it is expected that in future increasing emphasis will be given to protective means, e.g. remotely operated equipment, as a result of new international recommendations. In general, this aspect will serve as an impetus to re-evaluate available technology.

The ICRP and BSS publications also recommend organizational features to implement radiation protection. These features, most of which are highly relevant to decommissioning, concern aspects such as management requirements, dosimetry, verification procedures and emergency planning. Interpretation of ICRP and BSS criteria and other practical applications of radiation protection criteria in decommissioning are given in recently published documents, e.g. Refs [164–166].

In the selection of technologies for decommissioning, specific aspects include release criteria, monitoring and specific safety issues.

5.2. RELEASE CRITERIA FOR MATERIALS, BUILDINGS AND SITES

National regulations usually prescribe maximum radioactive concentrations and other criteria for the restricted or unrestricted release of low level contaminated materials. It has been shown in many cases [37, 167] that only a small fraction of the material arising from decommissioning should be managed as radioactive waste, since the rest may be recycled or reused in the public domain or disposed of by conventional means. An alternative recycling route is within the nuclear sector. Examples of items of interest for this method of recycling are waste boxes or spent fuel casks. A survey in the EU gave a clear overview of the expected radioactive waste arising within the EU over the next 50 years. These arisings were compared with potential recycling capacities (in the nuclear field) [37, 168]. Some countries, for example Germany, specify a set of release criteria depending on the destination of the recycled materials and other factors [10, 52, 53]. The availability of such criteria has been the driving force behind the establishment of a recycling industry in Germany for radioactively contaminated items [55, 56].

Examples of recent studies to determine clearance levels in specified cases are given below. Decontamination for clearance (unrestricted release) is discussed in general in Ref. [169]. Radiological aspects of recycling concrete debris from the dismantling of nuclear installations are discussed in Ref. [170]. Technical requirements for the determination of clearance levels for steel and concrete are given in Ref. [171]. The special case of recycling radioactively contaminated metal in concrete is dealt with in Ref. [172]. Research on the radiological impact of recycling slightly radioactive aluminium and copper is discussed in Refs [173, 174].

A recent IAEA publication tries to harmonize national criteria regarding the clearance of very low level contaminated materials/waste [45]. Such international criteria — in the past identified with the expression 'de minimis' — are particularly relevant in the context of decommissioning as scrap materials, for example, can be exported from the country of origin. The radiation protection objectives behind the promulgation of any such criteria are generally more restrictive than those allowed for exposure of the public from planned practices. The rationale for this approach stems from the absence of an easily identifiable critical group (group of individuals most likely to receive the highest doses from the practice) associated with the release of solid materials. It should be noted that conditions and controls (technical and/or administrative) associated with the release of solid materials may allow release of such materials at higher contamination levels (authorized use) [175].

Similar criteria should be in place to allow the release of the decommissioned site. Such criteria will normally be based on site specific factors. This subject is further dealt with in Section 6.4.1, and its impact on strategy selection in Section 4.1.1.

5.3. MONITORING

Monitoring for compliance with project objectives is an essential part of decommissioning. While this report does not focus in detail on monitoring and characterization techniques, as they are covered by other comprehensive publications, e.g. Refs [10, 15, 176, 177], monitoring/characterization aspects of decommissioning should however be taken into account when developing D&D technologies or applying them to a specific project. Examples of such interdependencies include:

— Decontamination techniques should take into account the possibility of measuring decontaminated items to the extent necessary to prove compliance with regulatory criteria.
— D&D techniques should not cause the spread of contamination to other areas.
— Demolition of contaminated structures/components should not result in the cross-contamination of clean areas, thereby invalidating previous release measurements.
— Hard to detect radionuclides, e.g. alpha emitters, should not result in the over- or under-classification of decommissioning waste.

5.4. TYPICAL SAFETY ISSUES

This Section highlights specific safety issues that should be taken into account in developing and/or specifying D&D techniques.

5.4.1. Hazardous materials

Hazardous materials are major factors for consideration in the decommissioning of old nuclear facilities and represent a risk both to the operators undertaking the work and to the environment in general. Examples of common hazardous materials are lead, asbestos [87], polychlorinated biphenyls (PCBs), mercury and beryllium [178]. All these materials, depending on national policy, require special disposal, even if they pose no radioactive hazard. In some regulatory systems, for example the US system, the handling and disposal of wastes containing both hazardous and radioactive materials (mixed wastes) can be problematic [179]. An EC study of the consequences of the presence of hazardous elements in some radioactive streams was published in 1998 [180].

5.4.2. Effects on other operations and facilities

A major consideration when choosing a particular decommissioning strategy or dismantling technique is the effect that it may have on surrounding structures or operations in adjacent areas. Examples of this are:

— The use of explosives, where the effect of the shock waves must be considered [181];
— The use of mobile cranes and the effects on floor loading;
— The use of thermal cutting techniques and the spread of contamination as a result of fume and aerosol generation [182–184];

— The use of chemical decontaminants, which may result in the generation of explosive gases such as hydrogen (Section 5.4.7).

5.4.3. Secondary waste

When choosing D&D techniques, the generation of secondary wastes such as decontamination media, cooling fluids, lubricants, abrasives, dross, used tools, ion exchange resins, etc. should be taken into consideration. Waste conditioning and disposal costs should be weighed against the benefits of fast decontamination or segmenting operations. Examples of assessment methodologies can be found in Refs [70, 71].

5.4.4. Criticality

Criticality can be a major safety concern in the dismantling of non-reactor nuclear facilities. D&D techniques should prevent the buildup of critical masses or the introduction of moderators such as water which may result in the formation of a critical assembly. The requirements for criticality safety assessment during decommissioning are described in Ref. [18].

5.4.5. Tritium

Difficulties and significant time delays may occur during the dismantling of systems as a result of the spillage of heavy water residues containing tritium [67, 185]. Quantities of tritium may also be found in the concrete of biological shields as a result of the activation of lithium impurities and deuterium [150], as well as in off-gas surge tanks and graphite blocks [186, 187]. A comprehensive discussion on tritium contamination and management of tritium contaminated waste in a particular decommissioning project is given in Ref. [188].

The effectiveness of various tritium removal techniques such as plasma etching, moist air soaking and gas purging is currently being investigated [189]. Other methods are ultraviolet/ozone [190] and catalysed burning [191].

5.4.6. Graphite

It is essential that the stored energy content and oxidation rates be taken into account when deciding on methods for the safe dismantling and disposal of graphite cores [192–194]. In this context, the example of the UK's Windscale 2 graphite pile is very informative. The reactors contain significant Wigner energy and elaborate precautions have been taken by the operators to ensure that intrusive (inspections or dismantling) operations cannot lead to sudden energy release. The safestore process foreseen for pile 2 requires extensive modernization of the safety case, including provision for seismic analysis [193].

In decommissioning of graphite moderated reactors, disposal of graphite poses a special problem. In Ref. [195] the options for the disposal of graphite from these plants are reviewed, together with actions being taken at individual reactors in France, the Russian Federation and the UK.

5.4.7. Alkaline metal coolants

The chemical reactivity of alkaline liquid metals in water and air may pose safety concerns and special provisions should be made when dealing with such materials [196]. One example of the treatment of radioactive sodium from the Rapsodie reactor, France, using the sodium hydroxide process, is described in Refs [197–199]. This process involves reacting small quantities of sodium in water inside a closed vessel, producing aqueous sodium hydroxide and hydrogen gas. However, the possibility of unexpected reactions occurring between sodium and water during reactor decontamination still needs investigation [200].

In the UK, more than 1500 tonnes of radioactive, hot liquid sodium and other metals are to be removed from the prototype fast reactor at Dounreay, as part of the United Kingdom Atomic Energy Authority's (UKAEA) long term decommissioning programme [201]. In this process liquid sodium is neutralized into a mixture of water and sodium chloride. Experience in decommissioning sodium cooled reactors in Germany and the USA, including sodium treatment, is given respectively in Refs [202, 203].

5.4.8. Industrial safety

Certain decommissioning technologies may require additional safety provisions owing to the specific hazards they pose to the workforce. These may include high pressure or corrosive liquids, lasers, electrical hazards or other hazardous properties. Additional provisions should be considered for those workers performing this work. Standards in the USA for special safety hazards associated with certain decommissioning technologies are specified in Ref. [204] (safe use of lasers) and Ref. [205] (safe use of high pressure liquids).

Some important safety issues exist for the use of explosives, including taking into account the effect of the shock wave created on surrounding structures and safety related equipment. Moreover, a very important issue for dismantling contaminated or activated structures is the removal and disposal of explosives which fail to detonate. It is not obvious whether explosives will be accepted (licence, safety review) in disposal sites with radioactive material owing to the risk of self-detonation or their instability under radiation. Another issue is how they can be removed safely from their location [18].

Noise levels produced by certain decommissioning technologies should be evaluated for the particular working area in which the technology will be used. Additional safety provisions may be required for the work area personnel [206].

While operating tools such as jackhammers, scabblers or needle guns the personnel are exposed to vibrations which could lead to the development of the so-called ‘white finger’ syndrome and other deleterious effects. These safety issues are normally addressed in national legislation. Practical experience from decommissioning projects exists [207].

5.4.9. Fire protection

The application of some D&D techniques requires special fire protection measures to be taken. The additional costs of these measures should be taken into consideration in the choice of a particular technique, e.g. thermal cutting techniques or grinding. If the selected decommissioning strategy is a long term safe enclosure, it may be necessary to install a new fire detection and protection system as the existing one may be too complicated for the envisaged requirements, or it may have to be partially dismantled. The new fire protection system should be maintained during the entire safe enclosure period and this may involve significant costs or additional commitments with the regulatory authorities. A detailed discussion on fire protection in nuclear facilities is given in Ref. [208].

6. METHODS AND TECHNOLOGIES FOR DECOMMISSIONING

An extensive research programme on D&D technologies has been conducted since 1979 by the EC with respect to the decommissioning of nuclear installations. Progress and results achieved mainly within the programme between 1989 and 1995 are described in Ref. [209]. Further information on recently completed and ongoing decommissioning projects under the umbrella of an OECD/NEA programme can be found in Ref. [117]. Extended verification tests on various decommissioning technologies are under way in Japan [210, 211]. A review of European technologies is given in Ref. [212]. A benchmarking study has been completed by the USDOE in order to identify best practices for selected decommissioning functions based on USDOE and non-USDOE experience as well as on the expected performance of technologies under varying work conditions [213]. A summary of the USDOE’s large scale technology demonstration projects, aimed at the demonstration of innovative D&D technologies, is given in Refs [87, 102, 214–217].

The following list of methods and techniques for decommissioning is based mainly on the USDOE Decommissioning Handbook [183] and the EC Handbook on Decommissioning of Nuclear Installations [39]. As stated in Section 2, the information provided here is not intended to duplicate that given in the above two publications, but rather to direct the reader to the experience gained over the last 10–15 years, both in field operations and in technology development. Guidance on preferred decommissioning technologies has been published by the USDOE [218].

6.1. RADIOLOGICAL AND NON-RADIOLOGICAL CHARACTERIZATION

6.1.1. Characterization criteria and experience

Characterization is essential to the success of a decommissioning project. This activity involves the collection of all relevant data concerning the status of a plant entering a safe enclosure or dismantling phase, including the inventory of non-radioactive hazardous materials and radionuclides in buildings, equipment and other materials.

An IAEA report was recently published, focusing on the radiological characterization of nuclear reactors [15] and another recent IAEA report extensively covers the subject of characterization of non-reactor nuclear facilities [18]. Radioactive waste characterization is extensively dealt with in Refs [219, 220]. Material monitoring programmes for unrestricted release have been described in several IAEA technical reports/documents, e.g. Refs [9, 10, 40]. As these publications reflect the state of the art in the field of radiological characterization, this report will not deal extensively with this topic. Some recent developments are described below and those for robotic applications in Section 6.5.2.

6.1.2. Characterization methods and techniques

The first phase of most decommissioning operations is to collect physical and radiological information about the facility. This data set then forms the basis for determining the decommissioning strategy, decontamination and dismantling needs, radiological protection requirements for the workers, the public and the environment, and final waste classification.

On the basis of the history of the facility, computational methods, and guidance by experienced plant personnel, the radiological characterization programme is carried out by performing both direct in situ measurements and taking samples for analysis.

Three kinds of equipment are necessary to perform plant characterization:

— Sampling equipment
— Spectrometers and radiological measuring equipment (Fig. 4) [221]
— Physical/chemical analysis and separation equipment.

