TECHNICAL REPORTS SERIES No. **395**

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

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
BANGLADESH
BELARUS
BELGIUM
BENIN
BOLIVIA
BOSNIA AND HERZEGOVINA
BRAZIL
BULGARIA
BURKINA FASO
CAMBODIA
CAMEROON
CANADA
CHILE
CHINA
COLOMBIA
COSTA RICA
COTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ESTONIA
ETHIOPIA
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
HAITI
HOLY SEE
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
LATVIA
LEBANON
LIBERIA
LIBYAN ARAB JAMAHIRIYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITIUS
MEXICO
MONACO
MONGOLIA
MOROCCO
MYANMAR
NAMIBIA
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
PAKISTAN
PANAMA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
SAUDI ARABIA
SENEGAL
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA
VIET NAM
YEMEN
YUGOSLAVIA
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

Printed by the IAEA in Austria
October 1999
STI/DOC/010/395

TECHNICAL REPORTS SERIES No. 395

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

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1999

VIC Library Cataloguing in Publication Data

State of the art technology for decontamination and dismantling of nuclear facilities. — Vienna : International Atomic Energy Agency, 1999.
p. ; 24 cm. — (Technical reports series, ISSN 0074–1914 ; no. 395)
STI/DOC/010/395
ISBN 92–0–102499–1
Includes bibliographical references.

1. Nuclear facilities—Decommissioning. I. International Atomic Energy Agency. II. Series: Technical reports series (International Atomic Energy Agency); 395

VICL 99–00230

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.

CONTENTS

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

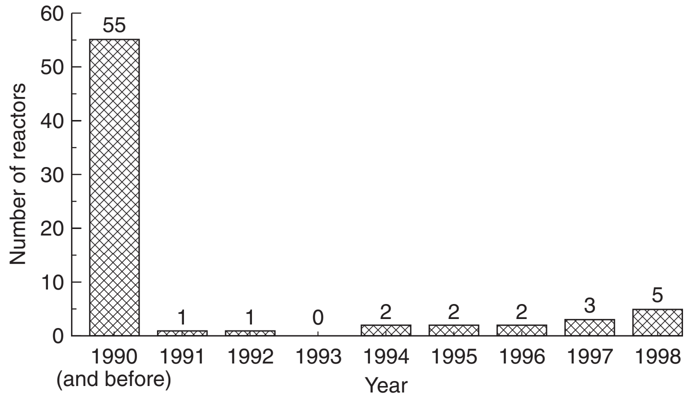

FIG. 1. Integrated number of shutdown nuclear power plants in a given year (IAEA elaboration).

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.

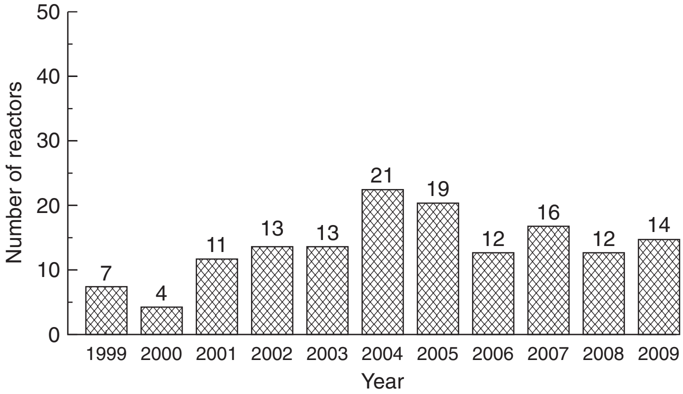

FIG. 2. Nuclear power plants reaching 30 years of age in a given year (IAEA elaboration). Note: 18 UK generating NPPs were over 30 years old in 1997 and have not been included: Bradwell A, B; Calder Hall A, B, C, D; Chapelcross A, B, C, D; Dungeness-A A, B; Hinkley Point-A A, B; Oldbury-A A, B; and Sizewell-A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

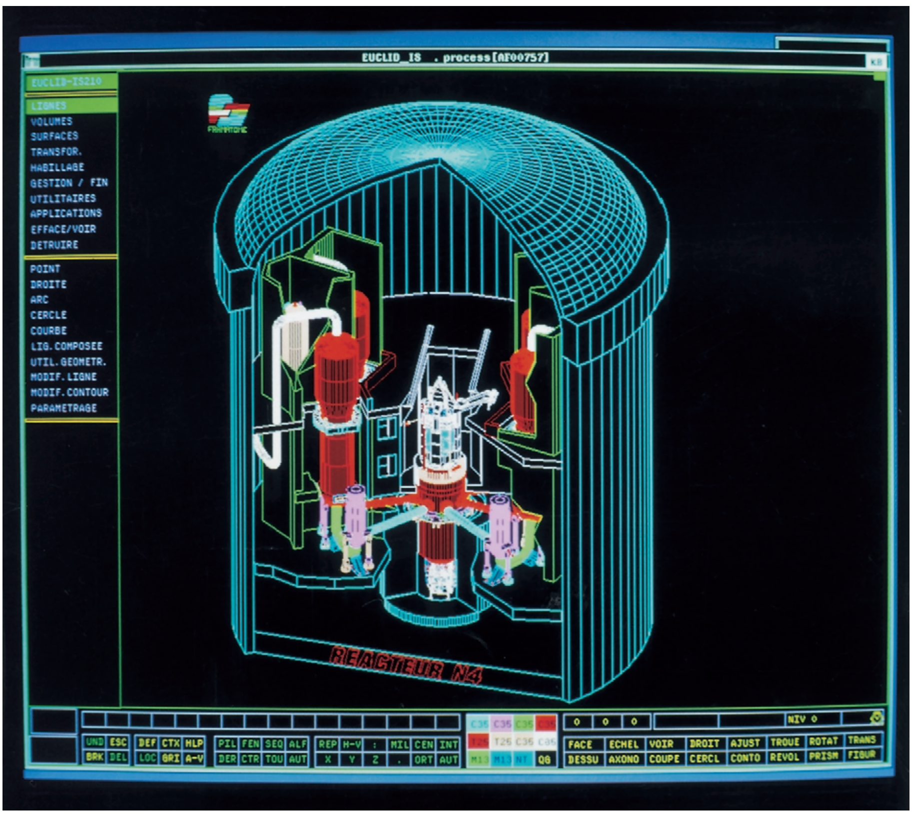

FIG. 3. CAD view of the reactor at the new N4 plant in France.

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 inter-dependencies 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

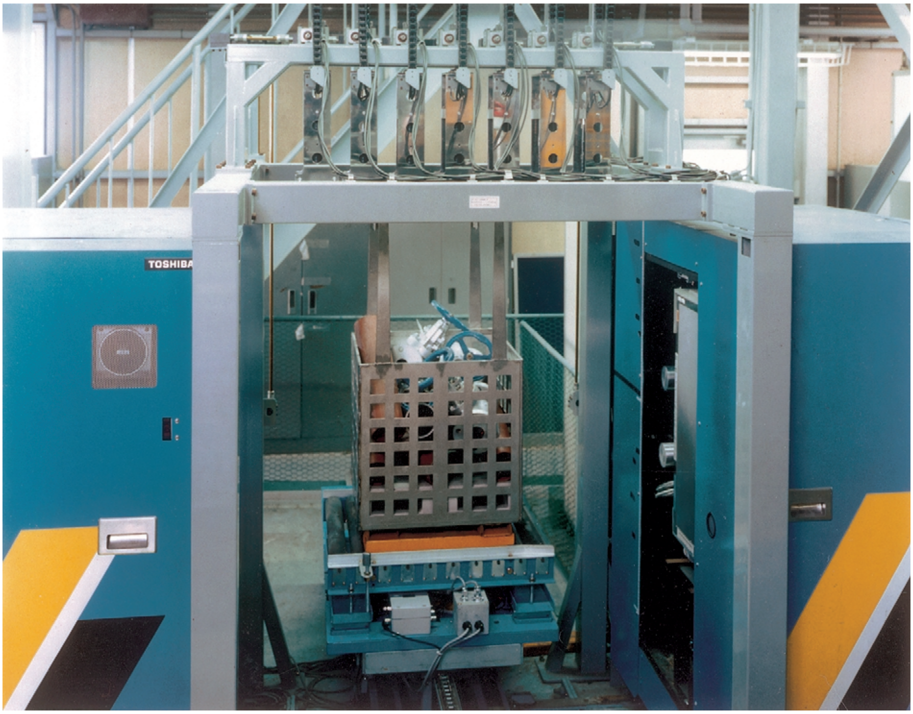

FIG. 4. Very low level radioactivity measurement apparatus, Nuclear Power Engineering Corporation, Japan.

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.

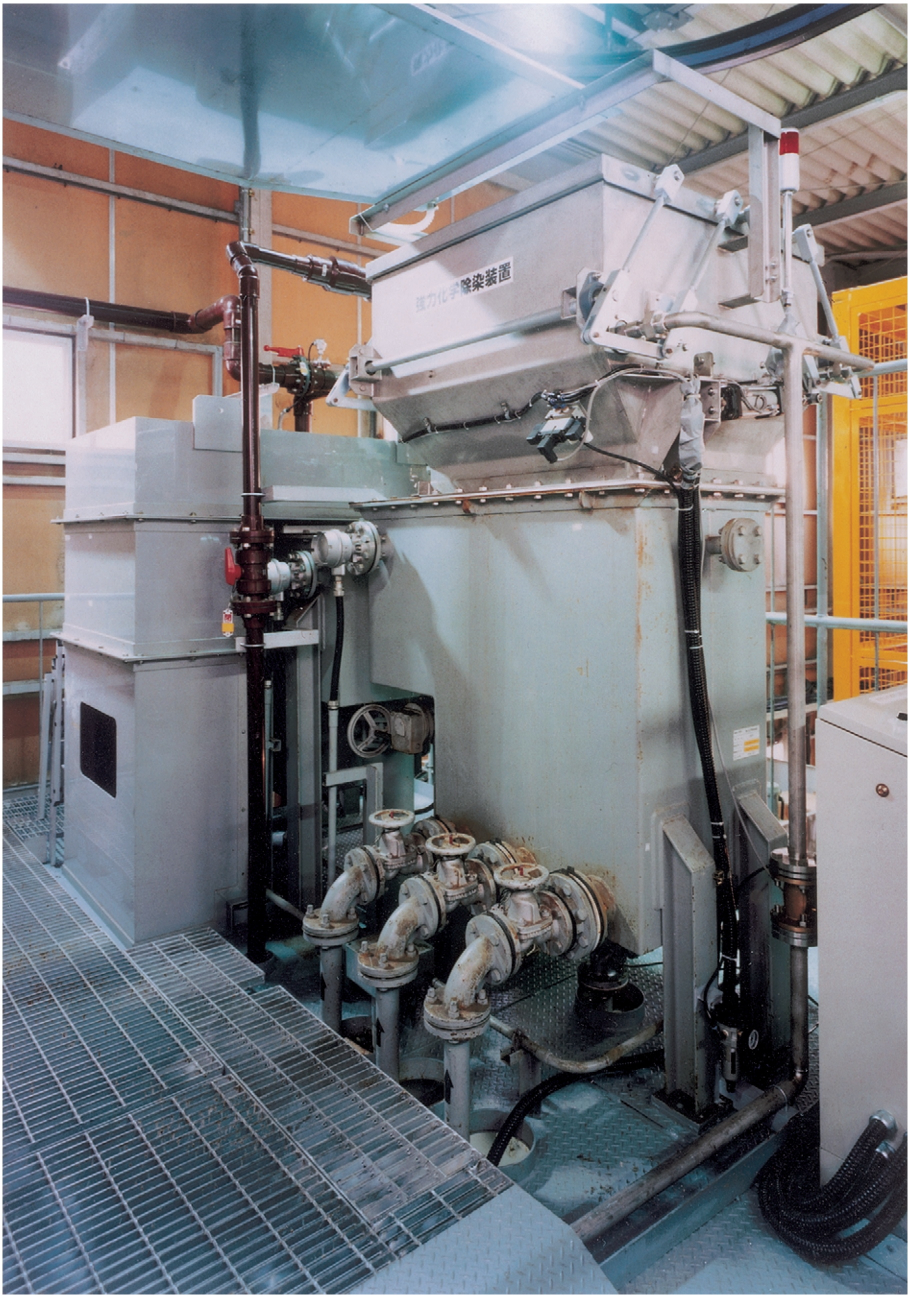

FIG. 5. Strong chemical decontamination apparatus, Nuclear Power Engineering Corporation, Japan.

(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.

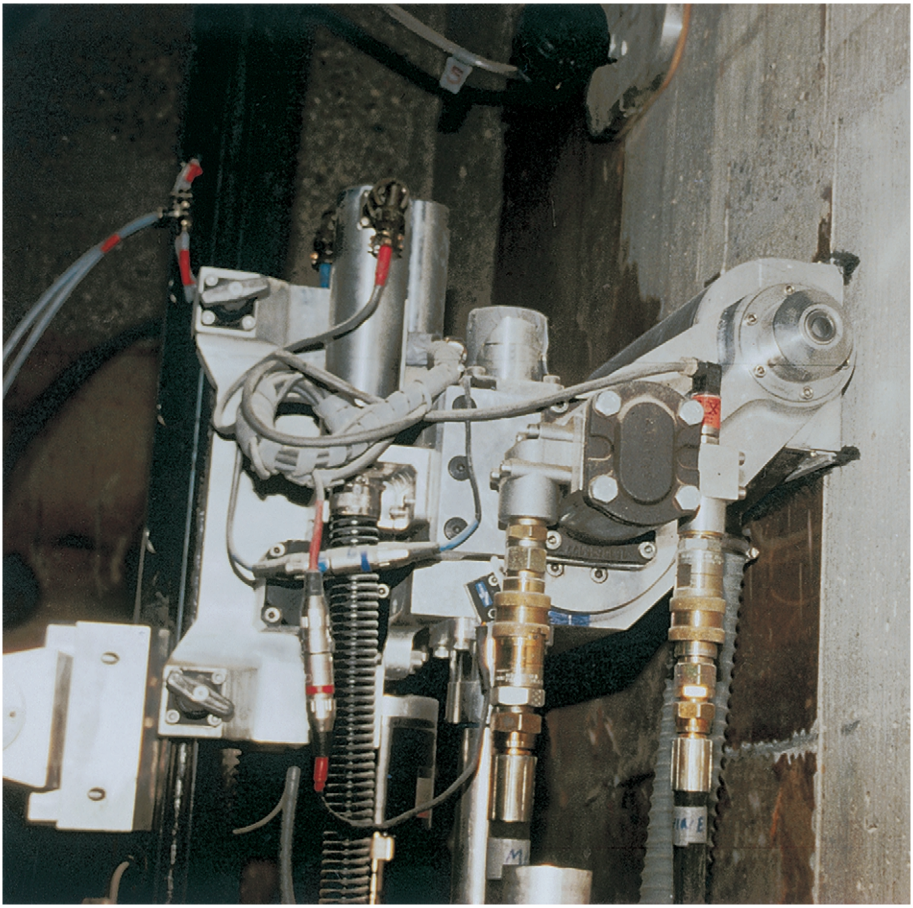

FIG. 9. Concrete decontamination using an automatic wall shaver equipped with a diamond tipped rotary cutting head (detailed view).

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

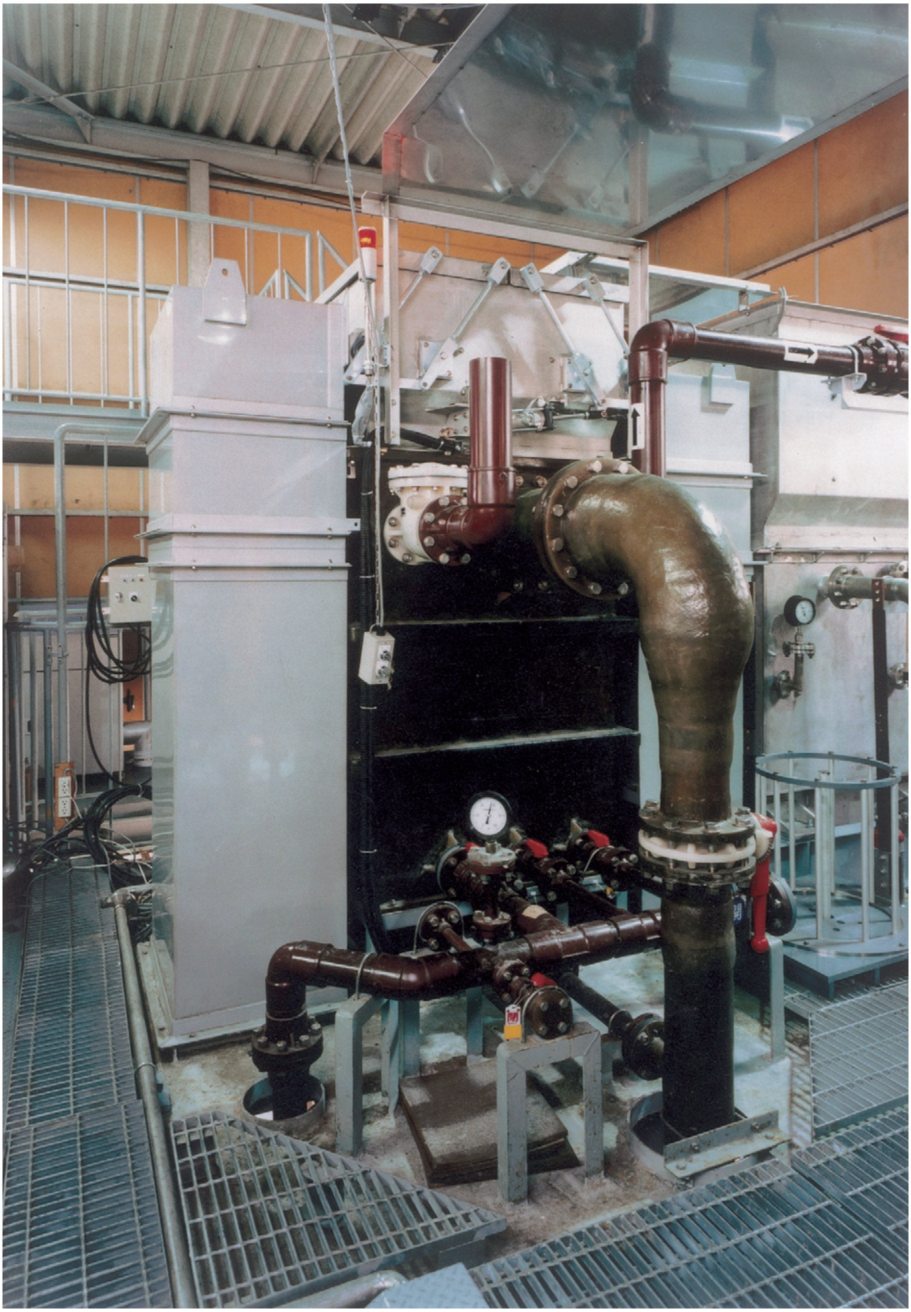

FIG. 12. Electrolytic decontamination apparatus, Nuclear Power Engineering Corporation, Japan.

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

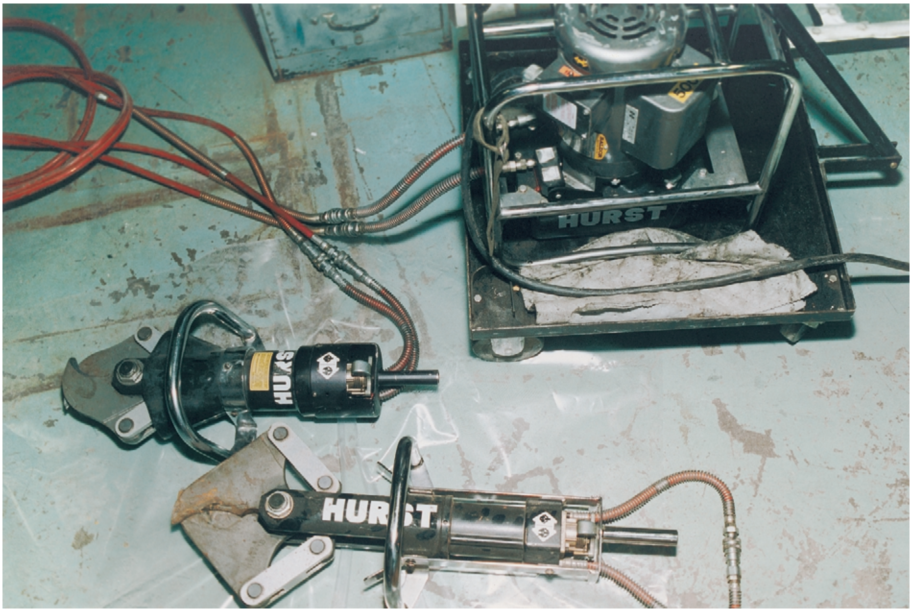

FIG. 15. Pipe cutter used for smaller diameter, tritium contaminated piping. The cutter both cuts and crimps the ends of the pipe. Courtesy Argonne National Laboratory, managed and operated by the University of Chicago for the US Department of Energy under contract No. W-31-109-ENG-38.