On the whole, sampling equipment is now well developed and is often based on equipment used in the non-nuclear field, such as diamond and carbide core drills used for sampling concrete and graphite. Some additional development has been undertaken on material containment systems and on techniques for minimizing secondary waste production. While established technologies for sampling contaminated and activated surfaces and materials are available, new techniques are emerging for specific applications. A few examples of emerging techniques are given in Ref. [222]. Examples of some recent developments are described below.

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 the level of soil contamination. During the later stages of decommissioning, the large surfaces of buildings, etc. often remain to be monitored to ensure that release levels have been achieved. Currently, this can be done using strategies for analysing

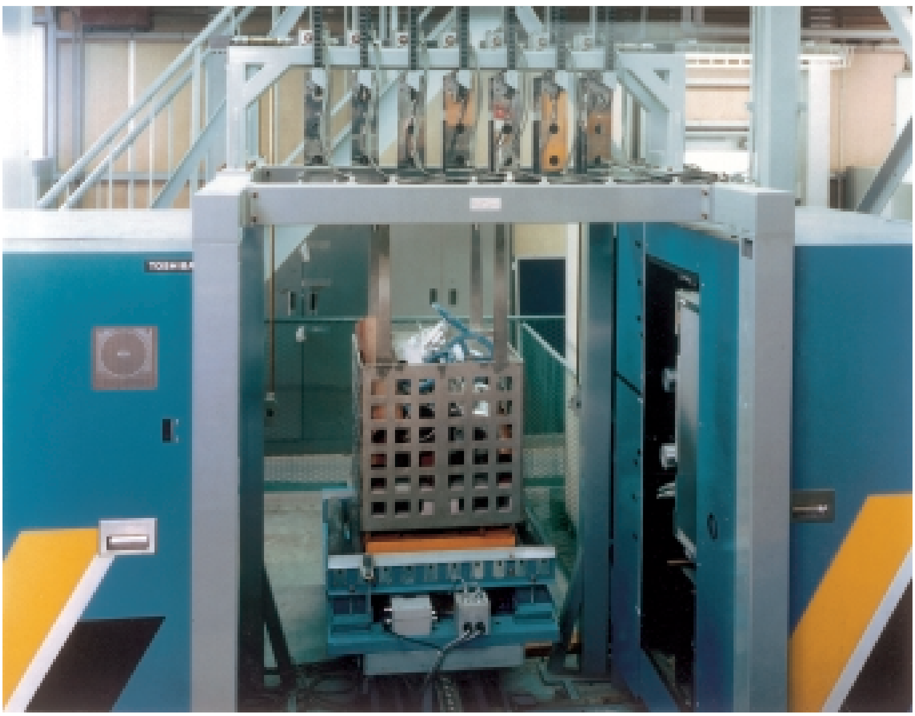

FIG. 4. Very low level radioactivity measurement apparatus, Nuclear Power Engineering Corporation, Japan.

samples taken from the surface or by measuring the surface activity using large proportional counts. An alternative approach is under development using a collimated in situ gamma spectrometer [223]. Prototype equipment has been tested at several facilities in Germany and France and comparisons made between the established method and the in situ technique. The device has been shown to be capable of meeting, in most cases, the required release criteria.

Owing to the short range of alpha particles in air, it can be difficult to detect them in complex assemblies such as pipe interiors. One method developed to overcome this difficulty is termed long range alpha detection [224]. This detects the presence of alpha particles by measuring the ions generated in the surrounding air or a carrier gas flowing through or over the contaminated workpiece. Although this method detects the alpha particles, it cannot determine the exact location of their source.

Other examples of emerging characterization technologies are:

— Systems for superimposing gamma radiation readings and spectrographic information onto visual images of an object [225–227].
— Methods for the direct recording of survey data from radiation measuring equipment and plotting these against positional data from the probe [228, 229]. Positional data are provided for 'indoor' situations by modified surveyors or 'outdoors' via a global positioning system. Data are collected directly by computer or data logger and displayed in the form of a CAD image of the survey area or a geographical map.
— Methods for inserting radiation probes into pipes while avoiding the problems of contamination of the detection head [230, 231].
— Use of segmented gas proportional alpha detectors [232]. These are used for surveying large areas for alpha contamination and accurately locating the positions of 'hot spots' without the requirement for additional secondary surveys.

6.2. DECONTAMINATION

A very general description of the various decontamination techniques was published by the IAEA in the 1980s [4]. These techniques include: sweeping or vacuuming; application of cleaning solutions such as household laundry detergents, foaming aerosol cleansers, organic solvents such as acetone, trichloroethylene, and Freon–113; use of high pressure liquid jets; use of strippable plastic membranes; blasting with wet or dry high velocity particles; and the use of frozen CO_2 and erosion cavitation processes. Guides for selection, with a limited list of decontamination methods, were given in another IAEA report [5]. This list was expanded by the IAEA in 1986 [6]. An overview of many of the techniques and equipment used for decontamination and demolition of concrete and metal structures during the decommissioning of nuclear facilities was published by the IAEA in 1988 [7].

In 1989 an IAEA technical document [19] reported on three research co-ordination meetings on these subjects. At that time, mostly R&D programmes were reported, not actual experiences. However, towards the middle of the 1990s, much more data from real projects started to be accumulated and extensive descriptions of many decontamination techniques and actual experiences are now available in the technical literature, e.g. Refs [20, 47, 233].

General approaches to decontamination and decommissioning techniques are given in the EC Handbook [39], followed by an extensive description of the relevant techniques. The decontamination issues have been classified according to the systems to be decontaminated: large volume closed systems, segmented parts, building surfaces and soil. A recent IAEA technical document [234] reports on R&D programmes on decontamination, both for decommissioning and for operation/maintenance purposes. Another IAEA report [15] focuses on decontamination techniques for operating water cooled reactors. A comprehensive review of advances in decontamination techniques for decommissioning was recently published by the US National Research Council [235].

Actual experience with some decontamination and dismantling techniques has been reported and evaluated, and reference is made to the source of information in Ref. [77]. A project at the Florida International University for selecting appropriate decontamination technologies is reported in Refs [236, 237]. A similar programme is under way at the Oak Ridge National Laboratory (ORNL) in the USA [238]. The JPDR decommissioning project was conducted as an integrated R&D exercise. Decontamination techniques tested at JPDR are described in Refs [239–242]. Recently, methods of removing oxide films have been evaluated in Italy [243]. Russian decontamination technologies for decommissioning are detailed in Refs [244–246].

As a general orientation to the reader, Tables I–IV highlight typical decontamination techniques and their main applications. The Tables also direct the reader to relevant sections of this report where general information on, and references related to, experience in the use of a given technique are provided. It should be noted that certain decontamination techniques can also be used for dismantling purposes, for example when dealing with concrete, explosives or jackhammers can be used and these are described in Section 6.3.

6.2.1. Chemical decontamination

Chemical solutions are generally most effective on non-porous surfaces. The choice of decontamination agents is based upon the chemistry of the contaminant, the chemistry of the substrate and the ability to manage the waste generated during the process [183].

TABLE I. GENERAL OVERVIEW OF DECONTAMINATION PROCESSES FOR DECOMMISSIONING

Technique	Section	Large volume and closed systems	Segmented parts	Building surface and structures[a]
Chemical decontamination	6.2.1			
Chemical solutions	6.2.1.1–6.2.1.8	×[b]	×	×
Multiphase treatment processes	6.2.1.9	×	×	
Foam decontamination	6.2.1.10	×		×
Chemical gels	6.2.1.11	×	×	×
Decontamination by pastes	6.2.1.12	×	×	
Decontamination by chemical fog	6.2.1.13	×	×	
Gas phase decontamination	6.2.1.14	×		
Mechanical decontamination	6.2.2			
Flushing with water	6.2.2.1	×	×	×
Dusting/vacuuming/wiping/scrubbing	6.2.2.2		×	×
Strippable coatings	6.2.2.3	×	×	×
Steam cleaning	6.2.2.4		×	×
Abrasive cleaning	6.2.2.5		×	×
Sponge blasting	6.2.2.6		×	×
CO_2 blasting	6.2.2.7		×	×
High pressure liquid nitrogen blasting	6.2.2.8		×	×
Freon jetting	6.2.2.9		×	×
Wet ice blasting	6.2.2.10		×	×
High pressure and ultra high pressure water jets	6.2.2.11	×	×	×
Grinding/shaving	6.2.2.12		×	×
Scarifying/scabbling/planing	6.2.2.13			×
Milling	6.2.2.14		×	
Drilling and spalling	6.2.2.15			×
Expansive grout	6.2.2.16			×
Paving breaker and chipping hammer	6.2.2.17			×
Other decontamination techniques	6.2.3			
Electropolishing	6.2.3.1	×	×	
Ultrasonic cleaning	6.2.3.2		×	
Melting	6.2.3.3		×	

TABLE I. (cont.)

Technique	Section	Large volume and closed systems	Segmented parts	Building surface and structures[a]
Emerging technologies	6.2.4			
Light ablation	6.2.4.1		×	×
Microwave scabbling	6.2.4.2			×
Thermal degradation	6.2.4.3			×
Microbial degradation	6.2.4.4	×		×
Electromigration	6.2.4.5			×
Exothermic, highly metalized powders	6.2.4.6			×
Supercritical fluid extraction	6.2.4.7			×

[a] Including concrete, bricks or metal surfaces such as liners, fuel ponds, etc.
[b] × denotes main uses.

A general description of chemical and electrochemical decontamination techniques is given in IAEA reports [4–7, 15]. An IAEA technical document was published in 1990 on the decontamination of transport casks and spent fuel storage facilities [247].

The results of a co-ordinated research programme on decontamination and decommissioning have been reported in an IAEA technical document [20]. This document addresses the following topics associated with chemical and electrochemical decontamination: understanding of oxide dissolution mechanisms, electrochemistry of V(II)/V(III)-picolinate systems, optimization of decontamination formulations and processes, and development of an electrochemical method for the decontamination of carbon steel.

The following issues were considered to require further work: the dissolution mechanism and kinetics of nickel and chromium containing oxides; the development of alternative decontamination reagent formulations and processes; and the formulation of guidelines for the selection, verification and application of decontamination processes. Regarding the latter point, verification tests on strong chemical decontamination techniques are being conducted in Japan [210]. Comparison tests on eight separate chemicals for decontamination are reported in Ref. [248]. Testing and evaluation of 17 decontamination chemicals are reported in Ref. [249].

The following list has been mainly adapted from a USDOE Handbook [183] and presents the status of each technique. Detailed descriptions and applications for

TABLE II. USE OF CHEMICAL TECHNIQUES IN DECONTAMINATION OF DIFFERENT MATERIALS AND SURFACES

Chemical techniques	Application material/surface[a]	Remarks
6.2.1.1 Strong mineral acids		
Nitric acid	SS[b], Inconel	
Sulphuric acid	CS[c], SS	
Phosphoric acid	CS	
Fluoroboric acid	Metals and metallic oxides	
Fluoronitric acid	Metals and metallic oxides	
6.2.1.2 Acid salts	Metal surfaces	
6.2.1.3 Organic acids	Metal and plastic surfaces	
Formic acid	Metals and metallic oxides	
Oxalic acid	CS, Al	Used to remove rust, niobium and fission products
Oxalic peroxide	SS, Al	
Citric acid	SS	
6.2.1.4 Bases and alkaline salts	CS	Facilitate degreasing and passivation
6.2.1.5 Complexing agents	Metals	Prevent redeposition
6.2.1.6 Bleaching	Organic materials from metals	Used to remove chemical agents
6.2.1.7 Detergents and surfactants	Organic materials from metals, plastics, concrete	Mild, all-purpose cleaners
6.2.1.8 Organic solvents	Organic materials from metals, plastics, concrete	Used to remove organic materials
6.2.1.9 Multiphase treatment processes		
REDOX[d]	CS, SS	Facilitates solubility
LOMI[e]	CS, SS, Inconel, Zircaloy	
Alkaline permanganate	SS	
CORD[f]/POD[g]	SS, Inconel	Chromium oxidation
Alkaline permanganate followed by ammonium citrate	CS, SS	
Alkaline permanganate followed by ammonium citrate with EDTA[h]	CS, SS	EDTA added to keep iron oxide in solution

TABLE II. (cont.)