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]).

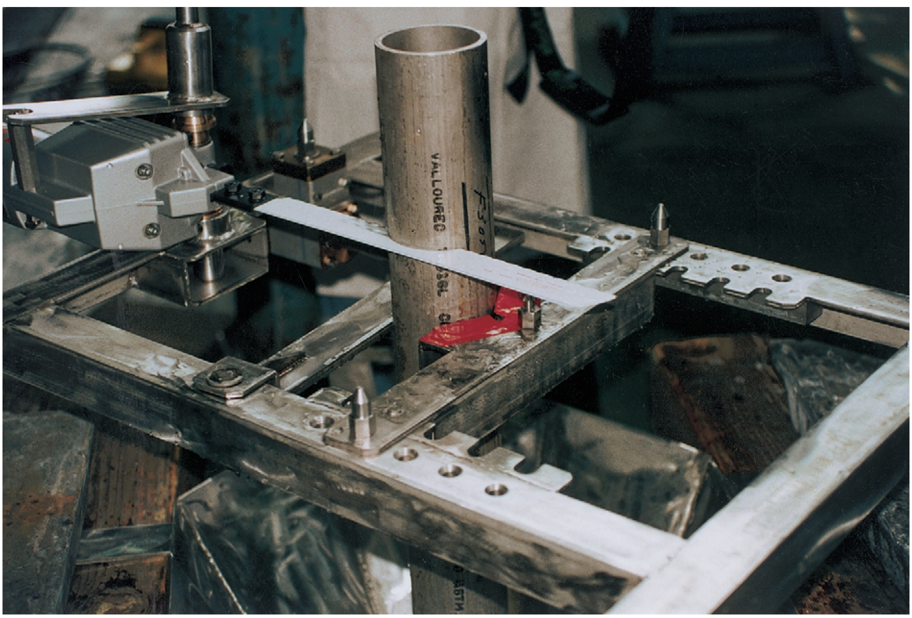

FIG. 17. Reciprocating sawing of tubes (remote/underwater application) at the BR3 decommissioning project.

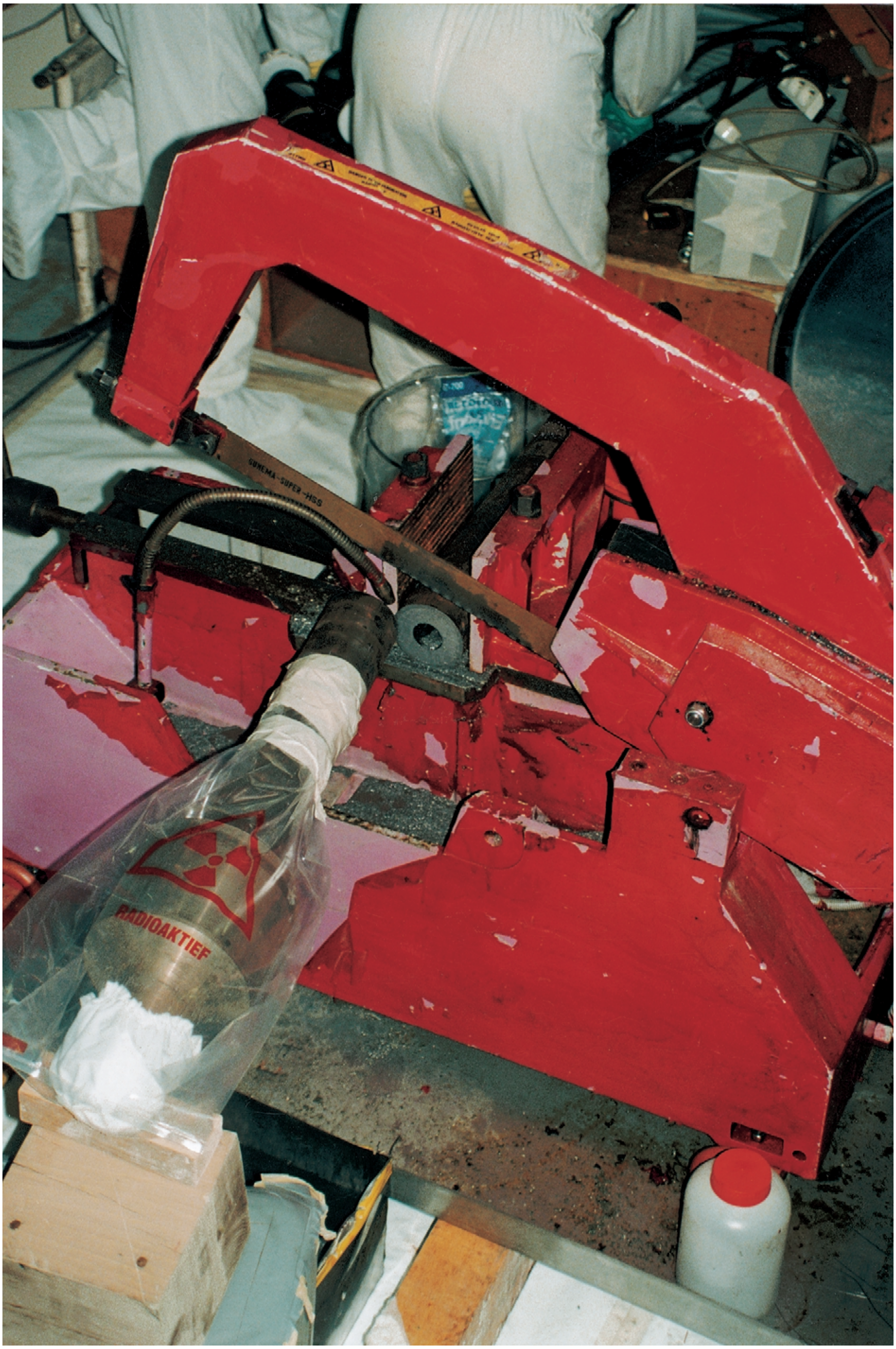

FIG. 18. Reciprocating saw in use at the BR3 decommissioning project.

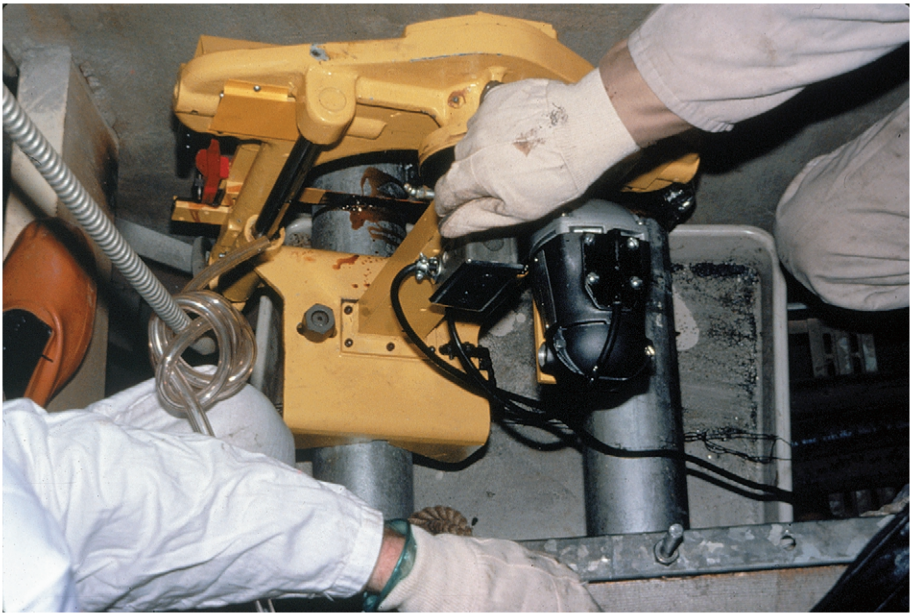

FIG. 19. Guillotine saw in use at Gentilly-1, Canada.

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].

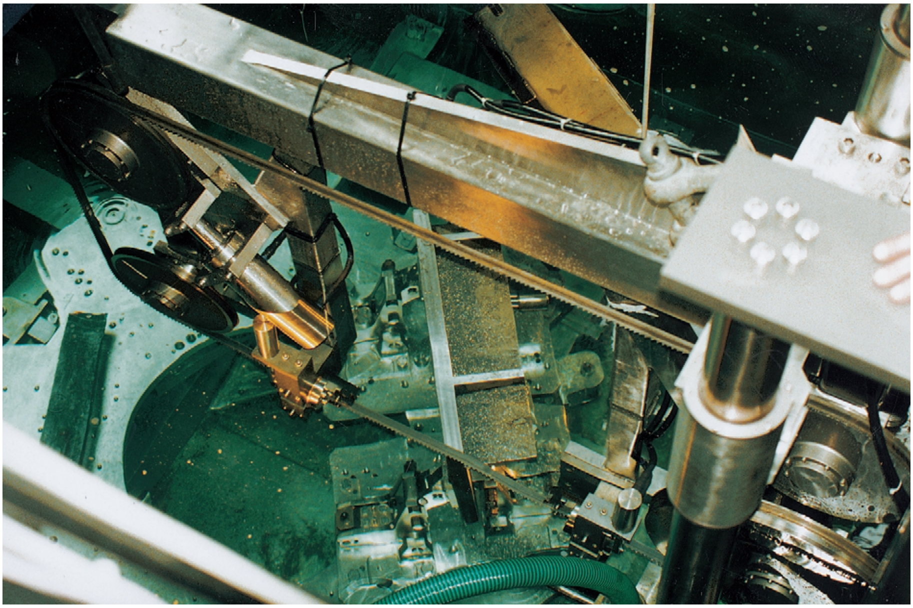

FIG. 20. Cold testing of the bandsaw at the BR3 decommissioning project.

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.

6.3.1.4. Orbital cutters

Orbital cutters can be manually actuated devices or self-propelled units that cut as they move around the outside or inside circumference of a pipe or vessel and they are an effective means of segmenting pipes and circular vessels (Fig. 21). Three different types of tool are used for orbital cutting:

- *Swaging cutter.* This uses a hardened wheel which compresses and shears the metal. This technique is able to cut thin walled metal pipes [437, 438].
- *Lathe tool.* Typically two lathe tools are placed diametrically opposite one another and rotate around the pipe to be cut; a ratchet system feeds the tool into the metal after each rotation, thus performing a cutting operation similar to that of a lathe. Such a tool can be used on small pipes [439] as well as on large cylindrical vessels [150]. The tool can be arranged to rotate either outside the pipe, as at the Hanford C reactor [440], or inside as at JPDR [132, 441–443].
- *Milling tool.* In place of the hardened wheels on the rotating head, a small milling cutter (e.g. slit cutter) is used to cut a slit in the pipe while rotating around or inside it. The tool can be fed by a ratchet after each rotation of the head, or fed continuously by a dedicated system. Such a tool has been used at Germany's Mehrzweckforschungsreaktor [444].

Orbital cutters can be controlled remotely, allowing the operators to work at a distance from the radiation area, but they often require manual positioning in the first instance [440].

6.3.1.5. Abrasive cutting wheels, blades, wires and core drills

These are electrically, hydraulically or pneumatically powered wheels, beads or chain links containing abrasive held in a semi-rigid supporting matrix. Typical abrasives used include aluminium oxide, silicon carbide or diamond and these cut the workpiece by local shearing at multiple cutting points. Abrasive cutters can be used either dry or with a coolant, such as water, which is often recirculated to reduce secondary waste volumes. The technique is used extensively worldwide, in a wide range of industries. At least 100 years of experience and development has taken place to establish this branch of cutting.

(a) Carbides and aluminium oxide

These abrasive materials are supported by a binding material in the form of a circular disc and will cut metal, brick, or concrete with reinforcing bars. Deployment systems for most applications are commercially available and are well developed.

FIG. 22. Dry cutting of cast iron shielding blocks using diamond tipped blade saw.

Examples of where such tools have been used are given in Refs [293, 371, 428, 445, 446]. General comparisons between grinding discs and other cutting tools are provided in Refs [182, 429, 433, 434].

(b) Diamond

Diamond abrasives are embedded in the beads of diamond wire saws, in cutting wheels and coring tools, and also in the chain links of diamond chainsaws. Typical applications are shown in Figs 22–24. Diamond wire has been conventionally used for cutting through concrete (also reinforced concrete) and masonry (e.g. at the Zimmer NPP) and also used at the FSV reactor [68, 136, 447] (see also Refs [448–450]). In a different application, wire sawing was used to dismantle the stack at the National Research Experiment reactor in Canada [451]. More recently it has also been developed for cutting through heavily reinforced concrete and pure metal structures and for cutting without the use of liquid coolant [183, 197, 449, 452, 453]. R&D activities in Japan are described in Refs [454, 455]. Diamond wire saws have also been used in Germany at KKN [456] and at the Grosswelzheim Heissdampfreaktor (HDR) [457].

Diamond blades or wall saws are widely used during civil construction work for cutting concrete and reinforced concrete and were used to dismantle the biological

FIG. 23. Creating new cell entrances using a diamond cable cutting machine.

FIG. 24. Concrete cutting using a diamond tipped blade saw.

shield at JPDR [25, 132, 253, 441, 443, 458–461]. These blades have now been developed for cutting without coolant and for the cutting of pure metal structures.

Diamond corers have a similar construction to that of circular diamond saw blades, except that they are cylindrical in shape. Like the circular blades, they can be used to cut concrete or steel structures with or without coolant. Corers have been used, e.g. at HDR, for concrete removal [457]. They are commonly used for drilling holes, for stitch drilling operations [25, 132, 183, 253, 441, 443, 448, 458, 459, 462], or for removing samples of material.

An emerging technology in the field of abrasive cutting is the use of diamond chainsaws. These can be used for cutting both concrete and reinforced concrete [197, 376].

6.3.1.6. Explosives

Explosive dismantling or cutting is well known and the three main types of charge employed are:

- *Conventional explosives.* These have a relatively low detonation speed, where the gas expansion and shock wave are used to reduce the workpiece size.

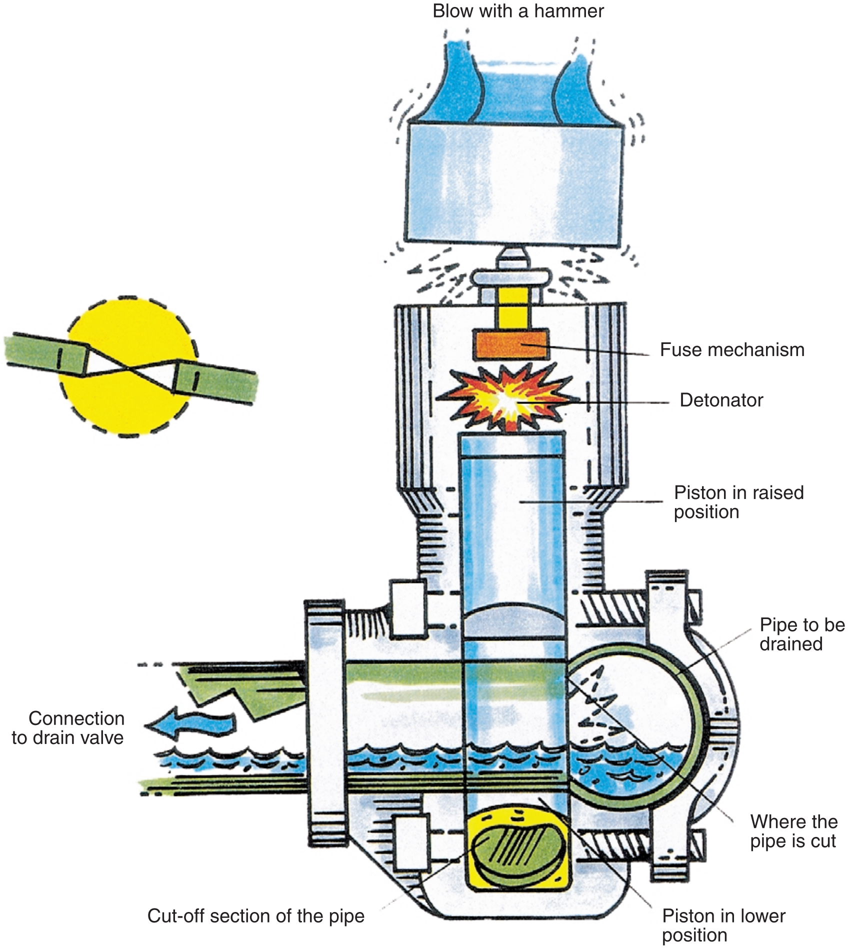

FIG. 25. Diagram illustrating the principle of an explosive drilling clamp, Kjeller reprocessing plant, Norway.

- *Shaped explosives.* These are high velocity compounds where the energy deposition and shock wave are used to fracture the workpiece at a precise point in a controlled manner.
- *Linear shaped charges.* These use the force of the detonation as the energy source to propel a metallic (usually copper) 'V' shaped 'blade' into the workpiece in order to cut it.

The use of, and references for, these different types of explosive dismantling and demolition techniques are summarized below (see also Fig. 25):

FIG. 26. Drilling being carried out for the insertion of explosives prior to the demolition of biological shield structures by controlled blasting, JPDR decommissioning project.

- *Controlled blasting:* This has been employed on the exhaust stack at SRS [185], at Fernald [18], at JPDR [253, 463, 464], at KKN [67, 197, 367], and at the LIDO reactor in the UK [181, 394, 465, 466]. Controlled blasting has also been tested on a 1:1 scale mock-up at BR3 [130, 467, 468] and an analysis made for the G2/G3 reactors in France [197, 469]. Figure 26 shows the preparation for demolition of a biological shield by controlled blasting at JPDR. A general overview of this technique is given in Refs [197, 250, 448, 449, 470].
- *Shaped explosives:* These have been used at JPDR [132, 183, 441–443, 460] to cut pipes up to 90 mm in diameter in air (Fig. 27), at the DIDO reactor in the UK to produce boreholes [197, 471] and at KKN [446]. A general overview of this technique is given in Refs [197, 448].
- *Linear shaped charges:* Linear shaped charges employing metal blades have been used at the AT-1 reprocessing facility in France [197] to dismantle tanks and have also been used at the LIDO reactor [197, 394] and at JPDR [123, 132, 441–443]. A general survey of this technique is given in Refs [197, 448].

The above techniques have been extensively used in the conventional demolition industry. However, the provision of adequate safety arguments may limit their use in the nuclear industry.

FIG. 27. Emergency condensate system pipe cut by shaped explosive, JPDR decommissioning project.

6.3.1.7. Milling

Metal milling employs a broad range of cutting tools. These include end mills, slitting wheels, face mills, etc. These milling tools were used in dismantling the reactor internals [289, 290] and thermal shield [266, 267, 287] at the BR3 reactor (Fig. 28). A special milling machine has also been developed and tested in the UK for the removal of the control blade mounting frames at the Universities research reactor [462].

An alternative strategy to recategorize RPVs into high or low level waste streams on the basis of milling was recently proposed [472]. This strategy advocates the use of a milling cutter to remove a layer from the pressure vessel wall, the reduction in wall thickness thereby lowering the active inventory of the remaining material before completion of dismantling. A general comparison of the performance of milling cutters with other dismantling techniques can be found in Refs [429, 448].