Chemical techniques	Application material/surface[a]	Remarks
Alkaline permanganate followed by citric acid	SS (300 series only), Inconel	
Alkaline permanganate followed by sulphamic acid	CS, SS	
Alkaline permanganate followed by oxalic acid	CS, SS	
Nitric acid, permanganate and hydrofluoric acid	CS, SS	
Strong oxidizing decontamination process	Inconel 600, CS, SS	
6.2.1.10 Foam decontamination	Porous and non-porous surfaces	
6.2.1.11 Chemical gels	Porous and non-porous surfaces	
6.2.1.12 Decontamination by pastes	CS,SS	
6.2.1.13 Decontamination by chemical fog	CS, SS	
6.2.1.14 Gas phase decontamination	Fuel enrichment systems	
6.2.1.15 Proprietary technologies		
CORPEX	CS, SS, Al, Cu, rubber, plastic	
TechXtract	Concrete, Pb	
CAN-DECON	CS, SS	Used on piping systems
EMMA	CS, SS, Inconel	
DECOFOR	CS, SS	
DECOPAINT	CS, SS	
DECONCRETE	Concrete	

[a] Suggested uses are for general guidance and consideration must be given to all materials used in construction prior to application of a given technique.
[b] Stainless steel.
[c] Carbon steel.
[d] Reducing oxidizing.
[e] Low oxidation state of metal ions.
[f] Chemical oxidizing/reducing decontamination.
[g] PWR oxidizing decontamination.
[h] Ethylenediaminetetraacetic acid.

TABLE III. USE OF MECHANICAL TECHNIQUES IN DECONTAMINATION OF DIFFERENT MATERIALS AND SURFACES

Mechanical techniques	Application material/surface	Remarks
6.2.2.1 Flushing with water	Large areas (too large for wiping or scrubbing)	
6.2.2.2 Dusting/vacuuming/ wiping/scrubbing	Concrete and other surfaces	Used mostly as a pretreatment
6.2.2.3 Strippable coating	Large non-porous surfaces, easily accessible	
6.2.2.4 Steam cleaning	Complex shapes and large surfaces	
6.2.2.5 Abrasive cleaning	Metal and concrete surfaces, hand tools	
6.2.2.6 Sponge blasting	Paints, protective coatings, rust, metal surfaces	
6.2.2.7 CO_2 blasting	Plastics, ceramics, composites, SS, CS, concrete, paints	Can damage soft materials
6.2.2.8 High pressure liquid nitrogen blasting	Metals, concrete	A variation of grit blasting
6.2.2.9 Freon jetting	Discrete parts inside a glovebox	Should be avoided for environmental reasons
6.2.2.10 Wet ice blasting	Coatings, surface of concrete	
6.2.2.11 High pressure and ultra high pressure water jets	Inaccessible surfaces, structural steel and cell interiors	Can drive contamination into porous surfaces
6.2.2.12 Grinding/shaving	Floors and walls	Used to remove thin layers of contamination
6.2.2.13 Scarifying/scabbling/ planing	Concrete and steel surfaces	
6.2.2.14 Milling	Large number of similarly shaped items	
6.2.2.15 Drilling and spalling	Concrete only	Used to remove a few cms of contaminated concrete
6.2.2.16 Expansive grout	Thick layers of contaminated concrete	Need to drill surface in order to insert grout
6.2.2.17 Paving breaker and chipping hammer	Floors and walls	

Note: SS: stainless steel; CS: carbon steel.

TABLE IV. USE OF ALTERNATIVE[a] TECHNIQUES FOR DECONTAMINATION OF MATERIALS

Techniques	Application material/surface	Remarks
6.2.3.1 Electropolishing	Conductive surfaces	Commercially available using a range of electrolytes
6.2.3.2 Ultrasonic cleaning	Small objects with loosely adhering contamination	Not recommended for concrete and materials which absorb ultrasonic energy and solvents
6.2.3.3 Melting	Metal	Commercially available
6.2.4.1 Light ablation	Epoxy paints, adhesives, corrosion products, concrete	Emerging technology
6.2.4.2 Microwave scabbling	Surface layers of concrete	Emerging technology
6.2.4.3 Thermal degradation	Organic coatings on non-combustible workpieces	Emerging technology
6.2.4.4 Microbial degradation	Walls and floors with hazardous residues	Emerging technology
6.2.4.5 Electromigration	Soil, concrete, groundwater	Emerging technology
6.2.4.6 Exothermic, highly metallized powders	Removal of coatings from concrete and metal surfaces	Emerging technology
6.2.4.7 Supercritical fluid extraction	Removal of contamination from surfaces and soil	Emerging technology

[a] Other than chemical and mechanical techniques.

most of the following techniques can also be found in the EC Handbook [39]. Actual experience with some of these is described in Ref. [250] with further references to the sources of information. A short review of chemical decontamination systems is provided in Refs [233, 251].

6.2.1.1. Strong mineral acids

The main purpose of these is to attack and dissolve metal oxide films and lower the pH of solutions in order to increase solubility or ion exchange of metal ions [183]. A recent application is shown in Fig. 5.

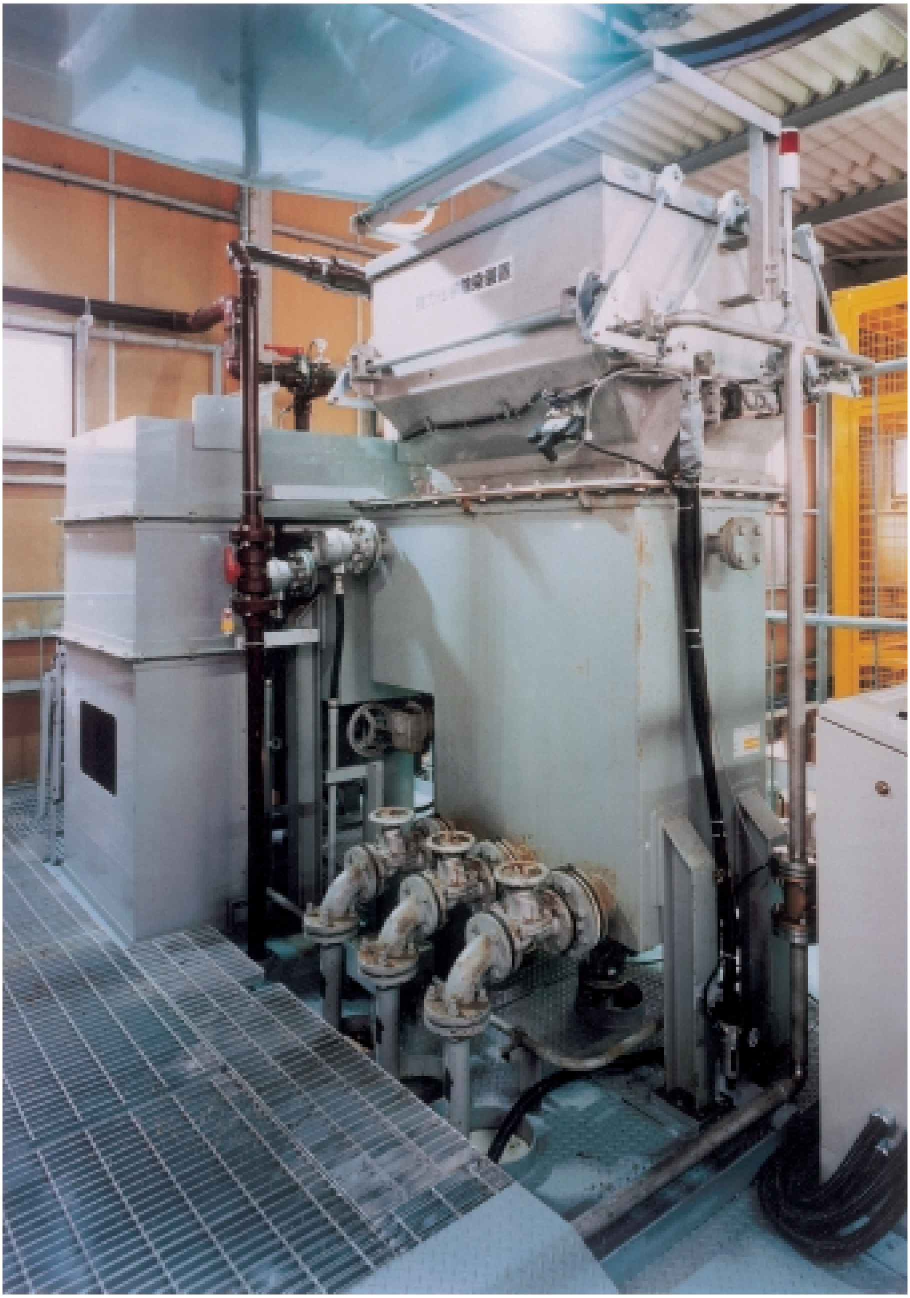

FIG. 5. Strong chemical decontamination apparatus, Nuclear Power Engineering Corporation, Japan.

(a) Nitric Acid

Nitric acid is widely used for dissolving metallic oxide films and layers in stainless steel and Inconel systems. However, difficulties may still arise in specific applications. For example, it was used on one section of a heat exchanger at the UK's Windscale advanced gas cooled reactor (WAGR) and while very good decontamination of the boiler tubes was achieved, residual activity in the internal insulation of the structure has proved to be a more difficult problem [80].

Successful industrial tests were carried out in the Russian Federation at radiochemical combines in Cheljabinsk and Krasnojarsk using a submerging process for molybdenum steels and EP-630 alloy [245]. Other investigations have been carried out at the Savannah River site (SRS) in the USA [77].

(b) Sulphuric acid

Sulphuric acid is an oxidizing agent used to a limited extent for removing deposits that do not contain calcium compounds. Tests with sulphuric acid–cerium (IV) solution are reported in Refs [252, 253]. It has been used successfully at the JPDR in Japan [132, 254] and sulphonitric acid has been tested successfully at the Rapsodie reactor, France [255, 256]. Cerium (IV) ions were added to increase the hardness of the reagents in order to balance the temperature decrease. This technique has also been used at the Capenhurst facility in the UK [77] (see also Refs [257, 258]).

(c) Phosphoric acid

Phosphoric acid is generally used for the decontamination of carbon steel because it rapidly defilms and decontaminates carbon steel surfaces. However, the resulting wastes may create a difficult treatment problem [191, 196].

(d) Fluoroboric acid

Fluoroboric acid technology was designed specifically for D&D. This acid attacks nearly every metal surface and metallic oxide [250]. It is reported (DECOHA process) that thin layers of the contaminated metal can be removed from the surface with minimal damage to the object [183], therefore creating a minimum volume of waste. A comprehensive description of the DECOHA thermodynamics and its main applications are given in Refs [259–261]. An advanced DECOHA process has been developed in the Russian Federation [262] and an experimental facility at Chernobyl NPP has been operating since 1997 [246].

A decontamination for decommissioning (DfD) process was tested in the mid-1990s with an aim of gaining the unrestricted release of major components. It uses:

low concentrations of fluoroboric acid, at temperatures ranging from ambient to 90°C; permanganate to vary the oxidizing potential; continual ‘rinsing’ to give the required decontamination factor; and ion exchange resin cleanup. A major achievement was the release for recycling in April 1997 of the reactor water cleanup heat exchangers of Quad Cities NPP [263]. Other applications of the DfD process are reported in Refs [264, 265].

(e) Fluoronitric acid

A process using fluoronitric acid has been developed for the rapid decontamination of stainless steel. It has been tested at the Belgian reactor no. 3 (BR3) [266, 267].

6.2.1.2. Acid salts

The salts of various weak and strong acids can be used in place of the acids themselves or, more effectively, in combination with various acids to decontaminate metal surfaces. Possible salts include: sodium phosphates and polyphosphates, sodium bisulphate, sodium sulphate, ammonium oxalate, ammonium citrate, sodium fluoride and ammonium bifluoride [183, 196].

6.2.1.3. Organic acids

The use of organic acids is widespread in the nuclear industry for decontamination, mainly during plant operation, and to a lesser extent for decommissioning activities. A discussion of the properties of these acids is provided in Ref. [268]. They are used not only on metal surfaces, but also on plastics and other polymeric compounds [183]. Examples include formic acid, oxalic acid, oxalic peroxide and citric acid.

(a) Formic acid

A process developed for Slovakia’s A1 NPP decommissioning project is based on the treatment of material with formic acid, complexing agent and corrosion inhibitor, and simultaneous agitation by ultrasound in a purpose-built bath. It is reported that this process allowed the fast and effective removal of surface contamination from levels of 10^3–10^4 Bq/cm^2 to below release levels [269].

(b) Oxalic acid

Oxalic acid is effective for removing rust from iron and is an excellent complexer for niobium and fission products [183]. During cleaning, however, secondary deposits of ferric oxalate containing radionuclides may be formed on the decontaminated surfaces [196]. Oxalic acid is a basic component of circuit decontamination technology used for RBMK reactors [196, 246, 270].