6.3.2. Thermal cutting techniques

In general, the main advantages of thermal techniques over other methods such as mechanical cutting are that:

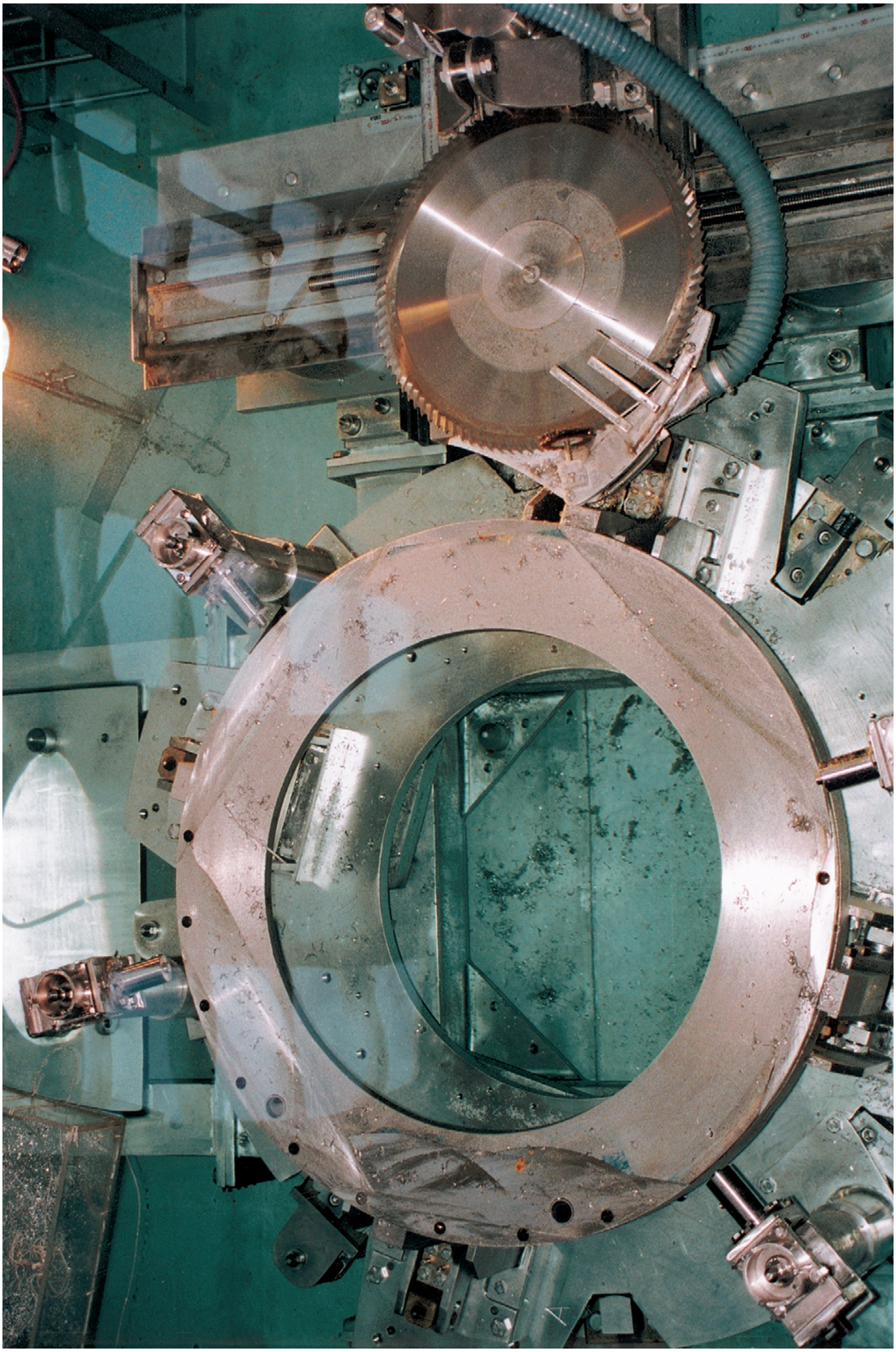

FIG. 28. Cold testing of the milling cutter at the BR3 decommissioning project.

— The cutting speeds are generally faster,
— Remote operation is often possible because the equipment is lightweight,
— The deployment system only has to accommodate small reaction forces during cutting as the tools do not require physical contact with the workpiece.

The main disadvantage is the production of aerosols, dust and dross which create issues of concern with respect to worker and environmental protection, visibility problems (mainly in underwater applications), and the production of large volumes of primary (owing to the thickness of the kerf) and secondary wastes. An additional drawback with the cutting of contaminated components which are to be decontaminated is the danger of the contamination being incorporated within the solidified slag on the cut workpiece.

For underwater cutting, it is necessary to have efficient water filtration processes to maintain water quality and to use filters working in series with decreasing holding capacity but with increasing performance in order to minimize the total waste volume. For cutting in air, it is necessary to have efficient air filtration, either locally or in the cutting containment, and to have regenerable pre-filtration processes to protect the main ventilation filters, which can be rapidly blinded by the aerosols produced.

6.3.2.1. Plasma arc cutting

Plasma arc cutting is based on the establishment of a direct current arc between a tungsten electrode and the surface of a conducting metal. The arc is created by ionizing a gas (plasma gas) and then blowing the ionized plasma towards the surface of the workpiece in order to form a conductive pathway down which the main plasma current passes (Figs 29–31). The heat generated by the impingement of the arc on the workpiece causes local melting and the force created by the velocity of the plasma gas stream blows the molten metal away from the melt pool, thereby creating the cut. Plasma cutting is a fast process and the cutting heads are lightweight, easy to use and can be deployed either manually or remotely. The process can be used both in water and in air, although control of the aerosols produced is an issue. Extensive references exist on the use of plasma arc in many decommissioning projects and these are listed below.

(a) Plasma arc in air

The plasma arc in air technique dates back to the 1930s. Developments in some of the details of the technique continue to be made although the technology can be considered to be mature. The cooling gas, which is often the same as that used to conduct the current (e.g. air), can be treated in many cases by existing ventilation

FIG. 29. Plasma cutting of metal components.

systems. The cutting rate when using gas-cooling of the electrode is lower than with water cooled systems owing to the need to reduce power density. Testing of this technique has been carried out at Fontenay-aux-Roses in France [197]. Flat metal surfaces (e.g. drip trays) have been cut using this technique at the Eurochemic plant in Belgium [136] and at JPDR [252] the storage pool lining has been sectioned, and metal piercing has been carried out at Elk River in USA [183]. Elsewhere, internal semi-remote cutting of small bore pipework and reactor standpipes has been successfully carried out at the WAGR [80, 129, 473, 474] and steam generator channel heads and tube sheets have been cut at the Ågesta reactor in Sweden [299]. Pipes and tanks have also been cut at the Rapsodie reactor [256] and remote air plasma cutting has been used to cut testing machines and maintenance equipment at the material monitoring facility (PNC) in Japan [346]. Other references to be consulted include Refs [77, 182, 305, 371, 433, 434, 445, 446, 448, 475, 476].

(b) Underwater plasma arc

Underwater plasma arc technology is well developed and used in many industries where high cutting rates are required. However, tests at the Pegase reactor in France revealed a loss in efficiency in cutting stainless steel sheet, 100 mm thick, below 2 m of water [477]. Reactor internals and other thick sections at JPDR have

FIG. 30. Plasma arc cutting being used during the removal of the equipment employed for decanning uranium elements, Kjeller reprocessing plant, Norway.

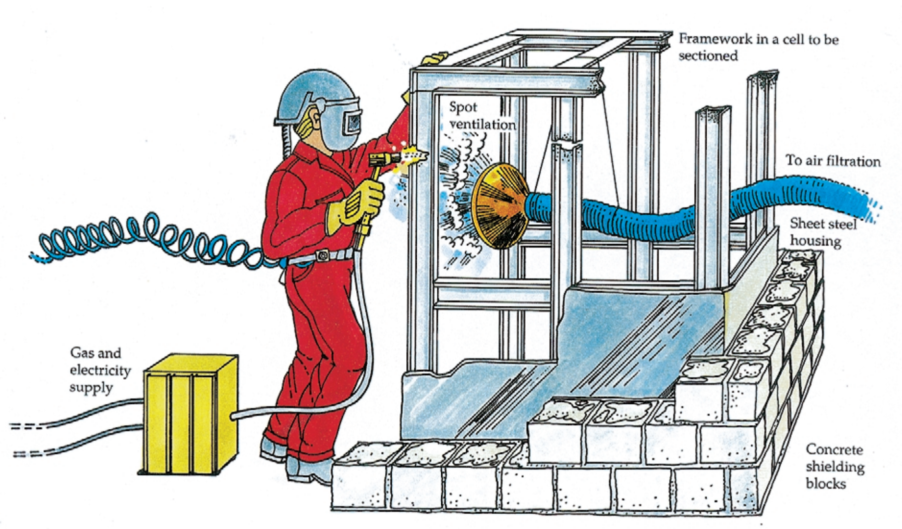

FIG. 31. Diagram illustrating the principle of a plasma arc cutting operation.

also been cut using this technique [25, 132, 441, 460, 478–480]. At the EBWR, size reduction of the reactor internals has been performed [423] and at the BR3 facility, segmentation of thermal shield rings was carried out, after in situ cutting by other techniques such as electrodischarge machining (EDM) and mechanical sawing [130, 266, 289, 290, 292]. The underwater cutting of plutonium contaminated materials has also been proven at Three Mile Island reactor in the USA [481]. Other references to be consulted include Refs [68, 183, 184, 267, 283, 287, 291, 376, 377, 426, 429, 434, 447, 482, 483].

6.3.2.2. Flame cutting

Flame cutting is a well established and mature technology and uses a flowing mixture of a fuel gas (acetylene, hydrogen, propane) or fuel vapour (gasoline), and oxygen, which are mixed and ignited to produce a high temperature flame. In the case of carbon steels the flame is brought into contact with the surface of the workpiece, which is allowed to heat up before the cutting oxygen is injected into the centre of the flame oxidizing the workpiece. As iron oxide melts at a lower temperature than the parent metal, the oxide melts and is blown from the melt pool by the flame, thereby producing a cut. Oxyfuel gas cutting can be deployed either manually or remotely, in air or water, and it can cut a wide range of steel thicknesses. Examples of its use are reported in Refs [80, 129, 146, 197, 429, 445, 448, 476, 484].

FIG. 32. Oxygas cutting equipment in use at the Fernald facility, USA.

Thicknesses up to approximately 3 m have been cut in a laboratory trial [483, 485].

The cutting of stainless steel has been less successful using this technique owing to the high melting points of the chromium oxides produced [486]. The technique has been used to cut thin sections as reported in Refs [252, 299, 487]. Cutting is achieved as a result of the flame causing localized melting of the parent metal, the gas stream removing the molten metal from the melt pool in a continuous process.

Testing of an oxygasoline torch for the cutting of steel has been undertaken at Fernald [488, 489] (Fig. 32) and in Japan tests have been carried out using an arc gouging and flame cutting system to size reduce sections of an RPV [490, 491].

FIG. 33. Thermal cutting at HDR in Germany.

6.3.2.3. Powder injection flame cutting

Powder injection flame cutting is a variant of the standard flame cutting process reported in Section 6.3.2.2. Powder injection flame cutting involves the introduction of iron or a mixed iron/aluminium powder directly into the central oxygen jet of the fuel gas flame, causing an exothermic reaction between the excess oxygen and the powder. This increases the flame temperature and gas momentum, allowing the cutting of a variety of materials such as thick sections of stainless steel and concrete. The technique can be likened to a continuous thermic lance. Details of laboratory tests and actual operation are provided in Refs [418, 449, 492]. The process produces a considerable amount of aerosol and secondary waste [448, 492] and for this reason has not been used on German decommissioning projects. The technique is well established for non-nuclear applications and is now available to the nuclear industry.

6.3.2.4. Thermic lance (oxy arc or arc slice)

The thermic lance consists of an iron pipe packed with a combination of steel, aluminum and magnesium wires through which a flow of oxygen gas is maintained. The lance cuts are achieved by thermite reactions at the tip of the lance in which all constituents are consumed. Lances vary in length from about 0.5 m to more than 3 m

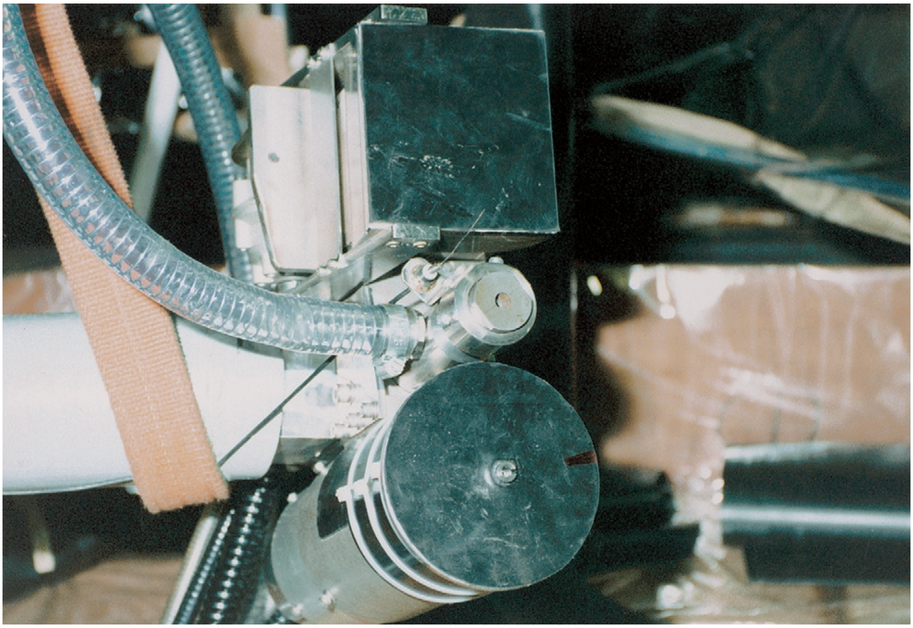

FIG. 34. Cutting nozzle of the water jet cutting system used in the demolition of biological shield structures at the JPDR decommissioning project.

and have a range of diameters. Ignition of the lance is normally performed using a flame, electric arc or battery pack.

This technique will cut a wide variety of materials and can be used for cutting slits and holes. It is not recommended for highly activated or contaminated components as it produces large amounts of aerosol and usually requires manual intervention.

This technique was used to cut the top biological shield of the WAGR [129, 445, 474, 476] and has also been used at the HDR in Germany (Fig. 33). Other details of its use are to be found in Refs [182, 183, 433, 434].

6.3.3. Abrasive water jet cutting

Abrasive water jet cutting involves the use of an abrasive, e.g. garnet sand, propelled by high pressure water. It is effective in cutting reinforced concrete and is capable of cutting virtually all materials [183]. This technique has been tested on a mock-up of the JPDR for cutting reinforced concrete [25, 132, 183, 253, 441, 443, 458, 460, 493, 494] with high cutting efficiencies being observed (Fig. 34). However, depth control proved problematic and resulted in the production of excessive quantities of sludge [464].

A study on the minimization of secondary wastes and handling of aerosols is reported in Ref. [495]. This technique has been also used at the EBWR in the test cutting of the reactor vessel [496] and at the SRS [77]. It is considered a proven method of cutting concrete [448]. Tests have been carried out in France under the EC R&D programme on decommissioning [354] and research work on this technique and its applications to industrial projects in Germany are described in Refs [352, 353, 483, 497]. A discussion of further developments and a comparison between abrasive water suspension jet and abrasive water injection jet cutting is reported in Ref. [498]. Other references are [429, 448, 449].

6.3.4. Mechanical demolition techniques

6.3.4.1. Wrecking ball or wrecking slab

A wrecking ball is a conventional demolition technique, typically used for demolishing non-reinforced or lightly reinforced concrete structures less than 1 m thick. This technique is recommended for non-radioactive structures. It was used successfully in dismantling the Elk River containment building, but was not successful at the Shippingport NPP, at the Penn Princeton accelerator (PPA) [448] and at KKN [446]. In these cases the concrete was too thick and heavily reinforced (see also Ref. [449]).

6.3.4.2. Expansive grout

Expansive grouting is a civil engineering technique which has found some use in the nuclear industry. It is used to fracture non-reinforced concrete by drilling holes and filling these with a wet grout mixture. As the grout cures it expands, creating internal stresses within the concrete substrate (see Section 6.2.2.16). It has been used during the PPA decommissioning project to separate activated concrete from non-activated/contaminated concrete blocks [423, 448] (see also Ref. [449]).

6.3.4.3. Rock splitter

Rock splitting is a technique which has been ‘borrowed’ from the quarrying industry. The rock splitter is a method of fracturing rock or concrete by hydraulically driving a wedge shaped plug between two expandable guides into a predrilled hole [183, 423, 448]. It is ideally suited for fracturing concrete in limited access areas. Hydraulic splitting devices and pneumatic hammers have been used, in addition to an electric excavator fitted with a jackhammer, to dismantle activated concrete at KKN [361, 367] (see also Refs [449, 462, 499]).

6.3.4.4. Paving breaker and chipping hammer

The paving breaker/chipping hammer is a conventional civil engineering method and as such the technique is well developed (see also Section 6.2.2.17). These tools are widely used to remove concrete (and asphalt) by mechanically fracturing localized sections of the surface [130, 183] and are also very effective in the demolition of cast iron structures. They can be used either manually or from remote deployment systems, e.g. excavators or manipulators [361, 367, 448, 467, 468]. Possible industrial safety issues with these technologies are discussed in Ref. [207].

6.3.5. Electrical cutting techniques

Electrical cutting techniques are based on metal evaporation, in contrast with thermal cutting techniques which melt the metal. Electrical techniques do not generate any metal flow in the melt pool but they do generate a larger volume of aerosols, and hydrosols under water, compared with thermal techniques.

6.3.5.1. Electrodischarge machining (EDM)

EDM is based on the principle of the thermomechanical erosion of metals through the accurate control of sparks. It is applicable to all materials which possess sufficient electrical conductivity and is ideally suited to underwater applications [183]. This technique has been used in dismantling reactor internals at the BR3 decommissioning project for cutting the thick walled (76.2 mm) thermal shield and for some delicate 'surgical' operations, such as the removal of bolts which were difficult to access [130, 266, 267, 285, 287, 289–292]. The EDM technique was applied underwater at the VAK experimental BWR [197, 293, 428] to cut the sparger ring. Some R&D has been carried out at Harwell with the aim of speeding up the process and reducing the amount of secondary waste [370]. Applications of metal disintegration machining (MDM) (see Section 6.3.5.2) and EDM are extensively described in Refs [500, 501] (see also Ref. [429]). Figures 35 and 36 illustrate different EDM applications.

6.3.5.2. Metal disintegration machining (MDM)

MDM is similar to EDM except that the cutting pulses are generated by vibrating the electrodes [183] or by contact and retraction of the electrode from the workpiece. This technique has been used in mock-up trials for dismantling the reactor internals at BR3 [130, 266]. A comparison of MDM with plasma arc properties/applications is discussed in Refs [502, 503].

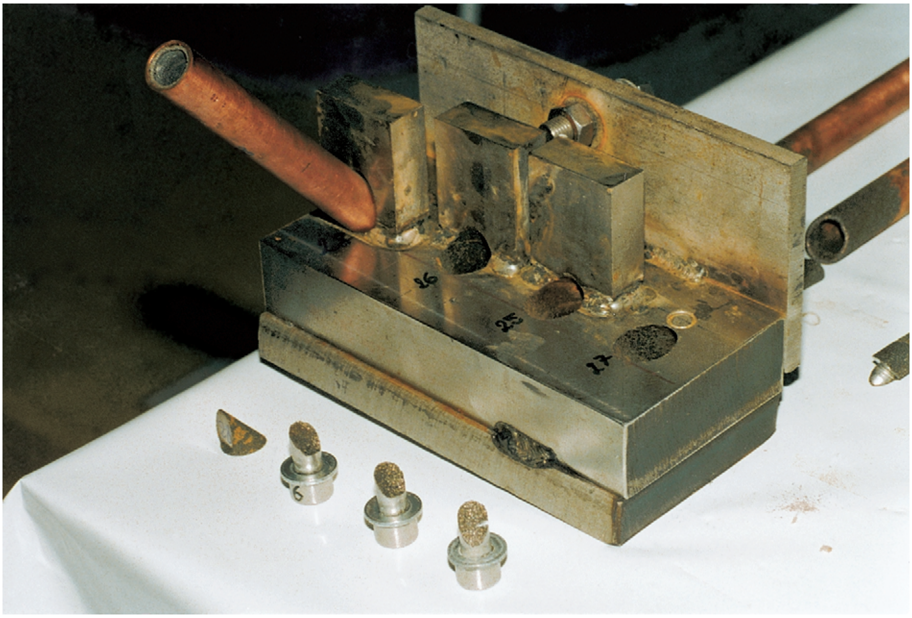

FIG. 35. EDM being tested on bolt cutting at the BR3 decommissioning project.

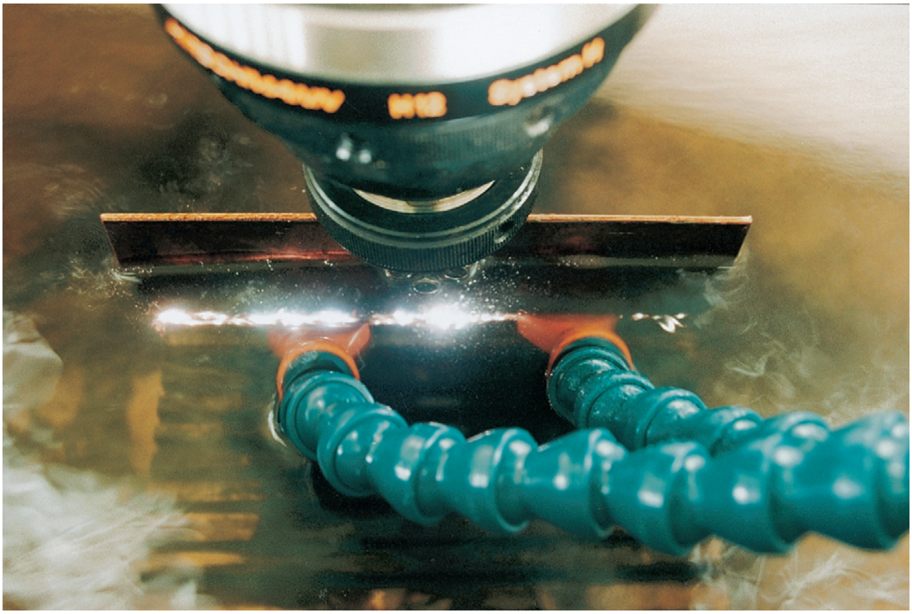

FIG. 36. EDM being tested on cutting thick gauge metal (underwater for remote use) at the BR3 decommissioning project.

6.3.5.3. *Consumable electrode*

The consumable electrode technique consists of a wire being continuously fed from a coil into the kerf, an arc being initiated by a short circuit between the wire and the workpiece [39, 183]. Three methods are reported in Refs [415, 485]:

— Oxygen jet cutting (mainly with mild steel wire)
— Water jet cutting (all metals)
— Water jet gouging (all metals).

A special prototype of a consumable electrode torch was developed and used at the JEN-1 reactor in Spain [197, 282, 283]. This technique has been tested for the underwater cutting of radioactive components at the Pegase facility in France [197, 477] where the maximum plate thickness that could be cut using a single power source and a 3 mm diameter wire was 100 mm.

6.3.5.4. *Contact arc metal cutting*

In the contact arc metal cutting process, the electrode is moved continuously towards the workpiece until contact is made between the two, thereby causing a short circuit. The electrode is then fed into the material to be cut. The high density of the current in the arc heats the workpiece, causing the material to evaporate [39, 197, 415]. This technique has also been tested at the Pegase facility for the underwater cutting of radioactive parts [197, 477]. The technique is being further developed via an EC R&D project [434] and at KRB-A for the removal of edges prior to the application of other techniques [421].

6.3.5.5. *Arc saw cutting*

Arc saw cutting uses a circular, toothless saw blade to cut conductive metals without making physical contact with the workpiece. This is achieved by maintaining a high current electric arc between the blade and the material being cut. It is effective in cutting high conductivity materials such as stainless steels, high alloy steels, aluminium, copper and Inconel [183]. It has been applied, under water and remotely operated, at JPDR for segmenting the body portion of the RPV [25, 132, 441, 443, 478, 504, 505] (Fig. 37). Arc saw cutting was proven to be effective in preventing the release of contamination, in addition to minimizing the radiation exposure of workers [480]. A comparison of arc sawing with other cutting techniques is provided in Refs [182, 429, 433, 434, 448].

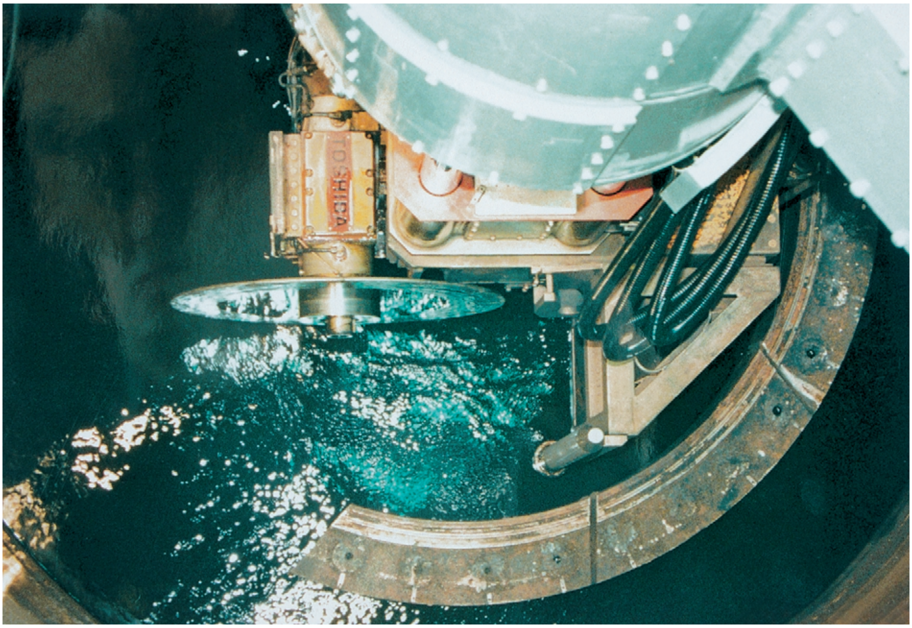

FIG. 37. Mast type arc saw cutting system employed in the vertical cutting of an RPV at the JPDR decommissioning project.

6.3.6. Emerging technologies

The following list presents the techniques that are currently being developed and/or which have not been fully evaluated as to their cost effectiveness [183, 250].

6.3.6.1. Liquified gas cutting

Liquified gas cutting is similar in principle to water jet cutting, except that the carrier medium is a liquified gas. Liquid nitrogen is being developed in the USA as a carrier medium [506]. The perceived advantages of this method include lack of a secondary waste stream; favourable economics; and absence of hazards from explosion, fire or oxidation.

6.3.6.2. Laser cutting

Laser cutting is a process by which a laser beam is used to heat locally a metal beyond its melting point, thereby cutting it. The technique can cut almost any material but is currently limited in its technical performance and by the high capital cost of the equipment [197, 429, 448, 507–509]. This process has been applied both in air and under water [509, 510]. To date, work in this area has focused on the use of the following types of laser: the CO and CO_2 in Europe [511] and Japan [512, 513], and the chemical oxygen–iodine laser in Japan [514]. The limited R&D work conducted to date in Japan has shown that optical fibre transmission would make laser transmission usable at a remote cutting location [486, 510, 515]. In addition, information and data have been gathered on aerosols, suspended particles and sedimented dross [184, 509, 516]. The laser technique has been applied at the VAK experimental BWR [197, 428] and produced a very thin kerf. The purpose of the study described in Ref. [517] was to evaluate the capacity of the pulsed YAG laser to cut thick metallic material and to compare it with CO_2 laser performance. A demonstration test to cut some 300 radioactively contaminated fuel storage tubes is described in Ref. [518]. Further R&D work is needed on this emerging technology [415, 486, 519].

6.3.6.3. Shape memory alloys

Shape memory alloys are novel materials in that they have the ability to return to a predetermined shape when heated, generating extremely large forces in the process. They can be used like expandable grout to break up concrete structures [183].

6.3.6.4. Electrical resistance

In the electrical resistance process, a large current is passed through the reinforcing rods of a concrete structure. The heat generated increases the rod dimensions and when the stress induced by the heating process exceeds the strength of the concrete, local failure will occur. This process is being developed for the BR3 reactor [130, 266, 286]. The results obtained so far show that the concrete can be fractured but that the dismantling still requires the use of an additional technique such as a jackhammer [467].

6.4. WASTE MANAGEMENT

6.4.1. Waste minimization, treatment, conditioning and packaging

Worldwide, many countries have developed comprehensive treatment strategies for waste arising from decommissioning projects. The starting point of these strategies is the production of an inventory of the radionuclides present, as these will dictate the operational, transportation and disposal practices to be employed during decommissioning and consequently will determine the costs of waste disposal [100].

Approaches to be exploited in order to reduce the volume of solid radioactive wastes include [423]:

- Segregation of non-contaminated and contaminated materials, particularly if this can be done at source;
- Use of on-site cleanup processes to recycle and reuse products whenever practicable;
- Use of super-compactors is widespread and has proved to be very effective [77, 520];
- Utilization of decontamination and decommissioning processes to prevent the spread of contamination or to recategorize waste forms;
- Recycling of products no longer needed on-the site;
- Planning and construction of the processes needed for the release of material from the site.

Conditioning and treatment techniques for liquids can include bituminization, drying, evaporation, cementation and incineration. Conditioning techniques for solids can include compaction, incineration, encapsulation within a solid matrix, direct packaging, dismantling and segmenting, melting, and chemical and biodegradation methods [39, 77, 245, 246, 521–528].

A system for dismantling, size reduction, decontamination, melting and encapsulation of decommissioning waste is described in Ref. [529]. A comprehensive description of the factors affecting the selection of a waste container and the packaging and how to optimize these processes is given in Ref. [530].

R&D activities in this field include the design of containers for waste items [424] (Fig. 38), in particular the large transport containers for intermediate level decommissioning waste [531] and the development of waste containers constructed from low level radioactive scrap steel [532]. Further development is needed in areas such as the treatment of waste originating from alpha contaminated material and non-ferrous scrap, the volume reduction of contaminated/activated concrete, the metallic coating of graphite parts to fix radionuclides, the recycling of reinforced steel in concrete and the recycling of slightly contaminated concrete [197]. For example, R&D activities on the treatment and conditioning of radioactive graphite by a series of controlled thermic desorptions in oxidizing and inert atmospheres and on the metallic coating of graphite by ionic deposition have been conducted in Spain and reported in Ref. [533]. A different conditioning technique for graphite bricks has been investigated in France [534]. A special waste treatment problem is that posed by sodium in fast breeder reactors [199] (see also Section 5.3.7).

The USDOE is currently undertaking development work on technetium and actinide solvent extraction methods, high temperature vacuum distillation separation

FIG. 38. Steel box for holding radioactive waste objects.

of plutonium waste salts, separation of tritiated water using membranes, and water soluble chelating polymers for the removal of plutonium and americium from waste water [87].

6.4.2. Recycling and reuse of materials, buildings and sites

A substantial quantity of waste generated from decommissioning activities could be recycled and reused [47]. Several hundred thousand tonnes of metal, concrete and other materials are expected to be disposed of worldwide [38, 535, 536] through the decommissioning of former weapon facilities and the future dismantling of power and research reactors. For example, dismantling of the Russian RBMK 1000 reactors will generate approximately 35 000 t of Cr–Ni steel [537], the major part of which would be suitable, after decontamination, for recycling.

6.4.2.1. Metal recycling

Melting is an adequate method of metal recycling for most decommissioning projects. A survey of existing and projected recyclable scrap inventories in the USDOE community is given in Refs [73, 76]. Practical demonstrations of the recycling of contaminated metals are being dealt with in USDOE D&D programmes [87, 538–543] and at US commercial facilities [544].

Recycling of steel and other materials has been reported from the decommissioning of the KRB-A facility [70, 374, 375]. Other references to German experience are given in Refs [367, 545–547]. Germany has a large industrial melting facility for radioactive materials which has been operational for a number of years [55, 56]. As the general size of melters for radioactive scrap metal is small compared with those for non-radioactive metals, the radioactive scrap has to be cut into pieces small enough to fit into the crucible. Cutting can be performed manually or, in the case of large quantities, in a more economical manner by using an automated process. A dedicated cutting facility to prepare metallic materials for melting is also in operation in Germany [548].

A report on the melting of uranium contaminated steel arising from the decommissioning of a fuel fabrication plant is given in Refs [549, 550]. Melting of steel, copper, brass and aluminium and the separation of different metals from electrical components by melting are reported in Refs [56, 551]. At Capenhurst, a decommissioning project dealt with over 160 000 t of suspect surface contaminated metals, concrete and other potentially hazardous materials. The significant nuclides were uranium and its daughter products, together with ^{99}Tc and ^{237}Np from the re-enrichment of reprocessed uranium. Over 99% of the total mass of materials were successfully treated and recycled via decontamination and melting [552].

A small melting facility for developing an aluminium recycling technique has been built at the JEN-1 reactor in Spain [282, 283] and a facility for melting aluminium and brass is in operation at Studsvik in Sweden [553, 554]. The melting of ferritic steel arising from the dismantling of the G2/G3 reactors has been investigated at a dedicated facility in France [555, 556] and Japanese test results on melting metals with low contamination levels and the manufacturing of new components are reported in Refs [253, 557–559] (Fig. 39). The recycling of Canada’s contaminated stainless steel fuel baskets is reported in Ref. [560] and an overview of industrial practices and investigative trials in the EU is given in Ref. [561].

In the Russian Federation, the first plant for metal melting was built at Belojarsk NPP (AMB-100 of BWR type) for the recovery of metals arising from plant decommissioning [245, 246]. The results were successful. To accelerate solutions to the problems of metallic radioactive waste in the Russian Federation, a special Federal programme entitled ‘The Treatment and Utilization of Metallic Radwastes’ was approved by the Government of the Russian Federation. In accordance with the programme, a pilot facility for remelting the radioactive scrap was built and put into operation in 1995. During 1995–1996 it melted about 100 t of stainless steel and cupro-nickel from the Leningrad NPP. This melting facility has been considered as

FIG. 39. The melting furnace at the Naka Energy Research Centre, Mitsubishi Materials Corporation.

the basic model of an industrial process [537], the main characteristics of the process and the proposed plans being given in Refs [246, 523, 537, 562]. An industrial scale melting facility is also planned for Chernobyl [563].

Although recycling is the main reason for melting metals contaminated with radioactivity, the melting process also results in some decontamination of the feedstock. This occurs as a result of separation of the different constituents of the melt, the degree of separation being controlled by the chemical and physical properties of the radionuclides present. For example, the melting of contaminated steel facilitates the separation of ^{137}Cs because Cs concentrates in the slag. On the other hand, ^{60}Co remains in the ingot, and therefore Co contaminated steel should be decontaminated before melting. In the case of neutron activated steels, Japanese test results on separating Co and Ni from Fe show that Co and Ni contaminated steel can be decontaminated by oxidation and reduction [558].

After the segmented steam generators of Sweden's Ågesta reactor were melted, measurements showed a reduced residual Co activity of 1–4 Bq/g [299]. Similarly, the experience gained from the melting of fuel element racks from a Spanish NPP showed that activity was reduced by a factor of three [564]. In Japan, nickel based alloys from reactor steam generators have been successfully melted by a continuous induction cold crucible process. Decontamination of the feedstock also occurred by the concentration of radioactive elements within the slag which formed on the surface of the melt [565, 566]. The possibility of melting metal after decontamination is also being evaluated at the BR3 reactor [266]. Use of melting technology for the homogenization and separation of radionuclides is also reported in Refs [47, 233].

Data on waste minimization, gained from melting techniques used in three facilities, are reported in Ref. [77]. After melting, the metals can be reused for a variety of purposes [559, 567, 568]. Initiatives now under way within the USDOE to utilize radioactive scrap metals to fabricate other products, such as radioactive waste shipping, storage and disposal containers, are described in Ref. [538].

Although the melting of metals contaminated with radioactivity can be regarded as a mature technology, R&D activities are still being performed to optimize the process or to overcome special difficulties. For example, R&D activities in Germany are reported in Refs [54, 569–571] and laboratory development of decontamination by melting is described in Ref. [572].

6.4.2.2. Concrete recycling

A process for the treatment of contaminated concrete has been investigated in the Netherlands [573, 574]. The conceptual process involves heating and simultaneously milling the concrete. The process effects the separation of the cementitious fines (representing a low volume stream, but containing most of the radioactivity) from the aggregate stream (the remaining high volume, low contaminated component). The latter is washed to remove residual contamination, enabling the aggregate to be reused. This concept, including the heating and milling of the concrete, has also been tested in Japan [558]. Results show that high quality aggregate can be recovered from concrete waste. Decontamination and recycling of concrete are also being investigated by the USDOE [87]. A study on how to deal with over 23 million cubic metres of concrete arising from the dismantling of USDOE buildings is described in Ref. [575]. Another US study is described in Ref. [576] and an EC study on the recycling of activated/contaminated steel scrap in concrete is reported in Ref. [172]. The mechanical and other properties of the reinforced concrete manufactured using scrap steel are investigated in Ref. [172] and preliminary conclusions given. Developments in Japan are given in Refs [558, 577].

6.4.2.3. Buildings and sites

The decision to clean up contaminated buildings and sites and the level of decontamination required depends on a number of factors. Experience in releasing sites and buildings exists in many countries where buildings [154, 578] or entire sites [367, 462] were released for restricted or unrestricted reuse. A US overview of decommissioned facilities/sites for which new productive uses were found after decommissioning is given in Ref. [579].

For small scale applications it might be a reasonable decision to reduce all the radioactivity to background levels. An example is the cleanup of a small shallow land burial site (40 m x 20 m) for low level radioactive waste formerly used by a research institute in the Netherlands. Because the waste site was very close to a densely populated area, the site was cleaned up by removing all the radioactive waste [580]. Other examples were presented at an international conference [581].

If the scale of the contamination is large, decisions to remove all radioactive waste may not be practicable. For instance, there are many contaminated sites, e.g. nuclear weapon facilities, that cover many square kilometres of land. The contamination may extend to all environmental media, as well as to on-site buildings and equipment. In these situations the decision to clean up, and to what level, depends on a comprehensive analysis of all aspects of the cleanup operation being undertaken in order to arrive at an optimal solution [50, 166].

6.4.3. Temporary storage

Temporary stores are an important component of the waste disposal strategy. These facilities are provided for a number of reasons, typically:

— As part of a strategy to enable the product form to achieve the specification required for acceptance in the final repository, i.e. vitrified glass;
— As temporary holding points until a final repository becomes available;
— As buffer stores, to enable optimization of the operation of the final repository.

A number of such facilities exist around the world, the following being a small selection.

As low level radioactive waste disposal facilities are not yet available in Canada, such waste is currently stored by the major waste generators in various engineered structures [582]. However, these storage facilities are not intended to store the entire stock of decommissioning waste that will be produced in the future. German experience, including the erection of dedicated storage facilities for some decommissioning waste, is given in Refs [583, 584].

The decommissioning and dismantling plan for Vandellos-1 NPP in Spain has allotted a dormancy period of some 30 years for completion of dismantling. During this period, it is proposed to (i) store the pre-conditioned graphite waste in a temporary radioactive waste storage area located in the low zone of the reactor building, and (ii) investigate management processes for the final disposal of the graphite [585].

6.4.4. Asbestos

Asbestos is a particular problem in both older nuclear and older non-nuclear facilities as the inhalation of even small quantities of asbestos fibre can result in lung disease. As a result of this, the removal and disposal of asbestos containing materials is subject to strict regulatory control, irrespective of the radioactive content. The techniques for the removal and direct disposal of asbestos are well developed, although the operational specifics may vary from country to country. In the USA, efforts continue to be made to develop a system for remotely removing asbestos from pipework, to convert asbestos containing material into a non-regulated material, and to develop an electromagnetic process for removing and separating hazardous and radioactive materials from asbestos [13, 87, 586, 587]. In the Russian Federation, tests on a semi-industrial scale have been undertaken for the compaction and melting of asbestos type insulation. Melting of the insulation resulted in a vitrified product and a 15–30 fold decrease in waste volume [246, 522]. Information on asbestos removal in Belgium can be found in Ref. [292].

6.5. ROBOTICS AND REMOTE OPERATION

Up until the early 1980s “only limited experience to date with the development and utilization of devices of this type...” existed [4]. The breadth of experience in

Europe expanded during the late 1980s and early 1990s as part of the Teleman project [588–590] and in the USA through the USDOE EM 50 Office of Science & Technology [591]. An overview of available remotely operated handling equipment was published by the IAEA in 1993 [11]. The purpose of this section is therefore to provide a series of references to developments and applications that have occurred since the above technical report was published.

Nowadays, in general, robotic wheeled/tracked vehicles are used for characterization, decontamination and dismantlement tasks. Other developments include: bridge mounted robotic platforms; power sources for mobile platforms; failure recovery equipment; automated separation technology; preprogrammed obstacle avoidance; programmed motions; teach/playback; voice control; transportable control systems; hardware (umbilical); laser based communication; force feedback; and flow, mass and volume sensors. All these are mature technologies [250].

According to Ref. [250], the following require further testing and evaluation: internal pipe/duct crawlers; light, medium and heavy duty long reach arms; arms with more than six degrees of freedom; remote/automated interchangeability; tool–arm interfaces; force limiters; multiple concurrent mobile platform controls; combined mobility/manipulation/end effector controls; sample management; data integration/fusion; fuzzy control; microwave communication; radio frequency based communication; 3-D vision; high definition television; directional audio; wall thickness measurement; laser range finders; and force controls.

Compact high capacity arms, multifingered end effectors, single human multiple vehicle control stations, human–robot symbiosis, imaging and image processing, proximity probes and positioning all require R&D according to Ref. [250].

According to the EC R&D programmes for 1984–88 and 1989–93, semi-autonomous manipulators should be adapted and tested with respect to specific dismantling tasks, as well as sensing systems and computer software. A telerobotic monitoring, decontamination and size reduction system was developed at the UKAEA for electropolishing of metal surfaces, clearance monitoring of concrete surfaces and glovebox size reduction [370]. Applications within the Sellafield decommissioning programme are described in Ref. [592]. At the Commissariat à l'énergie atomique, a master slave arm (RD 500) has been adapted for underwater use and successfully tested and is therefore qualified to perform underwater tasks [593].

A strategy known as contact deployment remote operation, which seeks to provide an acceptable and cost effective human–machine combination, is being exploited in the UK [592, 594]. As commercially available manipulator devices were not fully compatible with the constraints imposed by the WAGR environment, a custom-built, multiaxis manipulator was procured. Two different types of tool have

FIG. 40. Excavator being used for concrete removal at EBWR. 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.

been developed for deployment by the manipulator: a series of oxypropane cutting tools, and a series of electrically powered angle grinders. Over 30 handling systems have been developed for use at the WAGR, ranging from single mechanical plate grabs to remotely deployed vacuum cleaners. Large scale mock-ups have been used to test remote control devices, to optimize cutting parameters and to train operators [129, 445, 475].