(c) Oxalic peroxide

Oxalic peroxide is used for the simultaneous dissolution of UO_2 and for the defilming and decontamination of metals [183, 196].

(d) Citric acid

Citric acid is used as a reducing agent and it is very effective for decontaminating stainless steel in a two step process following alkaline permanganate treatment [183]. It has been used at Capenhurst in the UK [77] and solutions containing citric acid and Na_2-chromotropic acid have been used in the Kola NPP in the Russian Federation [196].

6.2.1.4. Bases and alkaline salts

Caustic compounds are used both by themselves and in solution with other compounds to remove grease and oil films, to neutralize acids, to act as surface passivators, to remove paint and other coatings, to remove rust from mild steel, to act as a solvent for species that are soluble at high pH, and as a means of providing the right chemical environment for other agents, mainly oxidizing ones [183]. Examples include: potassium hydroxide, sodium hydroxide, sodium carbonate, trisodium phosphate, and ammonium carbonate.

Experience in the use of sodium hydroxide baths at Gundremmingen-A NPP (KRB-A) and Versuchsatomkraftwerk Kahl (VAK) reactors in Germany proves that its use is often enough to reach free release limits in the case of materials with low levels of contamination [271]. Caution should be exercised when applying high pH solutions to aluminium [196].

6.2.1.5. Complexing agents

Complexing agents form stable complexes with metal ions, solubilize them, and prevent their redeposition out of solution [183, 196, 272]. Common applications include use of the following agents:

— Oxyethylidenediphosphonic acid (OEDPA)
— Diethylenetriaminepentaacetic acid (DTPA)
— Ethylenediaminetetraacetic acid (EDTA)

— Hydroxyethylenediaminetriacetic acid (HEDTA)
— Organic acids (see Section 6.2.1.3)
— Sodium or ammonium salts of organic acids
— Nitrilotriacetic acid
— Picolinic acid.

Problems may occur with the conditioning if the secondary waste contains complexing agents, i.e. solidification of concrete and stability of resins [273].

6.2.1.6. Bleaching

Bleach is most effective in removing chemical agents from surfaces. Traditionally, calcium hypochlorite has been used, although recently sodium based bleach formulations have found some applications [183].

6.2.1.7. Detergents and surfactants

Detergents are effective, mild, all-purpose cleaners for treating all facility surfaces, equipment, clothes and glassware. They are not effective in dealing with metal corrosion and long-standing contamination. Surfactants are used as wetting agents, detergents and emulsifiers [183, 196, 274].

6.2.1.8. Organic solvents

Solvents are used in decontamination for removing organic materials, for example grease, wax, oil and paint from surfaces and for cleaning clothes [183, 196]. Possible solvents include: kerosene, 1,1,1-trichloroethane, tetrachloroethane, trichloroethylene, perchloroethylene, xylene, petroleum ethers and alcohols.

6.2.1.9. Multiphase treatment processes

Multiphase treatment processes combine a variety of chemicals and processes to achieve a more effective decontamination and are widely used [183]. Specific experience from France is detailed in Ref. [275]. A few of these processes are described below.

(a) Reducing oxidizing (REDOX) agents

REDOX agents increase or reduce the oxidation state of the superficial metallic oxide layer on the contaminated metal thereby making it more soluble [183]. Verification tests on REDOX type decontamination techniques are being conducted in Japan [210] and China [276]. Most of these REDOX decontamination processes are multistep applications. An initial oxidation step (commonly alkaline or acidic permanganate) is used to increase the oxidation state of the metal ions. This is followed by a reduction step aimed at dissolving the metal cations. The performance of the REDOX process after abrasive blasting is discussed in Ref. [241].

(b) Low oxidation state of metal ions (LOMI)

The LOMI process was primarily developed for the Winfrith steam generating heavy water reactor (SGHWR) in the UK. It can be applied to structural materials such as different types of carbon and stainless steels, Inconels and Zircaloy [183]. In PWRs it is normally followed by an oxidizing stage. Many LOMI decontamination operations have been successfully implemented in various countries [233, 277–279].

(c) Alkaline permanganate

Alkaline permanganate is used to oxidize Cr (III) oxides (which are insoluble in acids and alkalis) present in the corrosion films to Cr (VI) in the form of CrO_4^{2-} anions which are soluble over a wide range of pH values [183, 196]. The alkaline permanganate–LOMI process has successfully decontaminated the stainless steel surfaces of the BWRs at the Tarapur Atomic Power Station in India [280] and a version of the process has also been used at the Paks NPP in Hungary [281]. Alkaline permanganate enhanced with ultrasound has been used at the Junta Energia reactor no. 1 (JEN-1) in Spain [282, 283] (see Section 6.2.3.2).

The ELOMIX concept has been developed to reduce the volume of waste arising from the LOMI process. This method has been successfully used in a small pilot cell at Dresden Unit 2 in the USA [183].

(d) Chemical oxidizing/reducing decontamination (CORD) and PWR oxidizing decontamination (POD) multistep processes

In the CORD process, permanganic acid is added to the system to oxidize Cr (III) and dicarboxylic acid is then added directly. Dissolved metals may be removed by ion exchange using ‘on-line’ systems or by subsequent evaporation of the solvent [183]. The CORD method was reported to be successful at Oskarshamn Unit 1 in Sweden [284], and at the BR3 facility, Belgium, where it was applied to a full system decontamination process and was demonstrated to be both cost and dose effective [266, 267, 285–292]. The CORD method was also used as the basis for the decontamination of the primary circuit of the VAK plant, Germany [293] and was shown on a laboratory scale to be effective at the Rheinsberg WWER [294], where the organic acids were decomposed by intense ultraviolet light. A comprehensive overview of CORD applications is given in Ref. [295] (see also Ref. [233]).

The POD method is similar to the CORD and other methods and is based on the reduction of an oxidizing solution using organic acids (e.g. oxalic acid). In the Russian Federation, such technology is standard for the primary circuit decontamination of WWER reactors [246, 270].

(e) Alkaline permanganate followed by ammonium citrate

Ammonium citrate has been successfully used after alkaline permanganate pretreatment and water rinsing to decontaminate stainless steel and carbon steel [183].

(f) Alkaline permanganate followed by ammonium citrate with EDTA

EDTA can be added to the former process, i.e. alkaline permanganate followed by ammonium citrate, to keep the iron oxide in solution and inhibit its redeposition [183]. One example of its application is at the nuclear submarine prototype reactor, UK [296].

(g) Alkaline permanganate followed by citric acid

A mixture of oxalic acid, citric acid and an inhibitor is an effective decontaminant of stainless steel as the second step after alkaline permanganate pretreatment [183].

(h) Alkaline permanganate followed by sulphamic acid

This technique is effective in removing the contaminated film from stainless steel piping without causing redeposition of a precipitate [183].

(i) Alkaline permanganate followed by oxalic acid

This process has been successful in removing aged films on high temperature stainless steel water piping, but it has the disadvantage of causing redeposition in the form of a tenacious oxalate film on the metal [183]. This can be avoided by using an acidic permanganate solution. Alkaline permanganate — oxalic acid solutions have been used in the Russian Federation for the circuit decontamination of Novovoronezh NPP (WWER-440), Belojarsk NPP (AMB-100 BWR type) and others. To prevent the formation of secondary oxalate deposits, hydrogen peroxide was used in the final stage [196, 246]. The main disadvantage of this process (as for other multistage technologies) is the large volume of spent solution and flushing water generated. This can exceed the original circuit volume by up to a factor of ten.

(j) Nitric acid, permanganate and hydrofluoric acid

The nitric acid, permanganate and hydrofluoric acid process has been investigated and proved successful in China [297].

(k) Strong oxidizing decontamination process

The strong oxidizing decontamination process is based on the use of ozone and Ce (IV) in an acid solution [298]. It was applied during the decontamination of the steam generator of the Ågesta reactor in Sweden [299]. A solution of nitric acid, Ce (IV) and ozone was used successfully in the decontamination of Inconel 600 tube bundles at several steam generators in Europe [300], including the Dampierre PWR, France [197]. The strong oxidizing decontamination method was later tested on stainless steel material from the Greifswald WWER, Germany. It proved capable of reaching clearance levels [301]. Three applications of the Ce (IV) decontamination process at the Pacific Northwest National Laboratory (PNNL) and the West Valley demonstration project in the USA are described in Ref. [302].

6.2.1.10. Foam decontamination

Foam, such as that produced by detergents and wetting agents, is used on its own or as a carrier for chemical decontamination agents. This process is well developed and widely used, especially for large components with complex shapes or large volumes. It can be applied to surfaces in any orientation [183] and produces low volumes of secondary waste. The equipment is cheap, simple and suitable for either manual or remote deployment [303]. When applied to a series of large carbon steel valves having complex internal configuration, it yielded very low residual contamination levels, allowing the metal to be melted down in an approved steel mill [255]. It was used effectively with a sulphonitric mixture during the decontamination of a graphite/gas cooler made of ferritic steel and brass, [197, 304].

Foaming equipment was developed in the UK and was used in the maintenance bay at the DIDO high activity handling cell [146] and at the co-precipitation plant at Sellafield [305]. An automatic foam spray device was developed in France for the decontamination of pipes 0.5–1.6 m in diameter and 2–3.5 m long [306, 307]. Some experiments with foam technology have been performed at the SRS [77]. Information on the development of foam decontamination in Italy is given in Ref. [308] (see also Refs [196, 233, 246, 309]).

6.2.1.11. Chemical gels

Chemicals gels are used as carriers of chemical decontamination agents and are sprayed or brushed onto a component or surface, allowed to work, then scrubbed, wiped, rinsed or peeled off [183]. Techniques using aggressive agents in liquid and gel-like forms have been developed and assessed within the EC R&D programme [310]. This method is effective in situations where long contact times are required, together with the need to minimize waste [77]. Gel spraying has been found to be a good process for dealing with beta/gamma emitters on mild steel pipes with simple geometry. At the G2/G3 reactors in France this technique enabled the operator to reach the residual activity objective with low volumes of secondary waste [197, 255]. This technique was also used at the vitrification pilot plant (PIVER) cell, also in France, with sulphuric/phosphoric acid and Ce (IV) gels [311] (see also Ref. [233]).

6.2.1.12. Decontamination by pastes

Pastes are widely used for treating metal surfaces, particularly stainless steel. They consist of a filler, a carrier, and an acid or mixture of acids as the active agent [233]. A variation on this method is widely used in the CIS. This involves the inclusion of an abrasive within the paste. Mechanical action with the abrasive assists in breaking down surface films, increasing the effectiveness of the chemical reagents [246].

6.2.1.13. Decontamination by chemical fog

Decontamination by chemical fog is being developed under EC sponsorship and this technique uses a chemical agent dispersed as a fog [233]. It was used in a laboratory at KRB in Germany where an experimental set-up for the ultrasonic generation and electrostatic deposition of the chemical on a target was constructed and tested [312]. Water and/or acidic fogs are used in the Russian Federation for the decontamination of equipment removed from liquid metal cooled reactors [196].

Verification tests on spray methods for large component decontamination techniques are being conducted in Japan [210] (see also Ref. [77]).

6.2.1.14. Gas phase decontamination

Demonstration of the effectiveness of this long term, low temperature technique is reported in Ref. [87]. It uses a mixture of treatment gases which are injected into a cell containing diffusion cascade equipment at low pressure and allowed to react with uranium deposits (see also Ref. [313] for the use of chlorine trifluoride and uranyl fluoride for the same purpose).

6.2.1.15. Proprietary technologies

A description and an evaluation of the CORPEX™ chemical process are reported in Refs [212, 314]. This is a non-destructive cleaning method that removes only the contaminant and the matrix that fixes the contaminant to the surface. Another proprietary method is TechXtract™, which is based on the application of a mixture of chemical agents to decontaminate porous surfaces such as concrete [77, 314–316] and metals such as lead [317]. Other multiphase treatment processes such as CAN-DECON (Canada), and the EMMA process (France) are reported in Refs [15, 39, 233]. New metal decontamination processes are: DECOFOR, based on formic acid; and DECOPAINT, based on alkalis; and the concrete decontamination process DECONCRETE, based on phosphoric acid; and mechanical stripping with steel brushes and these processes are described in Ref. [318]. It should be noted that other proprietary technologies may exist and their omission here does not reflect adversely on the capabilities of any of these processes.

6.2.2. Mechanical decontamination

In general, mechanical decontamination methods can be used on any surface where contamination is limited to near surface material. The following list has been adapted mainly from the USDOE Handbook [183] and represents the current status of each technique. Detailed description and applications for each of the following techniques can also be found in the EC Handbook [39]. Actual experience with some of these is described in Ref. [250] with further references to the sources of information.