The development at ORNL of a dual arm manipulation module to provide dexterous manipulation capability for remote characterization and D&D operations and to meet various deployment requirements is described in Ref. [595]. An automated, remote dismantlement system consisting of a set of end effectors and a number of auxiliary systems for task monitoring and waste control is being tested at ANL's CP-5 reactor [596].

Also developed within the USDOE D&D programme are diagnostics and data fusion of robotic sensors, a selective equipment removal system, and surveillance and maintenance risk and cost reduction evaluation methodologies [87]. The activated portion of the biological shield at the EBWR was removed using an electrohydraulic remote controlled jackhammer [423] (Fig. 40). Once the demolition work was completed, the machine was fitted with a bucket scoop and used to load the concrete rubble into shipping containers. A US market survey of commercially available manipulators, end effectors and delivery systems for reactor decommissioning activities is provided in Ref. [597].

A series of remote controlled devices has been developed at the University of Hannover in Germany [598]:

- An underwater tool carrier system (ODIN 1) designed to dismantle the steam dryer at the KRB-A reactor;
- A cutting device (RAMSES) developed at the KRB-A reactor to cut the internals of the reactor core, the head of the reactor vessel, the RPV steam drier and the standpipes using a small plasma torch [277, 371, 599];
- A combination of an ultrasonic sensor and an eddy current sensor (INDUS) to measure thickness, distance and orientation;
- A seven axis manipulator (ZEUS);
- A free diving handling system (FAUST);
- A wall climbing robot (HYDRA).

Additional information on German experience is provided in Refs [600, 601].

A comprehensive description of the French programme and experience on the use of robotics for decommissioning purposes is given in Refs [602, 603] and a review of Russian experience in the remote deployment of decontamination and dismantling systems is detailed in Ref. [244].

6.5.1. Deployment systems

Deployment systems in this context are systems such as manipulators, XYZ frames or remotely controlled vehicles which can be used to deliver a tool to a worksite and deploy it. Considerable advances have been made in this field and these are described in brief in Table VII, along with the appropriate references [604–626] (Figs 41–44).

Deployment systems can be used to facilitate the decommissioning tasks and to reduce human exposure to radiation and contamination. In the selection of equipment the following should be considered:

- Work specification and task analysis
- Dimensions and location of the workplace
- Access and disposal route
- Size and weight of the component involved
- Type and quantity of generated waste
- Environmental conditions
- Available services and auxiliary systems

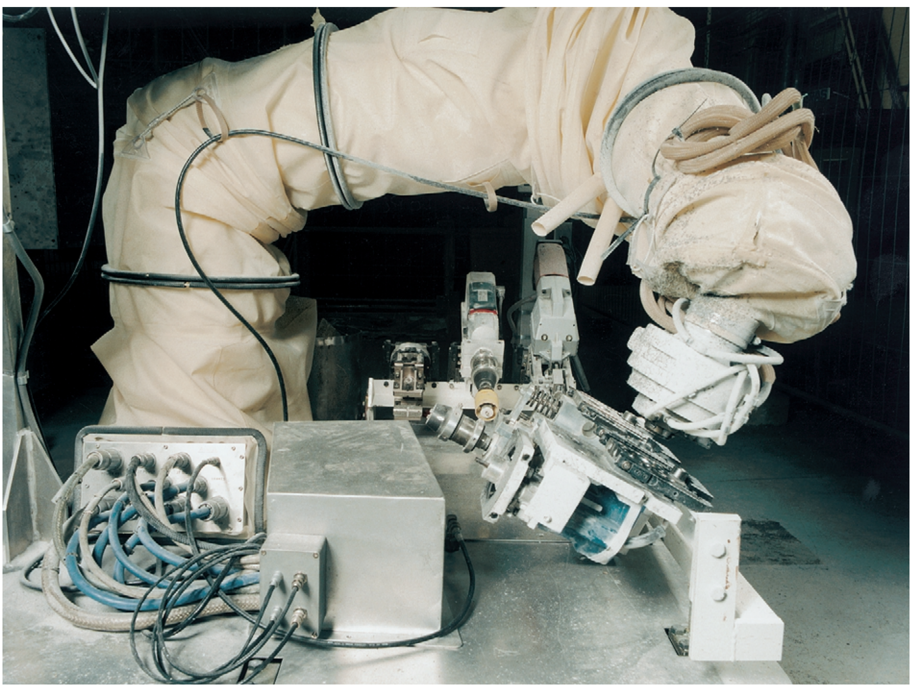

FIG. 41. NEATER 670 is a seven axis manipulator system.

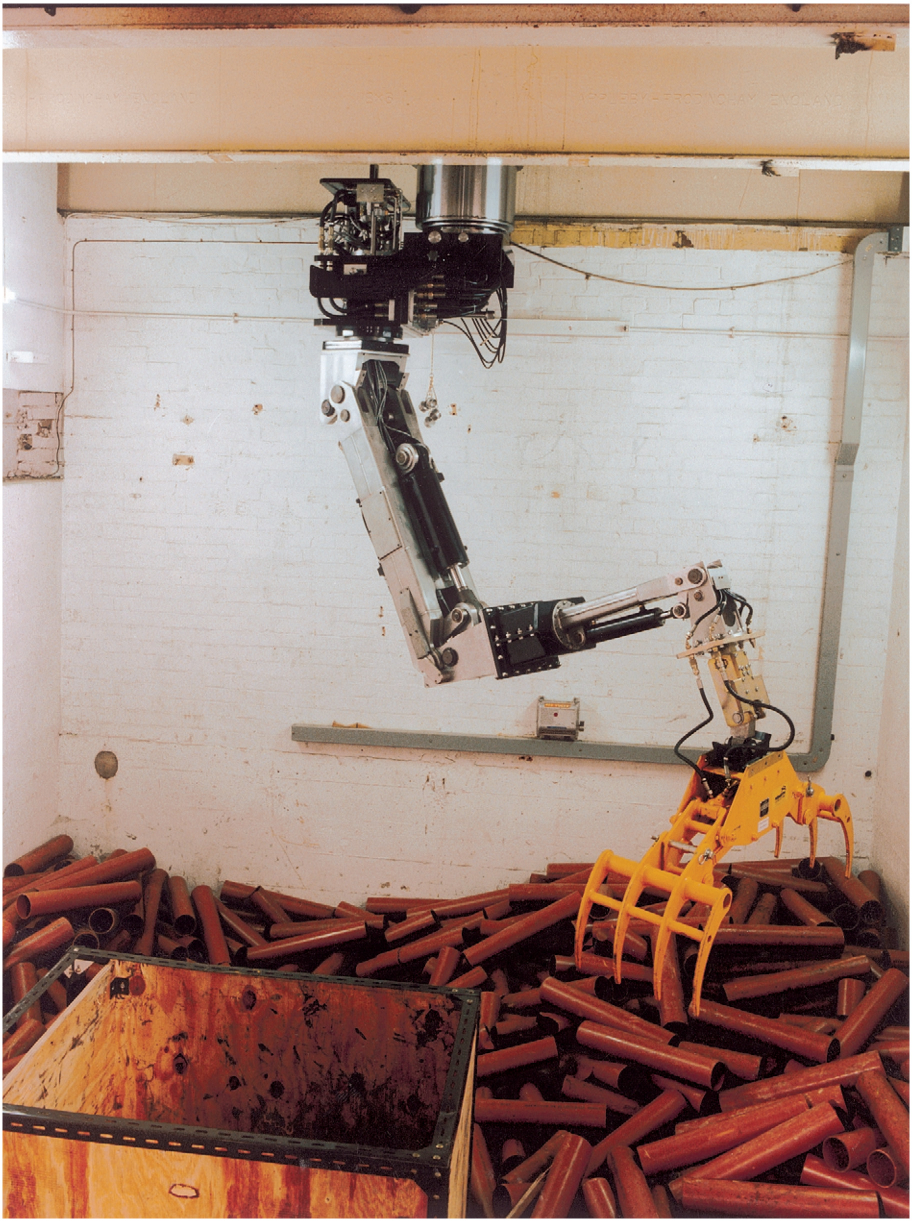

FIG. 42. An ARTISAN hydraulic manipulator with a 200 kg load capacity recovering simulated graphite sleeves. This manipulator is being used for clearing silos at the Vandellos NPP in Spain.

TABLE VII. REMOTE DEPLOYMENT SYSTEMS

Name	Project/country	Description	Reference
WAGR manipulator	WAGR, UK	Custom built multiaxis manipulator with suite of tools for dismantling reactor internals	129, 445, 452, 475, 476, 604
B204, B209, B212 dismantling systems	B204, B209, B212, UK	Custom built deployment systems incorporating robotic arms, viewing and lifting equipment	305, 605
NEATER	General purpose, UK	Multiaxis remotely operated manipulator for use in nuclear environments	146, 394, 606 (Fig. 41)
SCHILLING	General purpose, Windscale piles chimneys, UK	System for removing insulation and filters from the top of the Windscale piles chimneys	607
ARTISAN	General purpose, Harwell variable energy cyclotron, UK	Multiaxis remotely operated hydraulic manipulator	350, 608, 609 (Fig. 42)
Remote underwater vehicle	Windscale piles, UK	Cleaning of sludge and fuel elements from water ducts	610
Advanced tele-operation controller	Trawsfynydd, UK	Robotic's controller	611
Dual arm manipulator module	ORNL, USA	Dual arm manipulator for characterization and D&D operations. Reconfigurable to meet different requirements	595
Automated remote dismantling system	CP-5, USA	Consists of a set of end effectors and number of auxiliary systems for task monitoring and remote control	596, 612

TABLE VII. (cont.)

Name	Project/country	Description	Reference
ROSIE	USDOE	Heavy manipulator and control system for a variety of tasks	613
Mobile, multitask system	USDOE (Pentek Wall Walker™)	System consisting of end effectors suspended from cables	87, 614, 615, 616
Electrohydraulic remote controlled impact machine	EBWR, USA	Excavator mounted system for dismantling and packaging waste	423
Underground storage tank technology demonstration	Environmental restoration and waste management programme, USDOE, USA	Remediation of underground storage tank	617
REMEX	Environmental restoration and waste management programme, USDOE, USA	Remotely operated excavator	617
Remote controlled manipulator system	KKN, Germany	Central mast based on bridge with a ring universal gripper used for tools on a moving platform. Manipulator has four degrees of freedom	67, 361 (Fig. 43)
ODIN 1	KRB-A, Germany	Underwater tool carrier system	598
Remote cutting system	KRB-A, Germany	Plasma torch deployment system for reactor core, RPV head and RPV steam drier	371, 377, 599, 618
ZEUS	Germany	Seven axes manipulator	598
FAUST	Germany	Free diving handling system	598
HYDRA	Germany	Wall climbing robot	598

TABLE VII. (cont.)

Name	Project/country	Description	Reference
EMIR	General purpose, Germany	Long reach extended multijoint robot	619
JAERI manipulator	Reprocessing plant, Japan	Robotic manipulator and plasma arc cutting device	133, 390, 620
JAERI multifunct-ional system	JPDR, Japan	Multifunctional robotic system	621 (Fig. 44)
ATENA and MA 23	AT1, France	ATENA — remotely operated XYZ cranes. MA 23 is a master–slave manipulator	98, 197, 332, 350, 602
RD500	France	Watertight master–slave manipulator	593
MAESTRO	CEA, France	Teleoperated hydraulic, heavy duty, force feedback master–slave manipulator	622
TAO-2000	CEA, France	Manipulator controller	622
Manipulators M-22, M-31, M-51, MEM	Under development by Ministry of Nuclear Power, Russian Federation	Manipulator for repair and D&D operations	244, 246
MASCOT IV system	ITREC plant, Italy	MASCOT IV based system for dismantling process cell	623
ENEA system	Eurex plant, Italy	Two arm force reflecting servomanipulator (MASCOT IV) inside a containment box	624
Long reach manipulator	Vandellos-1, Spain	Telescopic mast system with ARTISAN 200 attached	625, 626 (Fig. 42)

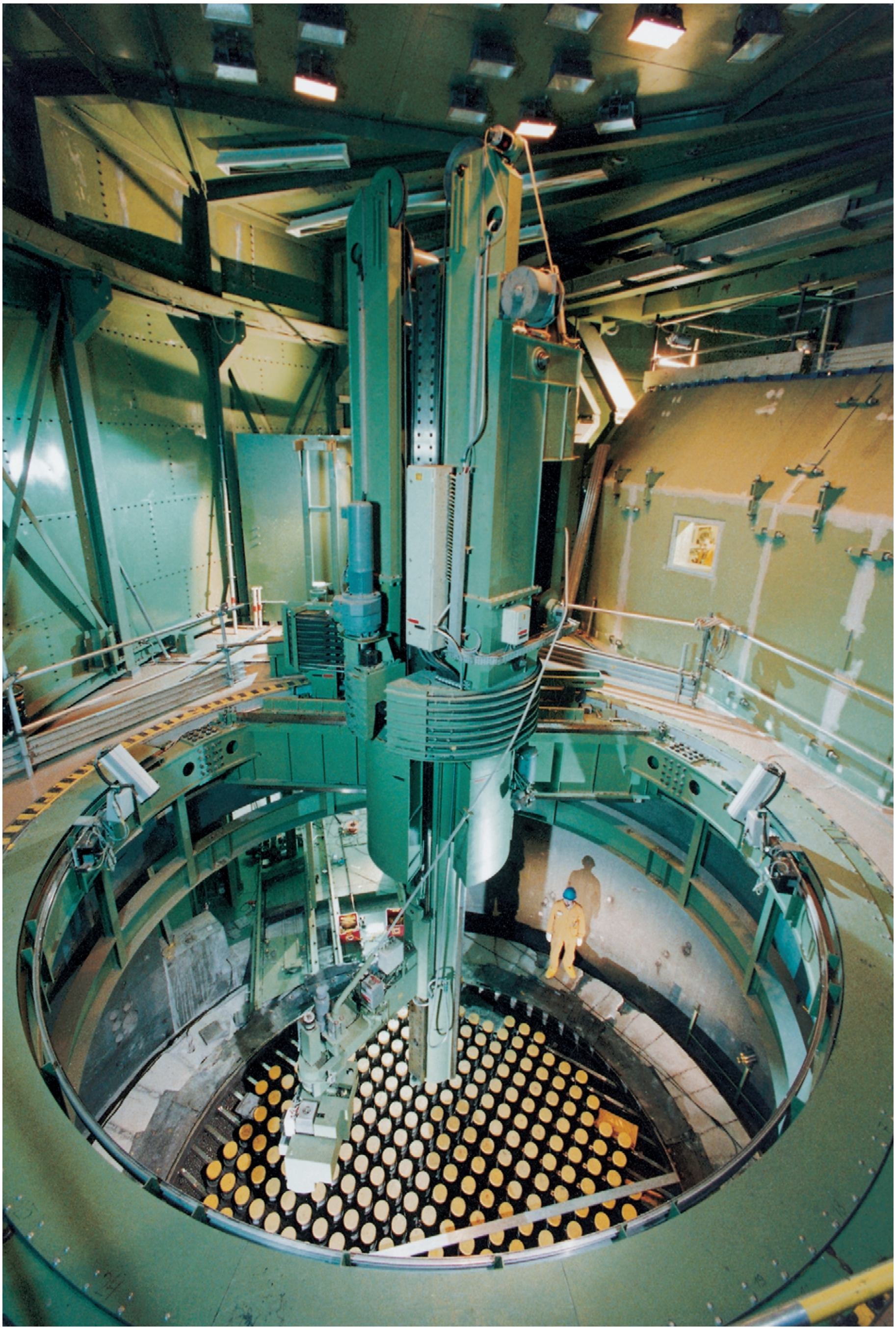

FIG. 43. Rotary manipulator used for the remote dismantling of the Niederaichbach (KKN) reactor.

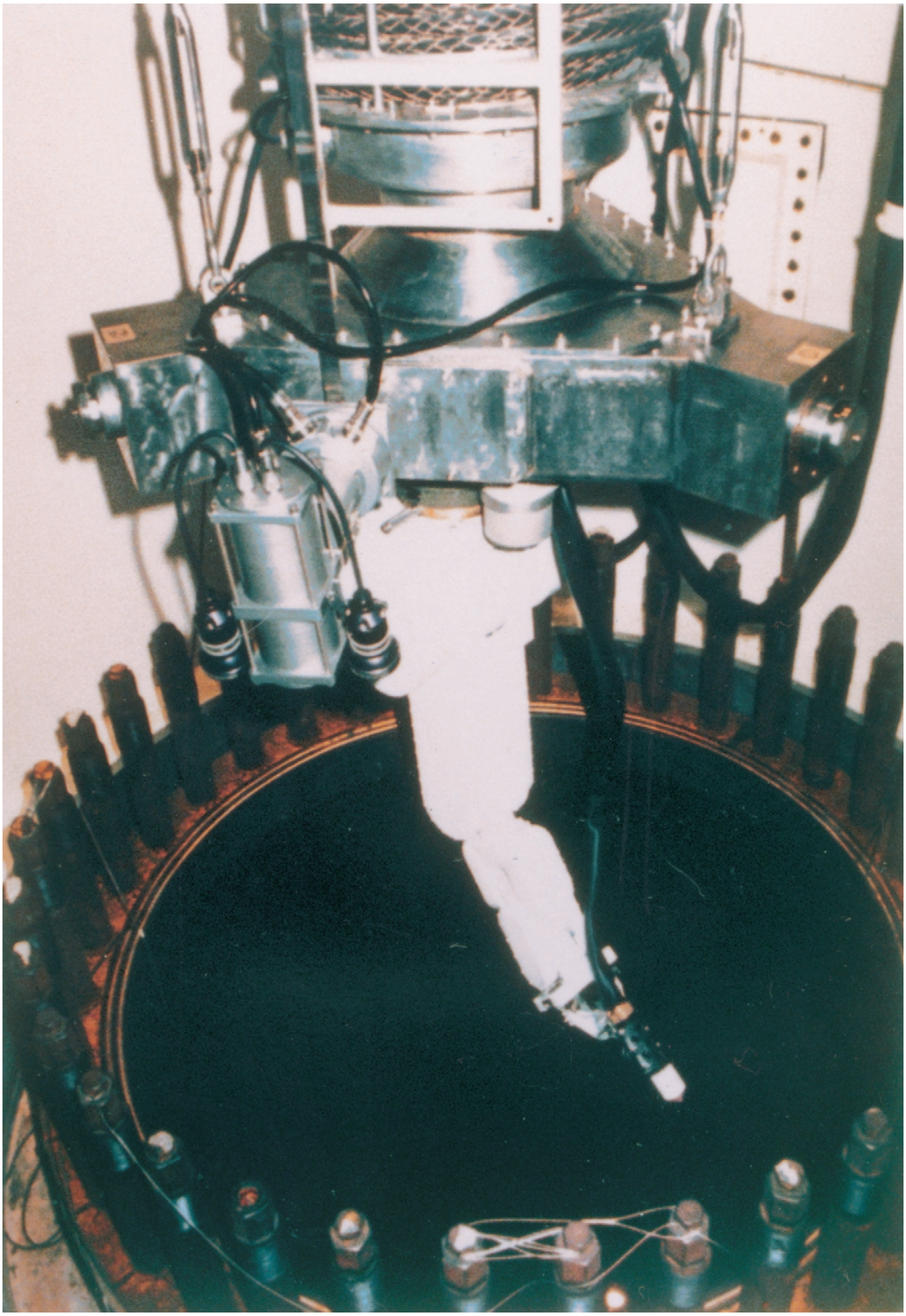

FIG. 44. Slave arm inside reactor vessel at the JPDR decommissioning project.

- Maintainability and reliability
- Failure recovery methods
- Safety and regulatory requirements
- Cost and schedule factors.

Other references of general interest are Refs [39, 87, 183].

6.5.2. Viewing and detection equipment

These are systems which allow the operator to view remotely the worksite or allow data and information on the operating environment to be collected without manual intervention. Advances in this field are listed in Table VIII [627–645] (Figs 45–48). Additional information on broader R&D programmes can be obtained from Refs [87, 197, 370].

6.5.3. Segmenting and disassembly equipment

The presence of high radiation fields or contamination levels often requires that segmenting and disassembly equipment be controlled and monitored remotely. A general discussion of the advantages and disadvantages of remote and manual operation is provided in Ref. [646]. Progress in electronics and sensor technology has led to considerable advances in the area of remote operation in both air and water. Considerable practical experience is now available and this is described in brief in Table IX, together with the appropriate references [647–652].

6.5.4. Decontamination equipment

The decontamination equipment described here is primarily for use as an end effector to a remotely deployed arm or other delivery device. As with the deployment systems described earlier, this is an area of considerable R&D activity and new advances are being made almost continuously. Table X gives an overview of recent developments in this field [653, 654] (Fig. 49).

6.5.5. Materials handling equipment

Remote materials handling equipment has been developed and used on various projects in the USA: the versatile remote handling system (LANL); the T-Rex materials system and a handling system, both being developed at ORNL [183]; a vehicle for autonomous waste transfer (Idaho National Engineering Laboratory (INEL)) [617]; and a mobile work system to be used specifically for retrieving Fernald K-65 silo waste [87, 617].