6.2.2.1. Flushing with water

As a decontaminant, water acts by dissolving chemical species or by eroding and flushing loose debris from the surface. Flushing with water, which can be used for areas that are too large for wiping or scrubbing [183], involves flooding a surface with hot or cold water, followed by water collection.

6.2.2.2. Dusting/vacuuming/wiping/scrubbing

Dusting, vacuuming, wiping and scrubbing involve the physical removal of dust, aerosols and particles from building and equipment surfaces using common cleaning techniques [183]. Suction cleaning is most useful as a pretreatment for removing large quantities of loose contaminants [303], for example the concrete hot cells at Risø in Denmark were remotely vacuumed before further decontamination took place [319]. Specially designed vacuum cleaners incorporating air filtration systems are widely used at Chernobyl NPP [246, 320]. A dustless decontamination system, followed by a manually controlled scabbler and a manually controlled needle gun, were used to remove contamination from concrete surfaces at Rocky Flats environmental technology site in the USA [77, 321] (see also Ref. [233]). Figure 6 shows details of hand scrubbing during the decommissioning of Gentilly-1 in Canada.

6.2.2.3. Strippable coatings

The strippable coating technique consists of a two stage process, (1) the application of a polymer and decontaminant mixture to a contaminated surface and (2) the removal of the stabilized polymer layer after setting. It is applicable to a wide range of contaminants and materials, with the best results achieved on large non-porous surfaces that are easily accessible [183]. Among many other applications this technique has been used at the SRS [77], at Rocky Flats for decontamination of gloveboxes [322], at the Sellafield co-precipitation plant [305], at Chernobyl [244, 246, 320], and at a hot cell in a radioisotope production facility in Indonesia [323]. Figure 7 shows the removal of a strippable coating from a size reduction containment facility used during glovebox decommissioning at ANL.

FIG. 6. Hand scrubbing during the decommissioning of Gentilly-1, Canada.

FIG. 7. Removal of strippable coating to decontaminate the glovebox size reduction containment. Courtesy Argonne National Laboratory, managed and operated by the University of Chicago for the US Department of Energy under contract No. W-31-109-ENG-38.

This technique can also be used as a fixative for contamination control purposes in order to simplify future dismantling [324–326] (see Section 6.6.4). Additional information can be found in Refs [233, 248, 327].

6.2.2.4. Steam cleaning

Steam cleaning combines the solvent action of hot water with the kinetic energy effect of blasting. It is recommended for removing contamination from complex shapes and large surfaces, even if grease or similar substances are present [303], and for removing contaminated soil particles from earth moving and drilling equipment [183]. Secondary waste volumes produced by the process are relatively low as the steam can be collected by vacuum extract, or similar means, and condensed [328, 329]. Decontamination by superheated steam has been successfully applied to Russian KT-50 transport casks [196, 246].

6.2.2.5. Abrasive cleaning

This process uses an abrasive medium such as plastic, glass or steel beads, or grit such as garnet, soda or aluminium oxide. It is used to remove smearable or fixed contamination from metal surfaces such as structural steel components and hand tools and also from concrete surfaces and coatings. In the case of concrete surfaces and coatings, a significant amount of the base material is also removed. This process is most effective on flat surfaces and can also be used on ‘hard to reach’ areas such as ceilings or behind equipment. The process produces comparatively large amounts of secondary waste.

The decontamination process can be carried out wet or dry, with the abrasive medium being driven against the surface by mechanical means, e.g. vibrating bed for small objects (this technique is sometimes called vibratory finishing) or blasted onto the surface using water or compressed air as the propellant. Water or compressed air are generally used for large surfaces.

Abrasive cleaning techniques have been applied in several countries, including Belgium [266, 267, 292, 330], the CIS [196, 244, 246, 320], France [311, 331, 332], Germany [333, 334], Japan [210, 254, 335, 336], the UK [296] and the USA [77, 87, 248, 337–339].

6.2.2.6. Sponge blasting

Sponges made of water based urethane, when blasted onto a surface, create a scrubbing effect by expanding and contracting. An ‘aggressive’ grade of sponge, impregnated with abrasives, can be used to erode material such as paints, protective coatings and rust [183]. Applications and more details are given in Refs [340, 341].

6.2.2.7. CO_2 blasting

Carbon dioxide blasting is a variation of grit blasting, in which CO_2 pellets are used as the cleaning medium. The technique has proven effective with plastics, ceramics, composites and stainless steel, although soft materials can be damaged by the process and brittle materials may shatter [183]. One advantage of the process is that the bulk of the secondary waste is in the form of a gas which is easy to treat [303]. Testing of this technique is being undertaken at ORNL for the decontamination of lead [77] and at the Idaho Chemical Processing Plant (ICPP), also in the USA [248, 342, 343]. Successful application of the technique is reported for the Joint European Torus project in the UK [344] and other applications in the USA and Japan are reported in Refs [345, 346]. A centrifugal dry ice blaster has been used at ORNL [347]. More recent results were reported from Belgium, where over 300 t of carbon steel, stainless steel and polypropylene were decontaminated for free release [348].

6.2.2.8. High pressure liquid nitrogen blasting

High pressure liquid nitrogen blasting is a variation of grit blasting whereby abrasive is injected into a liquid nitrogen jet, the jet propelling the grit onto the surface to be decontaminated. The contamination is removed by the embrittlement induced by the liquid nitrogen and the abrasive action of the grit. This technique has been evaluated at the ICPP [248].

6.2.2.9. Freon jetting

Decontamination by freon jetting is effected by directing a high pressure jet of a freon cleaning solvent onto the surface to be cleaned. It is usually used on discrete components inside a glovebox, but experimental units have been developed for in situ cleaning. However, regulatory restrictions on the use of freon can limit the application of this technique [233]. For example, when it was learned that the dry cleaning of workers' protective clothing was responsible for 80% of Ontario Hydro's ozone depleting emissions, the company's nuclear division switched to traditional wet washing [349]. Russian experience with this technology is cited in Refs [244, 246, 320].

6.2.2.10. Wet ice blasting

Wet ice blasting is a variation of grit blasting where a compressed air jet is used to propel a mixture of water and ice crystals onto the surface to be decontaminated. This technique will remove coatings and some fixed surface contaminants but will not remove more than the surface layer from concrete. This process has been used at the PIVER cell in France [311].

6.2.2.11. High pressure and ultra high pressure water jets

High pressure water processes use a pressurized water jet to remove contamination from the surface of the workpiece, the contamination being removed by the force of the jet. Pressures can range from 10^5 Pa to more than 10^8 Pa; the pressures and flow rates being optimized for individual requirements. Recirculation and treatment systems can also be used to minimize secondary waste production. Typical applications include the cleaning of inaccessible surfaces such as the interiors of pipes [350], structural steel work and cell interiors [197, 319]. Figure 8 shows structural steel being decontaminated under water with a hydrolaser lance.

Depending on the pressures used, water jetting will remove paint, coatings, galvanized layers from sheet steel and tenacious deposits without damaging the underlying surface [351]. This technique has been used at the UK's Berkeley power station, where it proved an effective and efficient process [352]. Variations of this

FIG. 8. Structural steel being decontaminated under water using a hydrolaser lance at Gentilly-1, Canada.

technique include the use of glycerine as the pressurized medium [250] or the entrainment of grit in the water jet. When grit is entrained, then this is the same process as grit blasting (Section 6.2.2.5). Further information is contained in Ref. [77]. Recent R&D work in the EU and CIS is described in Refs [196, 244, 246, 320, 353, 354]. Experience with this technology at Paks NPP in Hungary is described in Ref. [355].

6.2.2.12. Grinding/shaving

Grinding/shaving uses coarse grained abrasives in the form of either water cooled or dry diamond grinding wheels or multiple tungsten carbide surfacing discs.

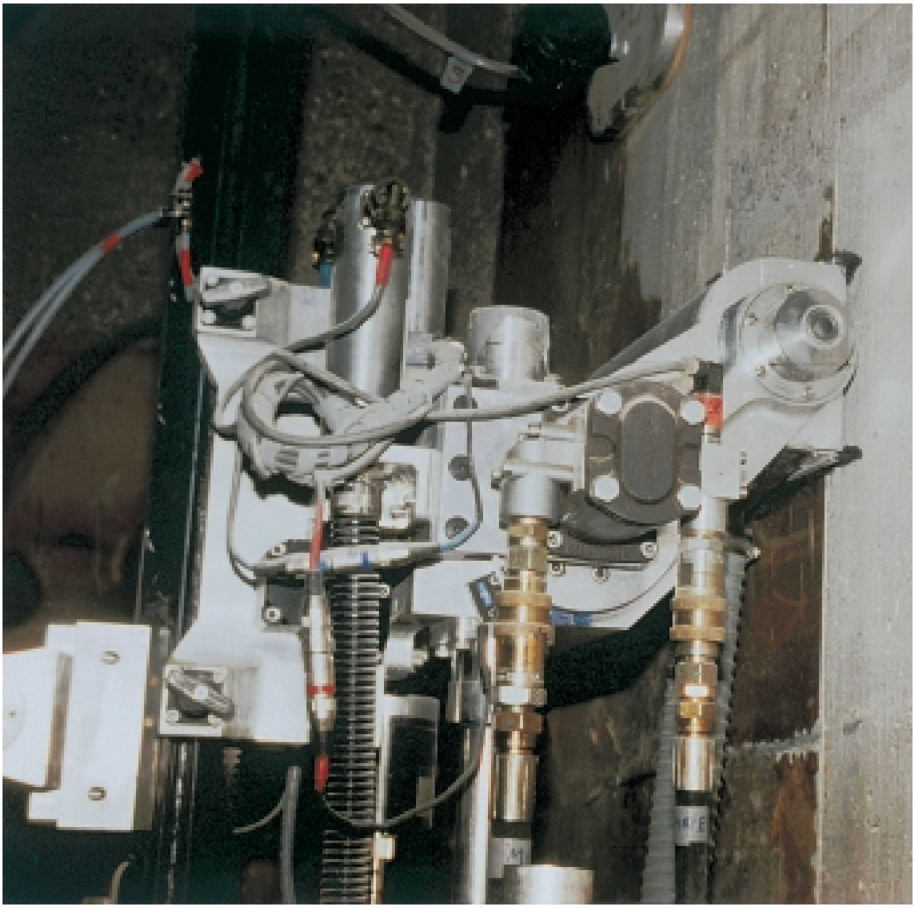

FIG. 9. Concrete decontamination using an automatic wall shaver equipped with a diamond tipped rotary cutting head (detailed view).

It is recommended for use where thin layers of contamination need to be removed [183]. Diamond grinders have been used for the decontamination of floors and walls at the JPDR [253] and also at the Los Alamos National Laboratory (LANL) phase separator pit decommissioning project [321] (see also Ref. [233]). Another similar technique to grinding is shaving; this has been used at the Eurochemic facility (Fig. 9) [292, 356] and is planned for use on the Windscale piles chimneys, having already been demonstrated at C reactor, Hanford [357, 358].

6.2.2.13. Scarifying/scabbling/planing

Scarifying/scabbling/planing are used to abrade the surface of concrete structures to remove contamination. One method uses scabblers, consisting of several pneumatically operated piston heads, to strike simultaneously a concrete surface. Another method is a needle gun, which is used on both concrete and steel surfaces and consists of uniform sets of several millimetre long needles, which are pneumatically driven. A decade ago, concrete scarification was considered a rudimentary approach to decontamination owing to poor performance. Nowadays, refined scarifiers are available which are reliable and provide the desired profile for new coating systems [183, 250]. These processes are very effective for removing the

FIG. 10. Decontamination of a floor using a scabbler, JPDR decommissioning project.

thin contaminated layer from the surface of concrete and a good range of industrial equipment is now available [303]. They have been demonstrated at the ICPP [248] and at ANL's CP-5 reactor [359]. A manually controlled scabbler/needle gun was used to remove contamination from concrete surfaces at a facility at the Rocky Flats site [77, 360] (see also Ref. [316]). Scabblers and a needle gun have also been used for the decontamination of floors and walls at the JPDR [252, 253, 335] (Figs. 10, 11). The steel dome of the KKN facility was cleaned by similar means [361]. Other references on this topic include Refs [233, 266, 267, 287, 292, 362].

A study comparing mechanical scabbling, the controlled use of explosives and microwave scabbling used in dismantling the LIDO biological shield is described in Ref. [181]. In a similar application, a planer was equipped with captive tungsten carbide shot, supported on flexible flaps, which were rotated against the contaminated surface. The particles removed were collected in a drum by a vacuum system fitted with a high efficiency particulate air filter [363].

6.2.2.14. Milling

Metal milling uses rotating cutters to shave off layers of material and is most effective where there is a large number of similarly shaped items, or large areas,

FIG. 11. Decontamination of a floor using a needle gun, JPDR decommissioning project.

requiring decontamination. In the USA, metal milling technology has been used at ORNL's K-25 site to decontaminate individual metal items [183], at FSV [364] and at ANL's CP-5 reactor [363, 365] (see Section 6.3.1.7).

6.2.2.15. Drilling and spalling

The drilling and spalling technique involves drilling 25–40 mm diameter holes approximately 75 mm deep into which a hydraulically operated spalling tool having an expandable tube is inserted. A tapered mandrel is then hydraulically forced into the hole to spread the 'fingers' and spall off the concrete. It is mainly applicable to concrete and is recommended for removing contamination which penetrates a few centimetres below the surface. It has been used at the PNNL [183, 233] and demonstrated at the Hanford C reactor [366].

6.2.2.16. Expansive grout

Expansive grout is used as a dismantling technique but can also be used for decontamination through its ability to remove a thick layer of contaminated concrete [183] (see further details in Section 6.3.4.2).

6.2.2.17. Paving breaker and chipping hammer

Equipment such as the paving breaker and the chipping hammer is primarily used in demolition activities and is also referred to as a 'jackhammer'. It is mainly used to remove surface contamination and the surface left on completion of operations may be very rough [183, 320]. Chipping hammers have been used for the decontamination of floors and walls at the JPDR [253] and Chernobyl NPP [320] and the floor pavement at KKN was chiselled off [367] (see also Ref. [233] and Section 6.3.4.4).

6.2.3. Other established decontamination techniques

Detailed descriptions and applications for each of the following techniques can be found in Ref. [250]. Actual experience with some of these is also described in Refs [39, 183] with further references to the sources of information.

6.2.3.1. Electropolishing

Electropolishing is generally an anodic dissolution technique where a controlled amount of material is stripped from the surface of the workpiece along with the contamination. The process works for any conductive metal, providing

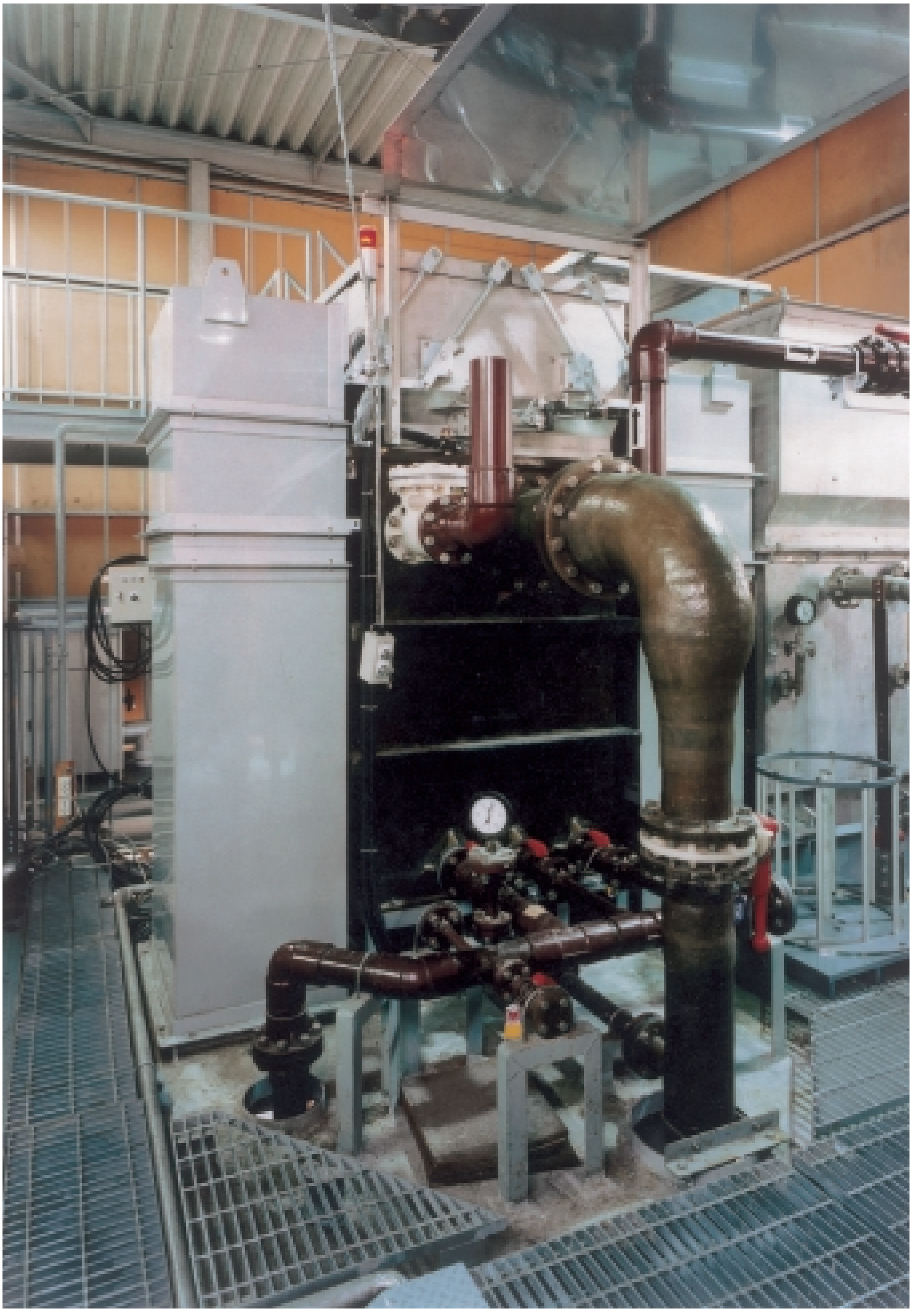

FIG. 12. Electrolytic decontamination apparatus, Nuclear Power Engineering Corporation, Japan.

protective surface coatings are not present, but the choice of electrolyte is important. The components are decontaminated following removal by immersing them in a bath of fluid [77, 183, 197, 233, 250, 252, 368] or treated in situ using closed circuit systems which can be deployed from manipulators or operated manually [369]. Both applications are reported to have been used at Slovakian NPPs [269]. In one application described in Ref. [370], decontamination trials were performed by deploying an electropolishing head unit under both closed circuit television control and programmed robotic control. Another remote control application is described in [336]. Decontamination by electropolishing of components and systems in the turbine house and of the primary water systems at the VAK reactor is reported in Ref. [371]. An electroetching decontamination technique has been developed at the RM2 installation in France for decategorizing alpha emitting radioactive waste [372]. Owing to their high efficiency and the low volume of radioactive waste produced, electrochemical methods for decontamination have been widely developed in the Russian Federation and successfully used at Kola, Belojarsk, Kalinin, Leningrad and other Russian NPPs and research centres [196, 244, 270, 320, 373]. Typical electrolytes are based on phosphoric acid [374–378], nitric acid [183, 283, 305] and organic acids [197] (see also Refs [258, 277, 292, 379, 380]). New developments in electrolytic decontamination are described in Ref. [381] (Fig.12).

6.2.3.2. Ultrasonic cleaning

In ultrasonic cleaning, high frequency energy is converted into low amplitude mechanical energy, i.e. vibrations. The vigorous scrubbing action produced by the cavitation of a cleaning solution is then imparted to a submerged object. This technique is usually applied to small objects with primarily loose deposits and adhered contamination. It is not applicable for concrete or for materials which absorb ultrasonic energy. The simultaneous use of ultrasound and aggressive chemicals was used to decontaminate the tube bundle of a feedwater preheater at the Garigliano BWR in Italy to below unrestricted release levels. Test results are reported in Refs [382, 383]. Radiometric measurements indicate that the synergy between ultrasonics and chemicals will enhance the decontamination factor and also reduce the time needed for the chemical decontamination [196]. This process is being developed and tested at the BR3 reactor [266, 267] and has been tested at the JEN-1 reactor in Spain [283]. Russian experience is given in Refs [196, 244, 270, 320, 384] (see also Refs [183, 233, 385] on this technique).

6.2.3.3. Melting

To some extent, melting can be considered a decontamination technique. In reality it is a technique with a threefold purpose. While the main goal of the process is the recycling of metals, simultaneous decontamination of the metal occurs during melting because many of the radioactive isotopes separate from the melt and concentrate in the slag. Melting also provides a means of volume reduction and this aspect is of growing interest as waste disposal costs increase. More details and references are given in Section 6.4.2.1.

6.2.4. Emerging technologies

The following list presents some new decontamination technologies which have been developed over the last decade. However, because these technologies have not been extensively field tested, there are still uncertainties in determining their effectiveness and performance. Detailed descriptions and applications for each of the following techniques can be found in Ref. [250]. Actual experience with some of these is also described in Ref. [183] with further references to the sources of information.

6.2.4.1. Light ablation

The light ablation technique uses the absorption of light energy and its conversion to heat to achieve the selective removal of surface coatings or contaminants. Surface coatings such as epoxy paints, adhesives, corrosion products, accumulated airborne pollutants and up to 6 mm thick layers of concrete can be removed using this technique. Laser and xenon flashlight sources for this application are commercially available and a pinch plasma lamp is under development [183].

According to Ref. [250], laser etching and ablation and flashlamp cleaning require demonstration, testing and evaluation. Decontamination by light ablation has been tested at the USDOE's CP-5 and ICPP demonstration projects as well as in other US laboratories [87, 248, 386, 387]. Three types of laser have been tested at the ICPP: continuous wave CO_2, Q-switched Nd:YAG, and Excimer using a krypton fluorine gas [248]. A high power, high repetition rate industrial laser for controlled ablation of coatings from metal and concrete surfaces is being developed by the USDOE [87, 388]. This technology has been evaluated against other techniques and the results are described in Ref. [77]. The development in France of an ultraviolet laser for the decontamination of plastic or metal tanks and chambers is reported in Ref. [389] and laser decontamination of concrete surfaces is being developed in Japan [133, 390].

Laser decontamination might have two advantages over other methods, firstly the production of secondary waste is reduced owing to its being a 'dry' process, and secondly, since the laser beam can be transmitted through an optical fibre, the whole decontamination process can be operated remotely [391].

6.2.4.2. *Microwave scabbling*

Microwave scabbling is a new method of removing the surface of concrete which uses microwave energy to heat the moisture present in the concrete matrix. Continued heating produces steam under pressure which generates internal mechanical and thermal stresses, bursting the surface layer of the concrete. This technique has been developed at the ORNL [183, 392] and a system has also been designed and tested at the Trisaia Research Centre in Italy [197, 393]. The analysis showed that the main factors affecting scarification are the pore dimensions and the evaporable water content of the cement. It was concluded that this is a reliable apparatus, but should be further developed to improve its flexibility and ease of operation.

It was used during the dismantling of the biological shield of the UK's LIDO reactor [39], but the concrete was found to be too dry and unable to produce enough steam to promote fracturing [181, 197, 394]. The technique needs demonstration, testing and evaluation according to Refs [181, 250] (see also Refs [77, 87, 233]).

6.2.4.3. *Thermal degradation*

Thermal degradation uses a controlled high temperature flame or arc which is applied to the surface of a non-combustible workpiece in order to thermally degrade organic surface coatings. Such systems have been used at the Frankford Arsenal in the USA [183]. Scarifying of concrete has also been undertaken using both high temperature flames [197] and plasma [395]. The local heating caused by the passage of the flame or arc causes differential expansion and spalling of the concrete surface.

6.2.4.4. *Microbial degradation (biodecontamination)*

In biodecontamination, a microbial solution is applied to the contaminated area, allowing the microbes to penetrate the surface and contact and consume the contamination. A detergent or solvent wash is then used to remove the reaction products. This technique could be useful for the in situ removal of hazardous residues from walls and floors, abandoned process equipment, storage tanks, sumps, piping, etc. Developments in this field, including laboratory scale demonstrations and field tests, are reported in Refs [396–399].

6.2.4.5. *Electromigration*

Electromigration (or electrokinetics) involves the movement of charged species under the influence of an applied electric field. It can be used for soil cleanup, concrete decontamination, contaminant separation of groundwater and wastewater, containment structures, underground mapping and barrier detection [87, 400]. Initial investigations utilizing this technique to remove contaminants from intact concrete structures are reported in Refs [87, 401]. The performance of this method at the ICPP is reported in Ref. [248] and a theoretical model of the method is described in Ref. [402].