TABLE VIII. REMOTE VIEWING AND DETECTION SYSTEMS

Name	Facility	Description	Reference
Pipe explorer and characterization system	CP-5, Grand Junction, INEL, USA	System for carrying out radiological surveys inside pipes	87, 230, 231, 248, 350, 362, 627, 628 (Fig. 45)
Coherent laser vision system	General, USA	Three dimensional position and orientation data collection system	87
ALPHA contamination monitoring	LANL, USA	Long range alpha detector (LRAD) technology	629
Floor radiation surveys	CP-5, USA	Mobile automated characterization system (MACS) robot	(Fig. 46)
SIMON	SRS, USA	Robotic monitoring machine for carrying out floor surveys	77
Pipe crawler	SRS, USA	Visual and radiological inspection	630, 631
LDUA	Environmental restoration and waste management programme, USDOE, USA	Light duty utility arm	617
LARADS	Hanford C reactor, USA	Civil surveys and radiological detection	228, 632 (Section 6.1.2)
SCM/SIMS	Hanford C reactor, USA	Surface contamination monitor and survey information management	232, 632 (Section 6.1.2)
GRI	Hanford C reactor, USA	Building contamination survey	632
High precision monochrome CCTV system	General, UK		633
Stereo camera system	General WAGR, UK		197, 370

TABLE VIII. (cont.)

Name	Facility	Description	Reference
Semi-automatic contamination measurement system	AT-1, France		197
SOISIC	EDF/MENSI, France	As built modelling	634
ALADIN	CEA, France	Gamma and alpha imaging	635, 636, 637
Automated large scale radioactivity measurement facility	Germany	For use on low level waste	638
Remotely controlled data acquisition system	Reprocessing plant, Japan	Robot equipped with ITV camera to identify data, such as location and size of apparatus, as input to 3 D CAD system	390
GAMMA camera	General, UK, (C reactor, CP-5), USA, Russian Federation	Remote system for providing an image of active areas within a facility overlayed onto an image of the facility or internals	225, 226, 227, 639, 640, 641, 642, 643, 644, 645 (Figs 47, 48)

The development of long reach manipulators for the removal of waste from the vaults of the Vandellos-1 reactor in Spain is discussed in Refs [625, 626]. The system consists of:

— A containment bell,
— A telescopic mast,
— An ARTISAN 200 manipulator (Fig. 42),
— A range of manipulator end effectors,
— Equipment to position the above components,
— Shielding to protect operators.

A manipulator for removing slag, measuring temperature and taking samples during the melting of metals contaminated by radioactivity was installed at the

FIG. 45. Pipe Explorer™ being used to perform characterization of the CP-5 facility's embedded piping system. 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.

CARLA plant in Germany and following a campaign of inactive and active tests was then removed from the foundry for necessary modification and improvement [197]. A manipulator developed for assisting during scrap metal melting at Latina, Italy, is described in Ref. [650].

6.6. MISCELLANEOUS TECHNIQUES AND OPERATIONS

6.6.1. Water filtration

At the FSV reactor, the previously dry reactor vessel was filled with water to provide shielding and contamination control during the process of cutting open the

FIG. 46. The mobile automated characterization system robot being used for floor radiation surveys at the CP-5 facility.

reactor vessel head [68, 447]. A shield water system was constructed, tested off-site and installed to control water chemistry. The clarity of the shield water was maintained by treating the water with a flocculent and a polymer; the previous method of filtration and demineralization using polymers was not effective [68]. At the JEN-1 reactor, a filtration system for the pool water was designed and introduced to maintain water clarity [282]. Membrane filtering systems for water filtration have been tested at the CP-5 demonstration project, at INEL, at Hanford and elsewhere in the USA [248, 655]. At the Vandellos-1 NPP, two filtration systems for the decontamination, disassembly and emptying of fuel pools were designed and

FIG. 47. Gamma camera as used for gamma radiation field imaging at the CP-5 facility.

introduced to retain the remains of wire from the graphite sleeves and the graphite fines and sludges deposited on the bottom of the pools [656].

6.6.2. Ventilation/air filtration

Some D&D technologies may require modification to existing plant systems in order to allow dismantling operations to proceed. In particular, ventilation/off-gas systems may require modification prior to decommissioning because of the production of aerosols/fumes which did not occur during normal plant operation. This is an active R&D area [492, 657, 658].

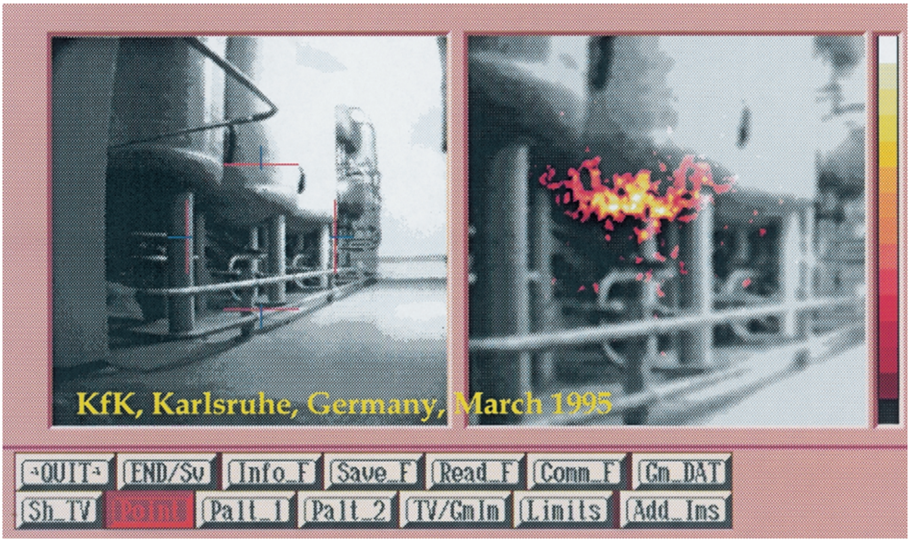

FIG. 48. Russian gamma camera images showing activity distribution within the water circuits of a nuclear reactor at Nuclear Research Centre Karlsruhe in Germany. Before measurements were taken, it was supposed that the activity was concentrated in one 'hot' point. In reality, the entire base of the middle reservoir is contaminated.

6.6.3. Diving

Divers were used at the FSV reactor to remove insulation and other components prior to the lifting out of the reactor vessel [68]. Development work has been carried out in France and Italy to produce and qualify a new diving helmet and a real time dose monitoring and data acquisition system in order to improve diver efficiency and safety [624]. In another development from France, cutting techniques such as plasma arc, saw and diamond wire were employed underwater by divers [659]; in Italy the fuel pond at ISPRA 1 reactor was cleaned by divers using a jetting system [660].

6.6.4. Worker protection

As well as actually performing the D&D activities, it is important that operations be carried out safely and that workers be protected from external hazards. In recent years there have been a number of developments in this field, examples include those in protective clothing, radiological monitoring, heat stress prevention and monitoring, and in fixative/stabilizer coatings.

TABLE IX. REMOTE SEGMENTING AND DISASSEMBLY EQUIPMENT

Name	Project/country	Description	Reference
USDOE development in remote segmenting equipment	USA	Various remote controlled segmenting and dismantling equipment	183
Remote dismantling	USA	Remote use of conventional segmenting equipment	647, 648
USDOE standardized tooling	USDOE	Remote handling system for performing various dismantlement tasks using overhead access facilities	596
Plutonium cells decommissioning	BNFL Sellafield, UK	Remote cutting systems for Pu handling	305
Windscale piles	Windscale piles and gas cooled reactor, UK	Chimney insulation and filter decommissioning; size reduction of pressure vessel; removal of refuelling channels; dismantling reactor internals	607, 649
Laser remote dismantling	Japan	Development of remote dismantling of reactor components using laser transmitted through optical fibres	515
Reactor internals	JPDR, Japan	Master–slave robotic manipulator–plasma arc cutting underwater	460
EMIR	Germany	Adaptation and testing of tools on telerobotic system: hydraulic hammer, hydraulic shears, crown drill, microwave scabbler, contamination monitor	619

TABLE IX. (cont.)

Name	Project/country	Description	Reference
RAMSES	KRB-A, Germany	Stand pipes cut with a plasma arc torch rotating automatically around the pipe	371, 618
Concrete dismantling	BR3, Belgium	Remote controlled jackhammer and shears installed on remote controlled excavator	266
Removal of steam generator tubes	Latina, Italy	Robotic system for the cutting and removal of steam generator tubes	197, 650
Cutting tool carrier and remote plasma torch cutting	JEN-1, Spain	Control system for fine positioning underwater dismantling of internals	282
Various remote underwater cutting tools for metal	BR3, Belgium	Underwater remote controlled plasma arc torch, EDM, circular saw, bandsaw for dismantling 2 sets of internals	267, 287
CLAUDIN	CEA/UDIN, France	Remote laser cutting	651
Concrete dismantling	EBWR, USA	Biological shield removal using electrohydraulic remote controlled impact machine	423

6.6.4.1. Protective clothing

In the USA there have been a number of developments with respect to protective clothing, e.g. the use of overgarments made from newly developed materials and the development of a liquid air ‘backpack’ to provide both oxygen and cooling air to the operator in the protective suit, which removes the requirement for an air supply umbilical. Tests performed at C reactor (Hanford) and at CP-5 (ANL) are described in Refs [217, 661–665]. Another interesting development is the use of an anti-dust helmet at the Kjeller reprocessing plant in Norway [424] (Figs 50, 51). Details of work undertaken in Belgium are described in Ref. [292].

TABLE X. DECONTAMINATION EQUIPMENT

Name	Project	Description	Reference
Concrete shaving	Eurochemic, Belgium	Automatic displacement shaving machine	136
Remote control underwater vehicles	Windscale piles, UK	Cleaning water ducts	610
Electropolishing head unit	Belgium, Germany, Japan and UK	Improved surface decontamination	336, 370
Vertical wall scabbler system	USDOE Office of Technology Development	Vertical wall decontamination	87, 652, 653
Remote operated vehicle	USDOE Office of Technology Development	CO_2 blasting of concrete surfaces	87
MOOSE™ decontamination robot	TMI-2 and other D&D projects	Concrete floor scabbling	654 (Fig. 49)
Hot cell decontamination activity	West Valley, USA	Remote decontamination	183
Tokai reprocessing facility	Tokai, Japan	Dissolver cell decontamination	183
Water jets GM-IM, GM-7, GEM	Under development by Ministry of Nuclear Power, Russian Federation	Remote flushing of tanks, vessels, canyons	244, 246
Steam injector heads GP-22, GP-31, GP-51, GP-MEM	Under development by Ministry of Nuclear Power, Russian Federation	Washing of premises and equipment with assistance of manipulators	244, 246
LOTOS	Under development by Ministry of Nuclear Power, Russian Federation	Decontamination of equipment by mixture of saturated steam and chemicals	244, 246

TABLE X. (cont.)

Name	Project	Description	Reference
COMPLEX ALPHA	Under development by Ministry of Nuclear Power, Russian Federation	Preparation of remote application and removal of strippable coatings	244, 246
Steam washing system	Under development by Ministry of Nuclear Power, Russian Federation	Removal of contamination from metals, brick and concrete by steam–abrasive mixture	244, 246

6.6.4.2. Radiological monitoring

A wireless remote monitoring system has been tested as part of the C reactor large scale technology demonstration project at Hanford [666]. The system allows supervisors, remote to the work area, to monitor in real time, by means of radio transmitters carried by the workers, the dose uptake of operators as they perform a variety of D&D tasks. The transmitters also allow communication between the operators and the supervisors.

6.6.4.3. Heat stress prevention and monitoring

In hot climates, the requirement for workers to wear additional protective clothing to protect them against radioactive contamination can cause them to overheat and suffer heat stress. A system for taking real time physiological measurements of the operators as they performed a variety of D&D tasks has been tested at C reactor [667]. The system requires the operator to carry a radio transmitter linked to sensors on the worker's body which measure heart rate, movement, skin temperature and core temperature. The data are then transmitted to a monitoring station remote to the work site which allows a supervisor to monitor constantly up to eight workers simultaneously and to advise them on their physical condition. Further progress in this field at Hanford is described in Ref. [668].

A separate development tested at Fernald [669] is a garment containing water cooling channels which are fed by chilled water from an ice pack. The suit is worn against the worker's skin and a pump on the ice pack forces chilled water through the cooling channels, thereby keeping the operator cool. Other technologies to alleviate heat stress are described in Refs [663–665, 670].

FIG. 49. Scabbling robot at work.

6.6.4.4. Fixative/stabilizer coatings

Various agents can be used as coatings on contaminated residues in order to permanently fix or stabilize the contaminant on the substrate, even though no removal of contaminants is achieved. These coatings may be used on PCB, explosive and radioactive contamination [183]. At Fernald Plant 7, after washing to remove gross decontamination, an acrylic latex coating has been used to fix any remaining loose surface contamination [423].

Aerosols containing capture polymers are a recent development. As the aerosol 'condenses', it covers all exposed surfaces in airlocks, gloveboxes or ventilation ducts with a viscous, tacky coating. This allows the capture of various contaminants in situ without necessitating human exposure [671].

6.6.4.5. Contamination containment

For short term operations, standard industry practice has been to construct a temporary tent-like enclosure from plastic sheeting. However, the tent's construction may impose operational constraints and create additional quantities of secondary waste.

FIG. 50. Protection helmet to prevent the inhalation of radioactivity. Clean pressurized air is fed into the back of the helmet and passes over the wearer's head, thereby preventing the inhalation of loose radioactive particulate. An additional advantage is that the air flow prevents condensation forming within the helmet.

A significant development in this field took place in UK with the introduction of the modular containment system (MCS). The MCS consists of prefabricated glass reinforced plastic panels which can be bolted together to form a self-supporting enclosure of the required size. Strippable coatings are applied to the walls and ceiling of the MCS for sealing purposes and contamination control. MCS applications to decommissioning activities are described in Refs [324–326]. Details of temporary airlocks and containments used in the Russian Federation are contained in Refs [244, 246].

6.6.5. Handling and lifting equipment

Normally, during decommissioning, use can be made of the handling and lifting equipment of the plant, if still serviceable. However, the dismantling and decommissioning operations are often very different from the ones carried out during

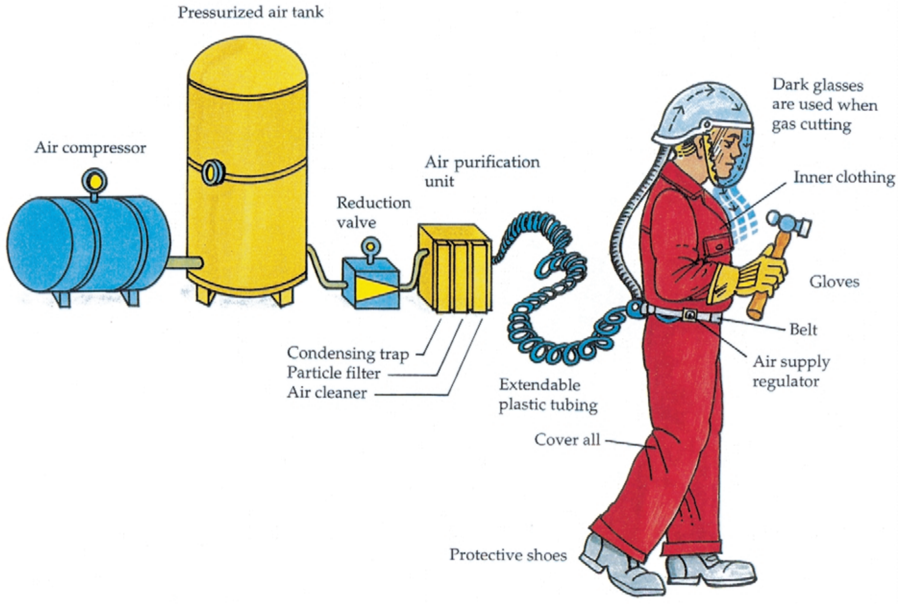

FIG. 51. Anti-dust helmet and protective clothing worn by operators.

plant operation. Therefore, new systems often have to be installed to cope with the additional requirements, e.g. the one-piece removal of a reactor vessel. Moreover, for high radiation areas, e.g. inside hot cells or reprocessing cells where no (or few) handling devices have been installed for normal operation, remote controlled cranes, hoists or lifting systems can be required.

Lifting yokes and hydraulic jacks were used to lift the core support floor at the FSV reactor as the existing reactor crane did not have the required capacity for this operation [68]. Hydraulic jacks were also used to lift the top biological shield at the WAGR [445].

Improvements in the payload capacity of telerobotic arms (see Section 6.5) can also help avoid the need for additional lifting systems and can allow the cutting of larger sized pieces. The shielding requirements for the transportation of activated or heavily contaminated sections often demand that the disposal routes be able to support the weight of the additional shielding as well as the item itself.

6.6.6. One-piece removal of large components

One-piece removal of large components has been performed at a number of nuclear facilities as a means of simplifying the dismantling or waste disposal processes.

FIG. 52. Removal of the WAGR top dome.

The benefits of this approach are reduced project costs, reduced time-scales, lower operator dose uptake and increased operator safety. This technique is especially attractive when there is close/ready access to either water or rail transportation facilities. One-piece removal can be divided into two distinct categories:

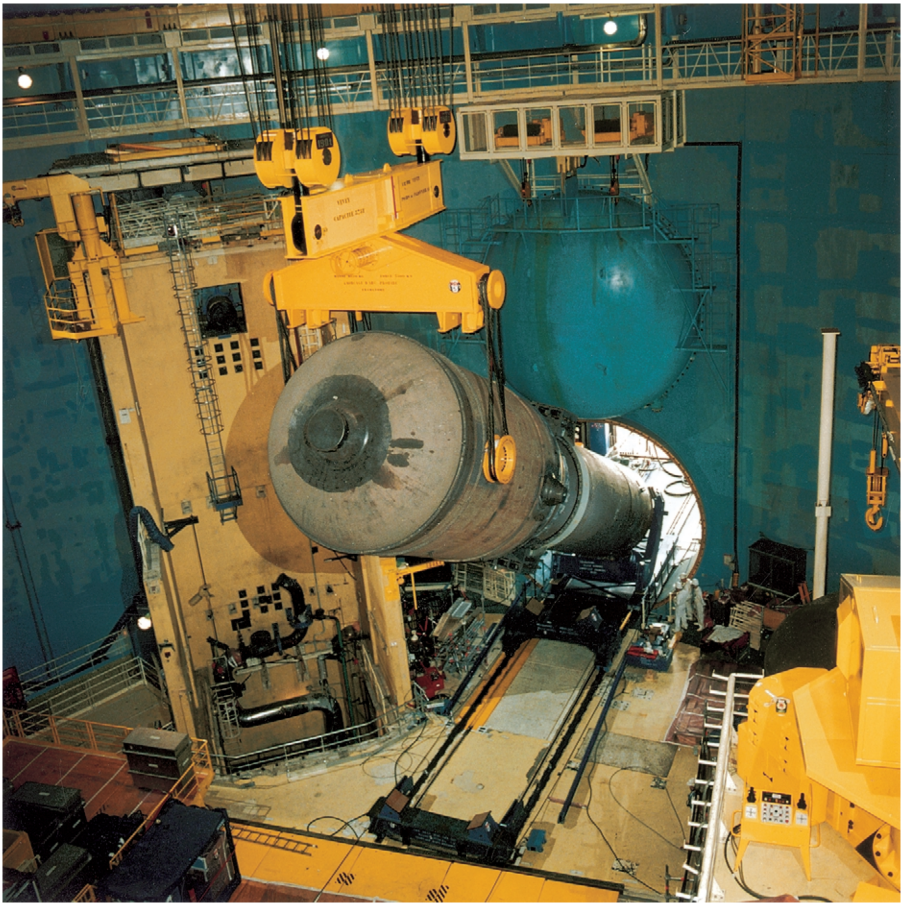

FIG. 53. Handling equipment used for removing a corrosion damaged steam generator at Dampierre (1990). Note the size of the main hatch which allows the one-piece removal of the unit.

- Removal of a large component to an adjacent facility, e.g. waste processing facility or special purpose containment, in order to reduce operator dose uptake and/or improve access in order to simplify subsequent size reduction processes. Examples of where this has been done are given in Refs [150, 423, 445, 672]. Figure 52 shows the removal of the WAGR top dome and Fig. 53 the one-piece removal of the Dampierre steam generator in France.

- Removal of a large component and one-piece disposal, i.e. after being lifted out the component is transported to its final disposal site and/or encapsulated

FIG. 54. A heat exchanger being removed from the WAGR.

without any further size reduction. Examples of where this has been done are reported in Refs [62, 65, 423, 487, 673–677]. One-piece removal could prove, in some cases, to be more cost effective and result in less radiation exposure than if the vessel were segmented. The removal of the four steam generators through the containment dome at WAGR was achieved using the biggest stand-alone crane existing in Europe [678] (Fig. 54). The transportation of these steam generators to the disposal site through narrow village roads also required the use of a special transporter.