6.2.4.6. Exothermic, highly metallized powders

This technique uses the flameless burning of powders containing Al, Mg, $NaNO_3$ and oil. The powder is applied as a flat layer, approximately 10 mm thick, and is used to remove surface coatings from concrete, e.g. asphalt. Semi-industrial scale tests of this method have been successfully carried out in the Russian Federation [246, 403–405].

6.2.4.7. Supercritical fluid extraction

In the supercritical fluid extraction method, developed in the Russian Federation, liquified CO_2 is used as a solvent together with other chemical reagents. Laboratory tests have shown that 95–99% of radionuclides can be removed from the treated surfaces and the CO_2 evaporated to minimize residual waste volumes [246, 406–408].

6.2.4.8. Other methods under investigation

Other emerging technologies about which only limited information is available and which are undergoing development at this time are: vapour phase transport separation, gaseous decontamination [183, 409], catalytic extraction and solvent washing [250], and explosive removal [77, 181].

6.2.5. Soil decontamination

Soil decontamination techniques are extensively dealt with in a recently published IAEA technical document [410]. A comprehensive publication of the EC in this field is given in Ref. [411]. One example of a new technique, a biochemical method for the decontamination of radioactively contaminated soil by biobleaching of the soil in tanks, has been developed during the last two to three years in the Russian Federation. This technique uses thiobacteria and capillary action and has already been tested on a semi-industrial scale [246, 412].

6.3. DISASSEMBLY

An IAEA publication from the early 1980s [4] presents the following disassembly techniques: plasma arc, arc saw, linear shaped explosive charges and ‘conventional cutting methods’ for metal cutting. For concrete removal the list includes blasting, drilling and rock splitting, flame or thermic lance cutting, diamond sawing and coring, and high pressure water jet cutting. A later overview of techniques and equipment for use in the decontamination and demolition of concrete and metal structures during the decommissioning of nuclear facilities is given in Ref. [7].

The results of a co-ordinated research programme on decontamination and decommissioning have already been reported in an IAEA technical document [20], along with major technical achievements. Areas of potential future work were identified as including: dismantling techniques, methods to minimize secondary waste, development of tools with multipurpose capabilities, continued development of methods to minimize radiation exposure, and exchange of technical information.

An overview and comparison of cutting techniques for piping is given in Ref. [413]. Studies on various cutting tools and techniques are also reported in Refs [210, 211, 292, 413–417]. Actual experience with some decontamination and dismantling techniques is reported and evaluated, and reference is made to the source of information in Ref. [77]. A database on cutting tools (DB TOOL) is also being prepared within the EC R&D programme [139, 197].

An overview of cutting techniques is given in Tables V and VI for general orientation of the reader. Relevant sections of this report are also mentioned. Actual experience with some of these techniques is described in Refs [117, 250] with further references to sources of information. Additional information can be found in the EC Handbook [39] and Ref. [418].

6.3.1. Mechanical cutting techniques

These are techniques whereby the direct action of the tool on the workpiece produces a cut. This is achieved by the tool fracturing, cleaving or eroding the workpiece surface. With the exception of grinding and explosive cutting, these techniques produce easily handled secondary waste streams which can be collected by local extraction systems. They also produce much fewer airborne fumes than thermal techniques, thus simplifying viewing of the cutting operation, although cutting speeds are generally lower.

TABLE V. OVERVIEW OF MECHANICAL CUTTING AND DEMOLITION TECHNIQUES

Cutting technique	Section	Material	Environment	Remote operation feasibility	State of development
Shears	6.3.1.1	All metals	Air/UW	+	+
Power nibblers	6.3.1.2	MS, SS	Air/UW	+	+
Mechanical saws	6.3.1.3	All metals	Air/UW	+	+
Orbital cutters	6.3.1.4	All metals	Air/UW	+	+
Abrasive cutting wheels, blades, wires and core drills	6.3.1.5	All metals, concrete	Air/UW	+	+
Explosives	6.3.1.6	All metals, concrete	Air/UW	+	(+) Controlled blasting (–) Shaped explosives
Milling	6.3.1.7	All metals	Air/UW	+	+
Wrecking ball or wrecking slab	6.3.4.1	Concrete	Air	+	+
Expansive grout	6.3.4.2	Concrete	Air	+	o
Rock splitter	6.3.4.3	Concrete	Air/UW	+	+
Paving breaker and chipping hammer	6.3.4.4	Concrete	Air/UW	+	+

Note: MS: mild steel; SS: stainless steel; UW: underwater; +: excellent; o: average; –: poor.

TABLE VI. OVERVIEW OF THERMAL, HYDRAULIC AND OTHER CUTTING TECHNIQUES

Cutting technique	Section	Material	Environment	Remote operation feasibility	State of development
Thermal cutting techniques	6.3.2				
Plasma arc cutting	6.3.2.1	All metals	Air/UW	+	+
Flame cutting	6.3.2.2	MS	Air/UW	+	+
Powder injection flame cutting	6.3.2.3	All metals, concrete	Air	o	+
Thermic lance	6.3.2.4	All metals, concrete	Air/UW	–	+
Abrasive water jet cutting	6.3.3	All metals, concrete	Air/UW	+	o
Electrical cutting techniques	6.3.5				
Electrodischarge machining	6.3.5.1	All metals	Air/UW	o	o
Metal disintegration machining	6.3.5.2	All metals	Air/UW	o	o
Consumable electrode	6.3.5.3	MS	Air/UW	+	NA
Contact arc metal cutting	6.3.5.4	All metals	Air/UW	+	+
Arc saw cutting	6.3.5.5	All metals	Air/UW	o	+
Emerging technologies	6.3.6				
Liquified gas cutting	6.3.6.1	All materials	Air	o	–
Lasers	6.3.6.2	All metals, concrete	Air/UW	o	o
Shape memory alloys	6.3.6.3	Concrete	Air	TBA	–
Electrical resistance	6.3.6.4	Concrete	Air	o	–

Note: MS: mild steel; UW: underwater; +: excellent; o: average; –: poor; NA: not applicable; TBA: to be assessed.

6.3.1.1. Shears

Shears can be manually, pneumatically, hydraulically or electrically actuated and are used for segmenting metal and crushing concrete. In terms of construction there are three basic types:

- A two bladed device which functions in the same manner as a pair of scissors. These tend to be small lightweight devices for segmenting small diameter pipework and rebar and can be manually or remotely deployed.
- A blade and anvil device where the blade is actuated to force the workpiece against a fixed anvil. These devices tend to be heavier in construction than the scissor type shears and consequently can cut metal components of larger cross-section and thickness. They have also been developed for cutting metal plate using a punch type action and can be deployed remotely, manually or positioned at a fixed location and the workpiece fed into them.
- Demolition shears which are designed for deployment by mechanical excavators and other large construction plant and can be of the anvil or scissor type. The shears are heavy and robust and are used for sectioning structural steel work such as I beams and for crushing concrete to expose or remove the reinforcing bars.

Shearing produces no secondary waste or waste in the form of discreet sections, punched from the workpiece, which can be readily handled and retrieved. The drawbacks of shearing are the size of the tools compared with their relative cutting capacity, and the fact that the action of the shear tends to crush the component being cut. This can result in the generation of projectiles owing to the sudden release of stresses, which in the case of pipework can prevent subsequent internal decontamination.

All three shear types are mature technologies which have seen extensive application worldwide for the decommissioning of both reactor and non-reactor facilities. General references include those for Belgium [136, 183, 289], Germany [419–422], the UK [129, 305], the USA [423] and Norway [424] (Fig. 13). Figure 14 shows hydraulic shears mounted on a balancer in order to reduce the physical load on the operator. Underwater applications are described in Refs [425, 426] and demolition in Ref. [423].

Examples of advances in shearing technology include:

- The use of cement grout infill to reduce tube end section deformation during the shearing of stainless steel test loop channels at WAGR [129]. This has the additional advantage of reducing the overall cutting force.

FIG. 13. Cutting with a hydraulic shear, Kjeller reprocessing plant, Norway.

FIG. 14. Cutting pipes using hydraulic shears mounted on a balancer to reduce the physical load on operators.

- The development of crimp shears for use at the co-precipitation plant in the UK [305]. These tools, as well as cutting the tube also crimp it, thereby sealing the end of the tube and preventing the escape of loose contamination from internal surfaces during subsequent decommissioning operations. A similar development in the USA is shown in Fig. 15.
- The development of self-contained hydraulic shears powered by batteries and with a hydraulic circuit integral with the shear body. Shears of this type were demonstrated at the Hanford C reactor [427].

6.3.1.2. Power nibblers

A nibbler is a punch and die cutting tool that normally reciprocates at a high rate, with the punch moving against the die. The process is not influenced by internal stresses in the workpiece [421] and can be considered a mature technology. The equipment can be deployed manually or remotely. For remote applications, nibblers can be attached to long support tubes or manipulators for the cutting of mild steel and stainless steel components (sheet material as well as small bore piping and tubing). Nibblers have been used at the Rocky Flats site [322], at the BR3 project to cut some

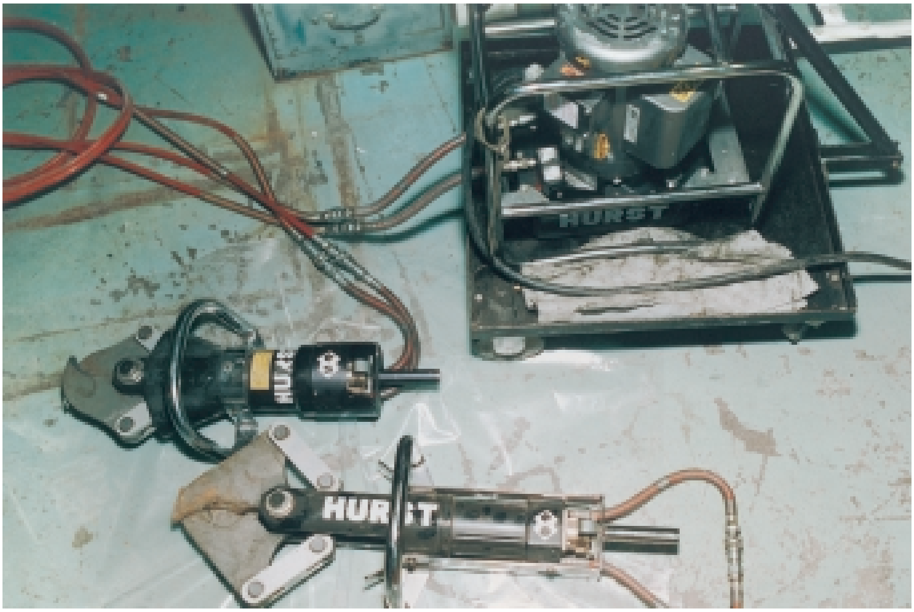

FIG. 15. Pipe cutter used for smaller diameter, tritium contaminated piping. The cutter both cuts and crimps the ends of the pipe. Courtesy Argonne National Laboratory, managed and operated by the University of Chicago for the US Department of Energy under contract No. W-31-109-ENG-38.

tanks (Fig. 16) and the insulation shroud of the reactor pressure vessel (RPV), and at VAK experimental BWR [293, 428] to cut thin walled internals and the chimney above the core. At VAK, nibblers were also used underwater. The technique has been used on a number of UK decommissioning projects [324, 325]. A comparison of nibblers with other cutting techniques is given in Ref. [429].

6.3.1.3. Mechanical saws

Sawing techniques make use of shearing processes, normally produced when a hard cutting edge bears against a softer material which is to be separated. Different kinds of mechanical sawing techniques can be used throughout decommissioning operations for different purposes. Mechanical sawing machines range in size from small hand-held hacksaws to very large and heavy bandsaws capable of cutting steam generators. There are three main mechanical saw types: reciprocating saws (including hacksaws and guillotine saws), bandsaws and circular saws.

FIG. 16. Nibbler cutting thin plates, BR3 decommissioning project.

(a) Reciprocating saws

Reciprocating saws are a well established technology and have been used in decommissioning projects worldwide. They can be portable (hand-held or remotely deployed) or stationary, i.e. the component selected for size reduction is brought to the saw. In their simplest form they consist of a saw blade supported by a frame at one or both ends and are manually actuated. For more complex applications they can be electrically or pneumatically actuated, as in the case of jigsaws, and can include clamping devices to lock them to the workpiece and mechanisms for the automatic ‘feed’ of the blade, e.g. guillotine saw. These saws can cut a variety of materials, including metals and a wide range of plastics, and can also be deployed in water as well as air. They produce a narrow kerf and minimal heat and the cutting residues are in the form of large particles which can be easily collected. For hard metals such as stainless steel, cutting speeds are relatively slow by comparison with techniques such as plasma arc. Figures 17 and 18 show saws being used at BR3. Figure 19 shows a guillotine saw being used during decommissioning of the Gentilly-1 reactor in Canada. Specific examples of their use are at Shippingport [183], at BR3 [130, 197, 285, 292], and at the KRB-A and VAK experimental BWR units [197, 293, 371, 421, 428, 430] (see also Ref. [77]).

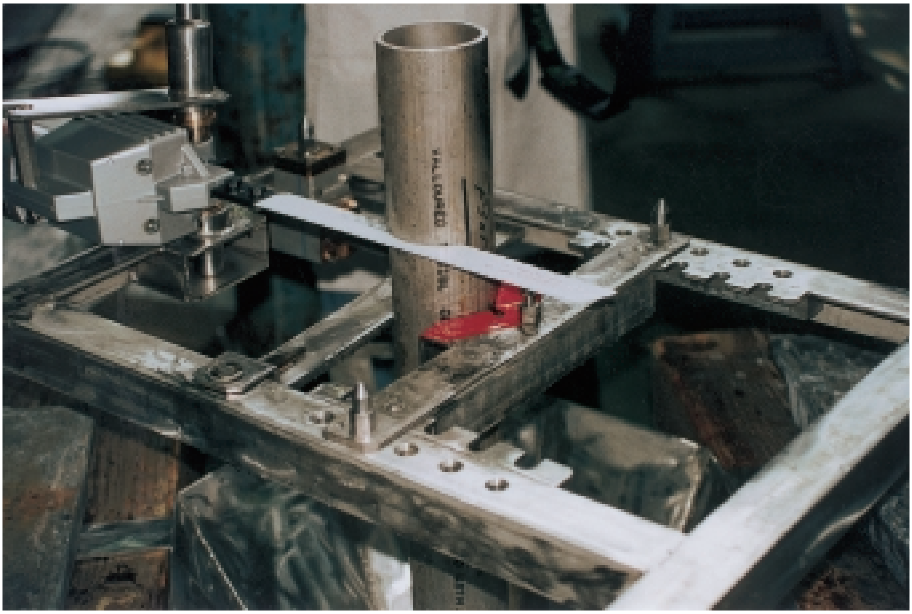

FIG. 17. Reciprocating sawing of tubes (remote/underwater application) at the BR3 decommissioning project.

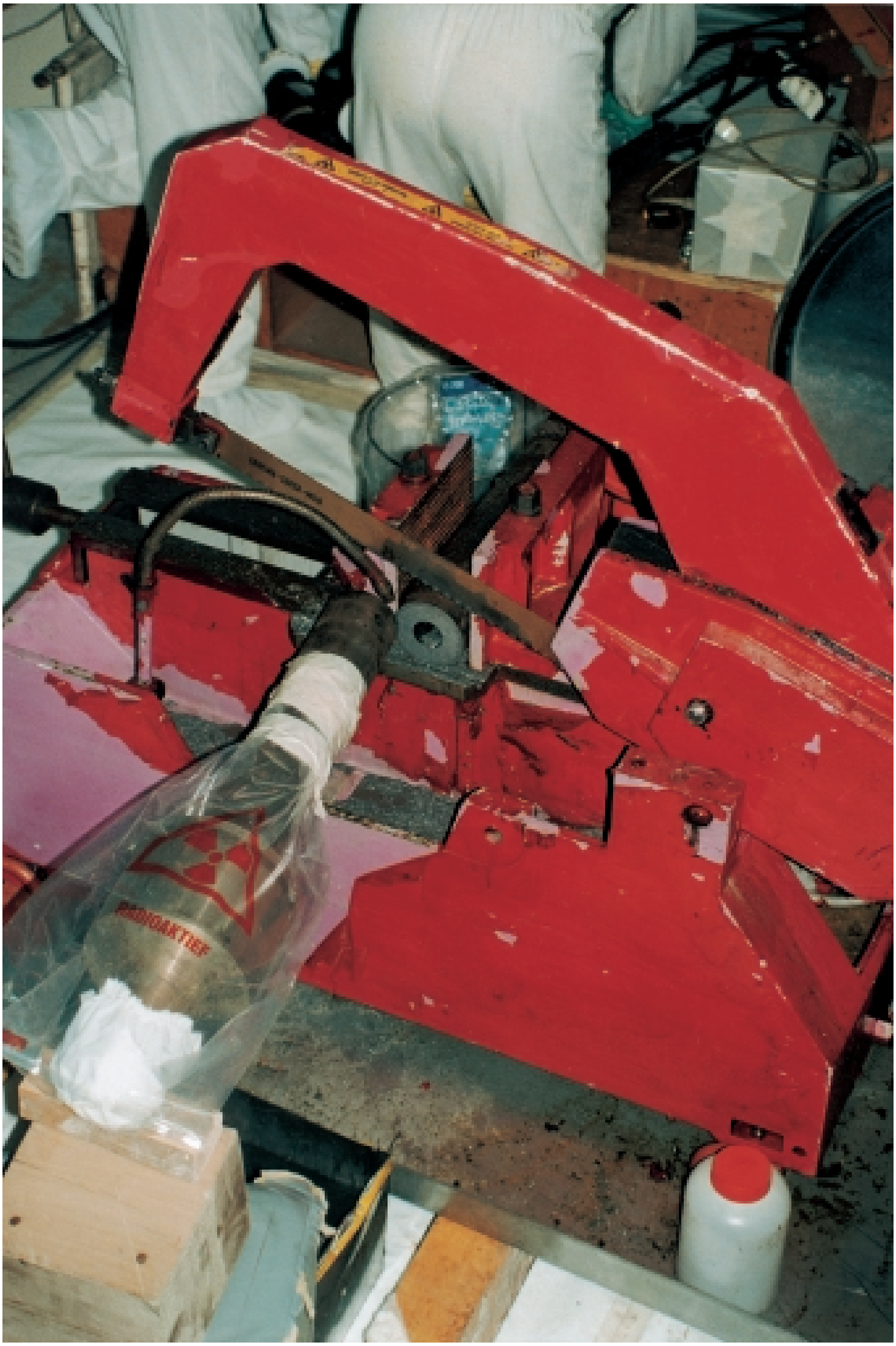

FIG. 18. Reciprocating saw in use at the BR3 decommissioning project.

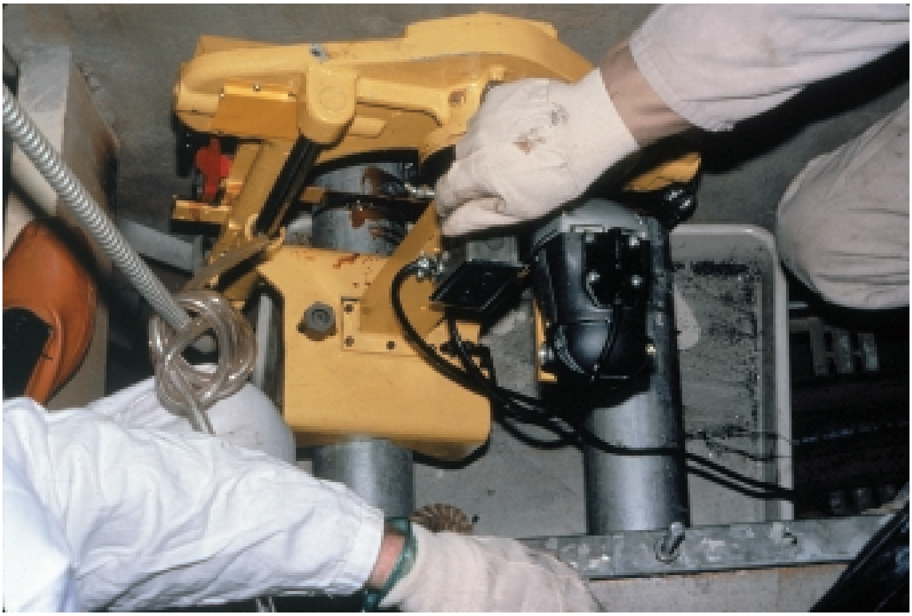

FIG. 19. Guillotine saw in use at Gentilly-1, Canada.

The remote application of hacksaws, reciprocating saws and jigsaws to successfully dismantle plutonium gloveboxes in the UK is described in Refs [431, 432]. General comparisons with other cutting techniques are provided in Refs [182, 429, 433, 434].

(b) Bandsaws

Bandsaws consist of an endless saw blade (a loop of steel or band), a frame which allows the band to circulate (when driven) and a motor to drive the blade. Bandsaw machines are produced in a wide range of sizes, from hand-held machines up to very large devices capable of cutting, in one pass, large steam generators (few metres diameter). They are useful for cutting contaminated (in air) or highly activated (underwater) pieces. The main advantages are the flexibility of the tool (capable of vertical as well as horizontal cuts), the thin kerf produced and the minimal production of aerosols or dust. Reference [435] provides a comparison of circular saws and bandsaws.

Underwater bandsaw cutting has been used at the BR3 reactor, where it was shown to be a very flexible technique, allowing vertical as well as horizontal cuts to be made with the same equipment [130, 197, 266, 267, 289, 291, 292, 436]. Bandsaw testing at BR3 is shown in Fig. 20. Bandsaws have also been used at VAK and KRB-A [421] for the size reduction of large parts such as steam driers, or turbine parts with diameters up to 3 m. Bandsaws have also been used at the KKN facility [67, 361].

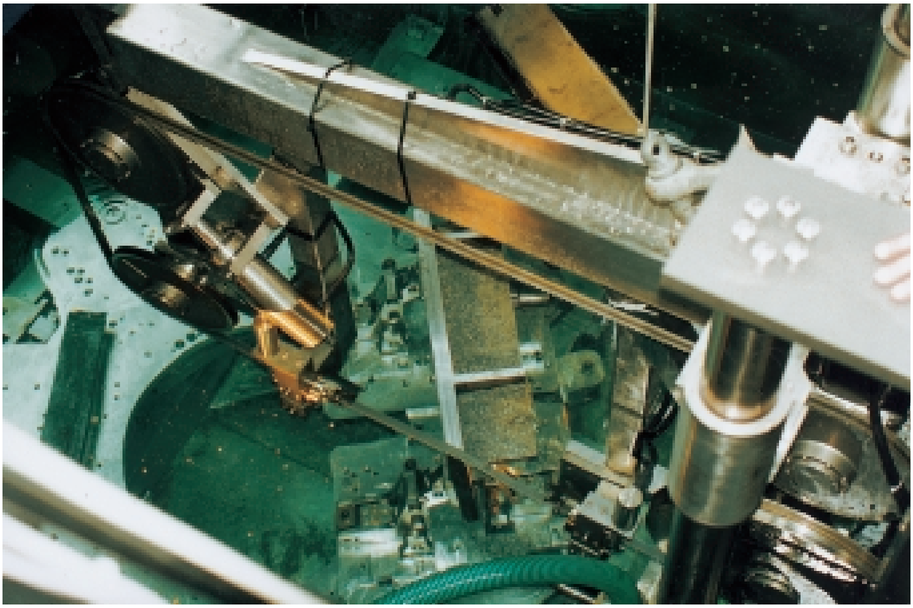

FIG. 20. Cold testing of the bandsaw at the BR3 decommissioning project.

A specific application of bandsawing is termed ‘ice-sawing’. Ice sawing involves the use of conventional sawing equipment to cut through a vessel (e.g. heat exchanger) filled with frozen water. The principle of this technique presents the following advantages: it reduces the area dose rate, permits remote control of the saw, minimizes the generation of aerosols, stabilizes the heat exchanger tubes during the cutting operation, and provides simultaneous cooling of the saw blade. The successful use of ice sawing techniques has been reported in the decommissioning of the KRB-A reactor in Germany [197, 371, 374–377, 430].

(c) Circular saws

Circular sawing is a very common technique which is now well developed. The saw blade is in the form of a disc, with teeth arranged radially around the periphery; the disc is rotated to perform the cutting operation. The saw blades range in size up to 1–2 m diameter and are readily available. The major drawback is the high reaction force, which necessitates the use of heavy and robust equipment. Underwater circular saws have been used at BR3 [267, 285, 289, 292] for cutting different highly radioactive reactor internals. Circular sawing is also similar to milling (slitting wheels) (see also Section 6.3.1.7).

Hand-held or telerobotic supported circular saws have also been used by BNFL in the UK and for dismantling plutonium contaminated gloveboxes at ANL [151].

FIG. 21. Circular cutter in use at the HDR facility in Germany.