The one-piece removal of the RPV at Shippingport [675], Trojan [65, 679] and Yankee Rowe [674] in the USA required a dedicated crane and cradle for handling and transportation to the disposal site. Sketch descriptions of one-piece reactor block removal projects at Shippingport and Hanford are given in Figs 55 and 56 (see also Ref. [680]). Additional references to specific techniques used for one-piece removal are provided in Refs [681, 682].

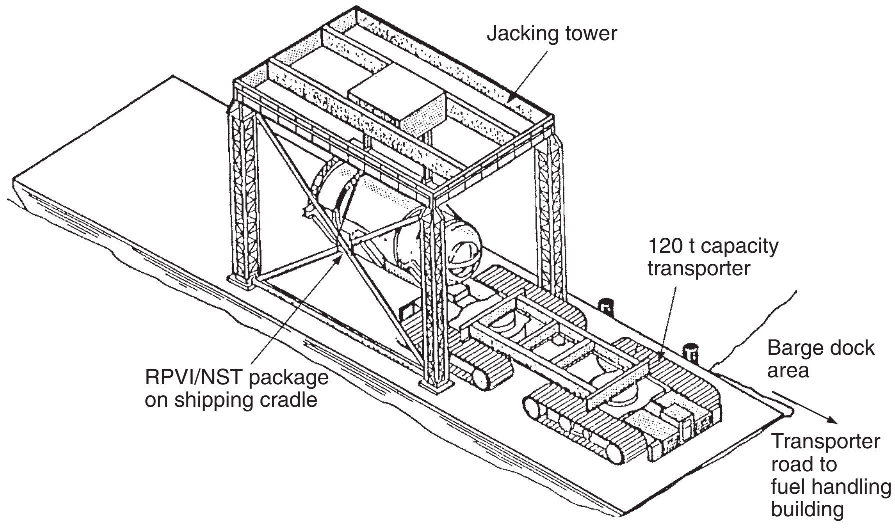

FIG. 55. Reactor block being loaded onto the barge during the Shippingport Station decommissioning project.

6.6.7. Use of mock-ups

Many problems can be solved by the use of mock-ups, such as:

- — Training of personnel to perform the planned work.
- — Positioning of remotely operated tools to optimize the planned work processes.
- — Adjusting and testing the performance of remotely operated tools, etc. [25, 445].
- — Selecting and defining the cutting/operating parameters of tools and equipment.
- — Optimizing radiation protection according to ALARA principles, which allow the identification of procedures and operations that can cause excessive operator dose uptake and which allow the modification of working practices to eliminate these.

Special remote controlled units were developed and tested on full-scale mock-ups before they were used for dismantling the KNN reactor [367]. Similar work, also in Germany, is being undertaken at the Wiederaufarbeitungsanlage reprocessing plant [683]. All the underwater cutting equipment (plasma torch, EDM, mechanical saws, shears, etc.) was tested on simplified full-scale mock-ups at BR3 in Belgium, as were dismantling techniques for the biological shield [130]. Reduced size simplified

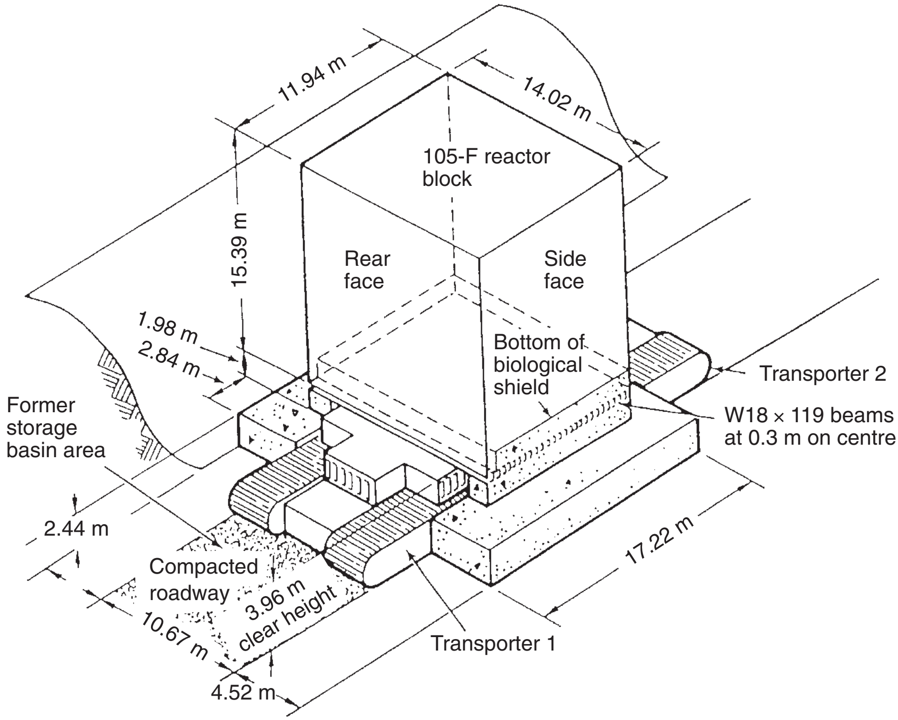

FIG. 56. Sectional view of the transporter in the excavated opening under the Hanford 105-F reactor block.

full-scale mock-ups were also used at WAGR [452] for training personnel and testing remotely operated tools for dismantling the internals of the reactor.

6.7. SOFTWARE TOOLS

There are currently several commercially available computer programs which can be helpful in planning and carrying out decommissioning. Such programs are sometimes also made available through organizations such as the IAEA, the OECD/NEA [684] and the USDOE. These software tools can be helpful in a very wide range of activities, from radiation protection optimization [685] including detailed shielding checks, exposure pathways [686] and estimated radioactive inventory [687], to more general tasks such as record keeping, operator training [688], computer mapping of facilities [689], project planning [690–692], data management [693], decision making [237, 246, 694, 695] and actual operation [268, 632]. A general discussion on the subject is given in Ref. [121].

7. GENERAL LESSONS LEARNED

Experience in the decommissioning of large nuclear facilities gained during the 1980s and 1990s has been evaluated and important lessons have been learned. Although the following list is not intended to be exhaustive, it may contribute to drawing the reader's attention to aspects important in decommissioning planning and management. Compilations of experience and lessons learned can be found in Refs [39, 117, 183].

7.1. GENERAL

- Decommissioning should be kept simple and should not be made overly complex. Mature, commercially available technologies should be used wherever possible to help decrease costs and optimize performance. However, oversimplifying decommissioning projects in the early planning phase should be avoided.

- Use of mock-ups and computer models is essential for operator training, dose reduction (ALARA), safety, feasibility and maintenance.

- Availability of accurate and complete records of facility operation and decommissioning is essential.

- Plant operators must be conscious of the need for the decommissioning activities. Personnel must recognize that this is a key part of the facility's life-cycle.

- Re-training and restructuring for decommissioning must take place at all levels in order to make decommissioning successful.

- Continuous quality improvement should always be a goal. This process should be driven by the facility operator and staff.

- Full use of existing, available structures and facilities (i.e. cranes, etc.) should be made.

- Good decommissioning requires some flexibility. The regulatory framework should not be unnecessarily complicated.

- Dose budgets are difficult to calculate and often overestimated.

- Alarm dosimeters have contributed greatly towards allowing operators control their own dose uptake.

- Handling and lifting equipment is not a minor item where decommissioning is concerned and must be considered in the initial planning phase.

- R&D should focus mainly on dose reduction, waste minimization and cost limitation.

7.2. CHARACTERIZATION

- Estimation of activation and contamination levels are often far from the actual values. Sampling is necessary to assess real values.

- Characterization can be expensive and cannot always be all-inclusive. In addition, if too exhaustive it may not be consistent with the ALARA principle. However, it must be thorough, carefully planned and well executed.

- There is a need for improvement in the area of direct radiation field measurement of facilities and in the fast characterization systems for waste and waste packages.

- Characterization and measurement for release is a critical area where there is still a need for further R&D.

7.3. DECONTAMINATION

- Often a combination of decontamination technologies is needed rather than just one particular technology.

- An evaluation must be made in order to optimize the decontamination needs of a project. Issues such as dose uptake, secondary waste generation and waste disposal can impact this.

- On-site decontamination is to be preferred if it is not inconsistent with optimization of dose uptake, costs and waste disposal routes.

- Current technologies for chemical decontamination are still case specific. Efforts should be made to enlarge the direct applicability of existing processes.

- Most of the processes used for decontamination are proprietary. In this case, special attention must be given to the analysis of specific chemical decontamination solution capabilities and resulting waste prior to selection for a given application.

- For closed systems, one stage decontamination and treatment processes generally produce the smallest volumes of secondary waste.

7.4. DISASSEMBLY

- Plasma arc and all other thermal cutting systems tend to spread contamination and require a means to contain it. Therefore, while mechanical cutting may be slow initially, it could prove to be more efficient in the longer term. All the advantages and drawbacks of the different methods (cutting speed, overall speed, secondary waste generation, dose uptake, cost, etc.) should be balanced.

- Underwater cutting (for highly irradiated pieces) is very efficient and the dose uptake does not depend significantly on the specific activity of the workpiece.

- The appropriate tool should be used in its proper place. Investment costs are minimal when compared with waste and staffing costs and should not be the driving factor in tool selection.

- Maintenance, tool replacement and ease of decontamination are important factors in selecting a tool.

- The amount of planning required for power supplies, support systems and a central cable network should not be underestimated. Flexibility is essential if unplanned events are to be accommodated.

7.5. WASTE MANAGEMENT

- The waste route, waste storage availability and acceptance criteria (with related constraints) should be established prior to starting operations. This can lead to staff savings and dose and waste volume reductions.

- The logistical requirements for removing the waste and packaging, and the requirements for temporary storage should not be underestimated. Transport, throughput and storage logistics must be clearly defined and agreed prior to starting operations.

- The sorting of waste items and streams should be done as soon as possible, preferably at the point of waste generation. This will allow optimization of waste management activities. Also, close monitoring of this process is critical to ensuring compliance with regulatory requirements.

7.6. ROBOTICS AND REMOTE OPERATION

- The use of robotics should be considered only after a thorough analysis of other options has been made. This statement reinforces the general message, which is to keep decommissioning simple.

- Few projects require telemanipulators or sophisticated tools. Simple tools, having only a few degrees of freedom, are often sufficient for most operations. Remote tools need to be user-friendly, readily adaptable and robust.

- To be useful for decommissioning applications, manipulators need a sufficient payload capacity and must be robust. In addition, in the selection of tools, it is good practice to allow for contingencies arising from reaction forces and other factors. Control of manipulators when operating at full payload capacity is often poor.

- Stereo viewing systems are beneficial for use with machines having several degrees of freedom.

- Umbilical and cable management is always a problem. This has been partially solved in some recent applications, but improvements are still needed.

7.7. LONG TERM INTEGRITY OF BUILDINGS AND SYSTEMS

- A cost–benefit analysis should be performed to determine which systems are worthy of being maintained as opposed to those that are easier to replace at decommissioning (e.g. ventilation equipment, cranes).

8. CONCLUSIONS

A significant amount of practical experience has been gained over the last 15 years in the wide range of technologies used in decommissioning nuclear facilities. Beginning with the decommissioning or dismantling of smaller plants and facilities, such as pilot or test reactors and small nuclear fuel cycle facilities or their constituent parts, there has developed a broad range of:

— Decontamination techniques,
— Dismantling and cutting techniques for metal and concrete,
— Options for segmenting or shipping intact large components,
— Tool deployment and support systems,
— Waste management approaches.

Over the last few years it has become apparent that an increasing number of large nuclear facilities worldwide have become candidates for decommissioning in the short term. For these kinds of facilities, a wide spectrum of measures and means are available which have been proven in previous decommissioning projects. However, for some nuclear facilities it is still necessary to have solutions related to special problems such as the management of graphite and sodium materials or alpha contaminated waste. Future R&D work will also be helpful in enhancing public acceptance before selecting any of the technologies identified in this report or before taking any course of action. Development in the field of international standards for clearance levels of materials and final site clearance is promising and will be of considerable assistance to practitioners. For planning decommissioning work, strategic factors should be taken into account, such as:

— Policies and regulations
— Future use of the site
— Availability of a waste storage or disposal site
— Impact on other decommissioning operations.

Preparatory work should be done before any planning or execution of decommissioning operations. This includes:

— Assessing the availability and operational status of items such as cranes, radiation monitoring systems, ventilation systems and waste treatment facilities;
— Undertaking a survey of dose rates and contamination levels and their radionuclide composition.

Only after this work has been carried out should the project staff consider the following items, which are the focus of this report:

- — Which methods are available and able to be used;
- — Whether any additional R&D work is necessary for a given method;
- — What the advantages and disadvantages of a measure or method are (e.g. the choice of a certain decontamination method based on its production of secondary waste and its cost effectiveness).

Current technologies can cope with almost all the needs of decommissioning. This report helps familiarize the reader with the state of the art in such technologies. Some techniques still need R&D to enable them to reach maturity or to reduce dose uptake or the amounts of waste generated or the costs. Lessons learned through current or completed projects advise the reader of specific actions to take, or to avoid, when selecting or using technologies for particular applications.

Appendix

EXAMPLES OF SPECIFIC LESSONS LEARNED FROM DECOMMISSIONING PROJECTS

The following examples of the lessons learned from decommissioning projects include brief technical information on the facility involved and an outline of the problems/requirements encountered. The situations described are typical of the issues that can arise in the planning or implementation of decommissioning activities. The following general categories of events/issues may be highlighted:

- *Environmental protection:* (i) KKN, unexpected presence of tritium; (ii) Atomic Weapons Establishment (AWE), end points and constraints.
- *Occupational radiation protection:* (i) various UK installations, control of operator dose uptake during decommissioning operations; (ii) various UK plutonium facilities, optimal strategy to dismantle plutonium facilities; (iii) Magnox reprocessing plant B205, refurbishment strategy; (iv) Building 212 (ANL), contamination control during dismantling; (v) EBWR (ANL), internal contamination; (vi) various Belgian facilities, worker protection in decontamination.
- *Lack of as built drawing, complicated geometries:* (i) KKN, grinding of pressure tube welds; (ii) KKN, removal of shielding spheres out of the reactor neutron shield; (iii) various UK plutonium facilities, optimal strategy to dismantle plutonium facilities; (iv) DIDO highly active handling cell, various operational issues.
- *Robotics:* (i) reprocessing plant B204, need for remote handling operations; (ii) DIDO highly active handling cell, various operational issues.
- *Decontamination and dismantling technologies:* (i) DIDO highly active handling cell, various operational issues; (ii) post-irradiation examination caves (Berkeley), refurbishment/decommissioning strategy; (iii) Fernald Plant 7, building demolition; (iv) EBWR (ANL), underwater cutting issues; (v) BR3, primary loop decontamination; (vi) various UK installations, reuse of existing facilities and services.

Although the information presented is not intended to be exhaustive, the reader is encouraged to evaluate the applicability of the lessons learned to a specific decommissioning project.

Facility name: **KKN, Germany**
Requirement/problem: **Unexpected presence of tritium**

In the shutdown phase from 1974 to 1976, the primary circuit and moderator tank were emptied of heavy water and gas. The system was then purged using hot deionized water and dried with hot air before the reactor was declared ‘free of D_2O’. Subsequent to this, the tritium release limit for the reactor exhaust was reduced by a factor of 10^4 compared with the operational limit and an absolute annual release limit for tritium agreed with the regulator.

In 1987–1988, in the dismantling of the small bore tubing used to sample the primary coolant and moderator during reactor operations, it was realized that the purging had not cleared this pipework of tritiated water. In total, some 100 L of D_2O remained and this released a significant quantity of tritium into the reactor containment, causing the annual tritium release limit for the facility to be reached within a matter of days. This resulted in dismantling work being postponed until the D_2O could be removed in a controlled manner and new release limits agreed with the regulators.

Lesson learned:

Caution should be used in decommissioning in reducing release limits with regard to the operational phase. Although, in general, total activity releases are expected to be considerably lower than in the operational phase, surprises are always possible.

Facility name: **KKN, Germany**
Requirement/problem: **Grinding of pressure tube welds**

The first remote controlled dismantling step on the reactor was the removal of the pressure tube internals. Following this, the side welds connecting the 351 pressure tubes with their respective shield sleeve at the lower neutron shield had to be opened. For this purpose a tube grinder unit was used.

The tool was lowered down inside the pressure tube by means of a purpose-made lifting attachment and positioned at the vertical level of the side weld to be treated, approximately 6 m below the upper end of the pressure tube. The grinding process was performed as planned, followed by an inspection of the weld, which was meant to be removed. However, although extensive mock-up tests at the factory had demonstrated that the process was effective in removing the weld, the inspection showed that this was not the case in practice. Further investigations led to the conclusion that the side weld had not been carried out as indicated in the drawing (3 mm wide) but was, instead, a seam 9–16 mm wide.

To remove the weld a second cut had to be performed. This created problems with respect to further increases in temperature at the cut position, and delays to the project programme arising from the need to reduce the dust produced by cutting and the need to replace grinding wheels.

Lesson learned:

The design of the pressure tube reactor was complicated and the internals could not be readily viewed. Therefore, in spite of the mock-up tests, each remote controlled dismantling step had to be carefully planned and the tools used made as flexible as practicable so that modifications could be carried out in a simple and fast way.

Facility name: **KKN, Germany**
Requirement/problem: **Removal of shielding spheres out of the reactor neutron shield**

The chambers which form the neutron shield of the reactor are filled with a large quantity of steel spheres which had to be removed to allow decommissioning of the neutron shield to progress. To remove the spheres the decision was taken to use a high velocity vacuum system to suck them into a transport/disposal container. The vacuum system used had an oscillating suction tube and a small inlet orifice (max. 38 mm diameter) through which individual spheres could be sucked. Development trials using mock-ups of the spheres led to the inclusion of an oscillating tandem suction tube and proved that the system should perform adequately during actual operations on the reactor.

When the system was deployed, problems were experienced for the following reasons:

- The spheres did not correspond to the design drawings and were in fact crude stampings, unsymmetrical in shape and having burred edges.
- The spheres had a resin-like coating which caused them to stick together to form a solid structure.

The consequence of the above was that removal rates dropped to one tenth of those achieved during mock-up trials, and a number of spheres could not be removed. These subsequently caused problems during removal of the shield girders as they tended to become trapped in moving parts. For removal of the lower neutron shield the unit was modified to improve suction capacity and the performance of the vibration device and suction tubes. These improved the efficiency of the operation such that the project programme could be maintained.

Solution/lesson learned:

The lesson that can be drawn from this case is similar to that described in the previous example and emphasizes the need for visual inspection of components, especially on old plants where the design drawings are very often not reflected in a plant's as built status.

Facility name: **Various UK installations**
Requirement/problem: **Reuse of existing facilities and services**

The use of existing facilities for carrying out reactor defuelling operations following final shutdown is accepted as standard practice. However, careful and detailed planning of the overall decommissioning sequence early on can lead to significant savings, since structures that would otherwise have been removed can be retained and reused in order to simplify later operations.

With cranes and other purpose-built lifting structures, it is often obvious where they may benefit subsequent operations, but for some other features this is not always the case. Two examples of this are:

— The removal of the top biological shield of the Windscale advanced gas cooled reactor was achieved by retaining the gantry and drive assembly of the refuelling machine after the rest of the machine had been dismantled. This was then used with a set of servo-controlled jacks to lift the bioshield plug and transport it to a purpose-built cell for size reduction. This led to a lower operator dose uptake than if it had been cut into sections in situ over the reactor in the direct shine path of radiation from the reactor internals [696].

— The existing water in the fuel ponds of the steam generating heavy water reactor was used to assist operators in accessing the fuel pond walls and for containing contamination during cleaning of the walls. This was achieved by using pontoons to support the operators on the surface of the pond and water jets to remove loose contamination below the water level [697].

Solution/lesson learned:

The lesson that can be learned from these experiences is that careful consideration should be given to the uses a structure may be put to prior to its being ultimately decommissioned as this can lead to considerable project savings in the longer term.

Facility name: **Various UK installations**
Requirement/problem: **Control of operator dose uptake during decommissioning operations**

In any decommissioning task which requires operator entry into a radiation area, the minimization of the radiation dose received by the operator is of primary concern. To minimize the potential dose prior to operator entry to the worksite the following steps in the radiation protection plan are usually carried out to meet ALARA principles:

— All aspects of the operation are planned in detail, including the tooling required, operator access and exit points, and the actions to be taken for abnormal occurrences. These form the basis of the operators' working instructions and the safety regime under which the work will be carried out.
— Operators are trained using inactive mock-ups of the work site to build up detailed experience of the operating conditions, e.g. setting up and operating times.
— The work site is surveyed and detailed radiation maps made highlighting any areas of concern. These are then used to calculate the theoretical operator dose uptake for carrying out the work and form a basis with which dose uptake during actual operations can be compared.

However, despite this careful planning of the operations and the detailed estimation of the likely operator dose uptake, the following is often observed:

— Operator dose uptake is considerably lower than that calculated on the basis of the measured radiation fields in the work area. This is particularly the case when there are a number of 'hot spots' present.
— Individual operators or teams can receive widely varying dose uptakes when carrying out the same task in the same radiation area and having received the same level of training.

The reasons for this are attributed to the points below and have been borne out during decommissioning operations on various UK facilities:

— Most operators behave in an intelligent manner when working in a radiation area in order to limit their own personal dose uptakes. This means operators, when not required for a task, retire to the lowest radiation area and do not stand watching others work. Also, when working, operators position themselves in the lowest available radiation field. The development of personal electronic dosimeters with audible rate alarms has assisted greatly in promoting this practice.

— Discrepancies between the dose uptakes of individuals or teams carrying out similar operations are usually due to working practices. Experienced operators tend not to rush when performing the work, therefore ensuring that the tasks are completed correctly the first time around. Also, the positioning of tooling relative to the operator and the use of secondary shielding are major factors. In many cases, for experienced teams, secondary shielding increases dose uptake rather than reduces it since there is a dose penalty associated with its installation and removal and it can restrict the operators' work space.

Solution/lesson learned:

In conclusion, even with careful planning, a major factor in minimizing operator dose uptake is the intelligent behaviour of the operator during actual operations. Those operators who fully understand why the work is to be performed and who plan and refine their working practices within the scope of the operational safety requirements usually complete the operation faster, safer and with lower operational dose uptake than those who simply follow instructions without questioning why. These operators should be identified and placed with other individuals in order to provide 'on the job' training and to promote best working practices throughout the operator teams.

Facility name: **Various UK plutonium facilities**
Requirement/problem: **Optimal strategy to dismantle plutonium facilities**

Plutonium handling facilities do not, in financial terms, form a very major part of the total UK nuclear facility dismantling programme. However, they suffer from progressive increase in radiation levels as a result of americium in-growth, and containment standards deteriorate on unused plants. All UK operators of major plutonium facilities have given containment standards a high priority in their programmes.

The objectives of the current programmes are therefore to remove redundant facilities, maintain safety and reduce surveillance costs. Additionally, and especially with the initial projects, it has been the aim to use these as testing grounds for experience and techniques, and to develop bases for more accurate assessment of decommissioning costs.

Positive lessons learned:

The range of UK Pu projects so far undertaken has provided experience in several areas:

— Containment and control of contamination. This is of particular significance in plutonium plants. In all radioactive facilities inadequate control of the spread of contamination causes significant increase in costs. This is due to increased decontamination needs, active waste volumes, and the likely increase in waste disposal costs as these relate to contamination levels in the wastes. In plutonium facilities, however, this consideration takes on greater importance owing to the stringent requirements for control of loose alpha activity on surfaces or as airborne particulates. Onerous, and expensive, working conditions and protective clothing requirements are necessary if activity levels are not maintained as low as possible.
— Waste handling and minimization. The difference in costs between intermediate level waste/plutonium contaminated materials and low level waste handling/storage/disposal requires stringent controls to minimize the former, together with segregation or assay and decontamination where appropriate. Control of the spread of contamination and the degree of plant clean out are major contributors.
— Material hold-up and nuclear safety. Accurate assessment of the radioactive material inventory is a problem in planning the decommissioning of any redundant facility. Again, this is particularly significant for facilities which have handled tonne or even kilogram quantities of fissile materials such as plutonium. In these cases, accumulation of residues which represent only a small fraction of plant throughput may be a criticality hazard if their configuration is changed or a moderator is introduced. The location and quantification of fissile residues in such a facility before and during clean out and dismantling are essential.
— External and internal radiation hazards. External radiation dose to operators has become a major concern in plutonium plants. The situation has been made worse by a reduction in the permitted annual exposure and in this particular context by the need to dismantle, within current dose limits, facilities which were designed to older standards.
— Decommissioning project planning. These uncertainties can be coped with by phasing detailed design, costing and safety studies throughout project life — this has been especially effective for larger projects. Effective planning tools are emerging, such as 3D modelling and varying databases and expert systems.

Negative lesson learned:

Detailed investigation at project startup cannot reveal features for areas which cannot be entered. Early plans must be based on available drawings and information, with adequate regard for likely inadequacies and a project plan for suitable hold points and changes in policy.

Facility name: **Magnox reprocessing plant B205, BNFL, Sellafield, UK**

Requirement/Problem: **Refurbishment strategy**

- To provide Magnox reprocessing well into the first decade of the 21st century additional dissolving capacity is required. Alternative proposals were examined ranging from in situ repair to 'greenfield' site replacement prior to the decision to refurbish the existing south dissolver facility and ancillary equipment.
- Cell access was a consideration. The largest item to be replaced was the dissolver vessel. This required an opening in the east wall of the cell measuring 4 m high × 5 m wide at the 5 m floor level. In addition, personnel doors 1 m × 2 m were required at four locations.
- Removal and replacement of all vessels and pipework within the cell on the 'hot streams' of the process were carried out.
- Refurbishment of the charge machines, various operational ejector containments and relevant instrumentation was undertaken.
- The condition of the vessels, pipework and equipment was fully assessed in order to decide on the extent of the replacement necessary. Some are being replaced and duplicated but one will be repaired in situ. Remote cutting, welding and inspection techniques have been developed to enable the refurbished plant to be reconnected to the existing highly active in-cell pipework using specially developed manipulators.

Positive lessons learned:

- An essential part of the project has been the establishment of the project control centre. This is the focal point for access and for all information relevant to the site work. The centre has been structured to enable personnel to enter the cell at all working levels from outside the building. This adequately segregates the extensive project engineering activity from the day-to-day operations within the plant. At each of the four access points a change room has been constructed, linked by enclosed corridors and an access tower to surveillance and conference facilities.
- The adoption of rigorous radiation dose assessment, control and recording procedures has brought about the introduction of a number of new techniques to cope with data handling on a scale (in this field) not previously undertaken.
- The investment in extensive modeling, both physical and computerized, in addition to detailed planning of activities, extensive briefing of the workforce prior to their undertaking in-cell work, provision of good audio contact and visual surveillance links have together been responsible for eliminating hold-ups, and for minimizing the dose uptake of the workforce.

— The highly radioactive plant has been decontaminated to a level where engineering work can be carried out manually. A sequence of alternate washing (hot and cold) was carried out using water, various acids and caustic solutions to reduce the radiation within the cell by a factor of 10^4 over a period of 4 years.

Negative lesson learned:

Where decontamination was not possible, the radiation source was either removed or shielded. A total of 65 t of shielding has been installed within the cell.

Facility name: **Reprocessing plant B204, BNFL, Sellafield, UK**
Requirement/problem: **Need for remote handling operation**

— Provision of cost effective technology, particularly utilizing available, robust and well proven techniques and including a mobile, long reach, heavy duty remote handling system.
— Provision of access for dismantling equipment, for personnel and for removal of materials in a cost effective manner.
— Upgrade existing ventilation systems to meet current aerial discharge criteria during decommissioning operations.
— Provision of remote size reduction facilities which use industrial robots and plasma arc cutting. Operating software to cope with plasma generated interference.
— Radiological design standards to be adopted are those currently applicable to existing BNFL plants. In particular, the targets for individual dose uptake will be a maximum of 15 mSv in one year and 150 mSv over a ten year period.

Positive lessons learned:

— A combination of remote handling capabilities with manual operations results in the development of 'fit for purpose' manipulators. Utilizing this, the contact deployment remote operation seeks to gain an acceptable and cost effective mix of humans and machines. Contact deployment and maintenance is employed, but equipment is operated from a central remote facility, which provides a better working environment for operatives.
— Use is made of a water/glycol hydraulic system to avoid detrimental effects on the building effluent treatment system in the event of leakage.
— A comprehensive manipulator system using proprietary components is employed, comprising:

i) A rail mounted bogie system to enable longitudinal deployment of the remote handling equipment on each floor of the cell.

ii) A 6 m extension telescopic arm fitted with a hoist to provide 3 t lift capacity at full extension. The telescopic arm is mounted on the rail bogie via a slew ring to provide 270° arc coverage.
iii) A 2 m reach hydraulic manipulator, with 100 kg lifting capacity, mounted on this arm by means of a self-levelling tilt table.

— Waste conditioning includes size reduction, sorting and packaging carried out at the robot work station. Two industrial robots capable of independent or synchronous operation are provided with plasma arc cutting capability. Supporting, gripping and turning operations are carried out utilizing a turntable. Size reduced items may be packed in disposal containers or removed for sampling and waste categorization tests.
— Decontamination facilities in the waste handling facility consist of lidded stainless steel tanks provided with electric heating, ultrasonic agitation, sampling, recirculation and ventilation systems. Provision is made for the use of nitric acid or other specified decontamination agents as required. Test tanks in the sampling facility enable trials to be carried out in order to maximize decontamination efficiency for specific items.

Negative lessons learned:
— Although the majority of waste from medium active areas was expected to meet acceptance criteria for land burial, the spread of alpha contamination was greater than expected, requiring some decontamination to make best use of this route.
— The adaptation of proprietary remote handling hardware proved easier than modifications to corresponding software, especially those made to cope with radio frequency interference from plasma arc cutting.

Facility name: **DIDO highly active handling cell, Harwell, UK** [698]
Requirement/problem: **Various operational issues**

— Decommissioning to Stage 3 of highly active cell used to support materials testing operations,
— Very high contact radiation levels as a result of processing ^{60}Co,
— Inadequate drawings and records.

Positive lessons learned:
— Value of robotic decommissioning (using the NEATER robot) as a way of making savings in terms of costs, dose and staffing,
— Value of mock-up trials of the robot before specific operations,

— Need for improvements in containment and ventilation before starting dismantling operations,
— Speed and convenience of oxyacetylene cutting.

Negative lessons learned:
— Need for extensive (and expensive) refurbishment of services after a period of minimal care and maintenance,
— Problems of hydraulic oil spillage resulting from attempting to operate long disused equipment,
— Ventilation problems of plasma arc cutting method.

Facility name:	**Post-irradiation examination caves, highly active caves (6) for post-irradiation examination of reactor fuel and components, Berkeley Nuclear Laboratories, Nuclear Electric, UK** [699]
Requirement/problem:	**Refurbishment/decommissioning strategy**

— Caves being refurbished for new duty;
— Caves 1, 2 and 3 to remain in use whilst 4, 5 and 6 are decommissioned and refurbished;
— D&D of in-cave equipment, ventilation systems, water treatment and caesium removal plant.

Positive lessons learned:
— Dose lower than expected,
— Convenience and speed of plasma arc cutting,
— Operator rotation to low active work.

Negative lesson learned:

Need for plans to be adaptable at all stages in order to cope with changes found to be necessary during actual decommissioning operations.

Facility name:	**Various actinide and depleted uranium handling facilities, AWE, Aldermaston, UK** [700]
Requirement/problem:	**End points and constraints**

— To remove the radiological toxic hazard (in a given facility) to a predetermined engineering/hazard status end point;
— All work to be pre-planned in accordance with current legislation;

— Key performance constraints are safety requirements, facility availability and Ministry of Defence programmes.

Lessons learned:

— Process facilities used for producing components to support the weapons programme generally consist of multiple glovebox suites and fume cupboards in which machine tools and equipment are housed and operated either by remote control or through conventional glovebox ports.

— Research and development facilities, consisting of multiple glovebox and fume cupboard suites, are often used for liquid/chemical research. Such facilities present a different decommissioning challenge, particularly with regard to the potential spread of contamination and the cleanup capability.

— In some cases a complete temporary ventilation system is installed and commissioned before work on removing the existing system commences. This maintains building containment and integrity throughout the decommissioning operations phase.

Facility name:	**Fernald Plant 7 (uranium conversion plant), USA** [701]
Requirement/problem:	**Building demolition**

Instead of the original concept of piece by piece removal (i.e. reverse construction) of the structure, it was proposed that the structural support columns of Plant 7 be cut using controlled detonation. By using a specialized steel cutting method comprising linear shaped charges with sequential charge detonation, the building was anticipated to fold within seven seconds. Plywood boxes and conveyor belting would be placed around the charges to prevent dispersion of material upon detonation; no toxic dust or fumes were anticipated from the detonation. The steel would then be size reduced, monitored for radiological contamination, and packaged once on the ground.

Prior to controlled detonation cutting of Plant 7, the interior and exterior walls, asbestos containing and asbestos contaminated materials, piping, equipment, west canopy, south shed and elevator were removed and packaged. Plant 7 was reduced to a simple structural steel skeleton and floor decking.

On 10 September 1994, the demolition contractor detonated 156 linear shaped explosive charges placed in 50 locations and intended to bring the building down. Approximately 416 copper clad, linear shaped charges were used as the primary steel cutting method. The net weight of RDX explosives was approximately 29 kg. Non-electric detonators of various internal delays were used to initiate the detonations of the explosives. Forty per cent strength ‘gelatin dynamite’ charges were utilized to displace structural columns after severance by steel cutting explosives charges. A redundant non-electric blasting system was used. The use of a non-electric system is much safer because there are no concerns with radio frequency or electricity hazards. All systems were designed and assembled in accordance with guidelines suggested by the manufacturer.

The first two floors of the building collapsed as planned. However, splice plates that had been pre-cut on the third and fifth floors did not separate as anticipated. The building dropped approximately 7.6 m instead of the planned 23.8 m. Following the partial take down by controlled detonation, the area was secured. The rigid steel structure was stable and leaning approximately 15° to the northwest. Following an extensive examination of the partially fallen Plant 7 structure, a decision was made to use shaped explosive charges to complete the take down on 17 September 1994. The successful take down occurred at 9:40 p.m. and utilized 260 shaped charges placed in 120 locations.

Lesson learned:

Safety benefits realized by the dismantlement method utilized included the following: reduced site worker risk to additional torch cuts, reduced worker time in high locations, ability to perform the controlled fall of Plant 7 on a weekend to ensure a reduced number of workers in the area, and reduced need for heavy lifts. The explosive demolition technique was successful and will be considered in future projects to significantly reduce worker risk, cost and schedule. Even with the need for the second explosive charge, the project will cost nearly $5 million less than alternative techniques and finish 7 months ahead of schedule.

Facility name:	**Nine laboratories housing plutonium gloveboxes for R&D within Building 212 at the ANL-East site, ANL, USA** [702]
Requirement/problem:	**Contamination control during dismantling**

During the preparations for the dismantling of more than 60 plutonium gloveboxes, an identified major item of concern was the release of any residual material during the size reduction of the gloveboxes and even more so during the removal of the neoprene window gaskets of the gloveboxes. In order to ensure that the release of any airborne contamination was minimized and was adequately addressed in work planning, some proactive procedural contamination control measures were incorporated into the work plan (1994–1995).

Solution/lessons learned:

Actions that were taken to contain airborne contamination events during dismantling of the gloveboxes were as follows:

— Tool effectiveness and the general operations were tested on a mock-up in a clean area.
— The glovebox cutting tool was vacuum cleaned after each use, therefore minimizing the generation of radioactive dust.
— Use of a clear plastic shield between the operator and cutter minimized the scattering of any contamination onto worker personal protective equipment.
— Local exhaust ventilation was used for radioactivity capture during the cutting of gloveboxes.
— Aggressive decontamination techniques were used only where other techniques were ineffective in removing oily stained areas of radioactive contamination.
— Administrative hold points were incorporated into the dismantling work processes to provide the opportunity to improve upon future glovebox dismantling based on recent operational lessons learned.

All of the above solutions combined to allow the project work to be completed with minimal airborne release events to the size reduction containment enclosure and minimal contamination of worker protective clothing.

Facility name: **EBWR, ANL, USA** [703]
Requirement/problem: **Underwater cutting issues**

During the process of performing the underwater size reduction of the EBWR reactor vessel internals using plasma arc cutting, several difficulties were encountered in the period 1993–1995. These included:

— Inability to strike and to maintain an arc,
— Water chemistry and pool clarity problems.

These problems quickly became a significant impediment to the project schedule. Not only did the labour force have to do the underwater cutting, but this was further complicated by the water clarity and conductivity problem.

Solution/lesson learned:

A water chemistry expert advised of several rather inexpensive simple approaches to solving the problems. One consisted of changing the composition of the gas supply used for the plasma arc cutting from 100% nitrogen to a blend of 95% argon and 5% hydrogen. After this there were no further problems with maintaining an arc. The water clarity and chemistry problems were addressed by adding between 1.9 L and 3.8 L of hydrogen peroxide per day to the fuel pool water circulation system. After this there were no problems with water clarity or conductivity.

Facility name: **EBWR, ANL, USA** [703]
Requirement/problem: **Internal contamination**

On 2 September 1994, ANL Dosimetry and Analytical Services notified the area health physicist that there were two individuals who had positive indications that an uptake of tritium and $^{241}Am/^{238}Pu$ had occurred since their baseline urine samples had been collected. Uptakes of transuranics were not expected. Work activities continued pending confirmation of bioassay results. On 9 September 1994, analysis of a faecal sample from one of the contract personnel confirmed the presence of ^{241}Am. D&D work inside the EBWR shell was immediately halted. Investigative work and health physics survey efforts proceeded to determine the cause for this and locate the source of the ^{241}Am. Required surveillance and critical maintenance, such as changing filters in air and water systems, were enacted to maintain a safe work environment and to protect operating equipment. Additional bioassay samples were taken to determine the number of people affected. Eventually, a total of seven contractor personnel had positive results for ^{241}Am and detectable levels of other nuclides.

Analysis of fuel pool water and fuel pool water filtration system filters indicated the presence of fission products (^{137}Cs, ^{90}Sr) and transuranics (^{241}Am). Analysis of air samples taken on 19 July 1994 near the fuel pool during control rod cutting operations indicated the presence of fission projects (^{137}Cs) and transuranics (^{241}Am, ^{238}Pu and ^{239}Pu). Previous characterizations had not reported these nuclides. The use of bioassays, daily air samples and administrative controls resulted in an accurate reconstruction of events. Six of the seven affected workers were involved with plasma arc operations in or above the fuel pool. The uptake occurred over a four-day period, with the greatest uptake in individuals working longest with the cutting operations. Speculation remains as to the source of the americium. It may have been a product of a ^{241}Pu foil lost in the EBWR facility during experiments run in 1967. The ^{241}Pu would have decayed into ^{241}Am, although no trace of ^{241}Pu was found. Another scenario is that although no fuel element failure was reported, undetectable microscopic cracks may have allowed the release of transuranics over the lifetime of the EBWR. Two of the contract personnel received approximately 3 mSv from the uptake of ^{241}Am. The remaining personnel are estimated to have received 500–600 µSv from the uptake of ^{241}Am. No personnel exceeded authorized limits.

The unexpected uptake of ^{241}Am in some workers caused major delays and cost increases that would not have been incurred otherwise. This problem reinforces the need to maintain and review all records and historical operational data. This information is essential in performing a complete characterization of a facility before initiation of D&D activities. The following are lessons learned which apply to all D&D projects in general.

Lessons learned — Prevention and early detection:

- Monitor to detect nuclides reasonably expected based on past operations, even if they are not found in characterization;
- Acquire a thorough knowledge of historic operations as this is the key factor of quality characterization, especially at experimental facilities;
- Establish personal protective equipment levels conservatively;
- Expand use of scheduled bioassays;
- Ensure bioassay data reaches key managers in a timely fashion;
- Use better quality air monitoring and dosimetry equipment as this is both desirable and cost effective.

Lessons learned — Recovery issues:

- Investigation committees should be preselected, trained and dedicated to the investigation function.
- Improvement in recovery procedure roles is desirable.
- 'Surge' analytical capability is needed for sample analysis.

Lesson learned — Management issues:

Clear consensus on balancing internal exposure against other health and cost variables.

Lessons learned — Noteworthy practices:

- Exposure was mitigated by prompt response of laboratory project manager.
- Entry and exit bioassay data were extremely valuable.
- Air sample archiving was key to dose assessment and event reconstruction.
- Events were better understood and reconstructed by keeping excellent records.

Facility name: **BR3 prototype PWR, Mol, Belgium** [704]
Requirement/problem: **Primary loop decontamination**

The decontamination of the primary loop was carried out in 1991. The decontamination was performed using the CORD process. The primary loop was therefore closed and slightly pressurized, and the process used the primary pumps and different loops and equipment of the plant to circulate the chemicals. The contaminants were trapped on ion exchange resins, mainly located in the existing exchange columns of the plant.

The full system decontamination reduced the dose rate of the contaminated equipment on average by a factor of ten. The ambient dose rate amounts are now about 0.08 mSv/h in the containment building where the primary circuit and most of the auxiliary circuits are located. The total dose for the decontamination operation amounted to 0.16 man·Sv; 85% of this dose was received during the preparatory phase of the operation including the ‘manual’ closure of the reactor head. The chemical decontamination appears to be very cost effective in man-sievert exposure reduction when dismantling of the primary loop is considered, a dose saving of more than 4.25 man·Sv is estimated.

Lessons learned:

- The process applied is a smooth one, only a few minor operational problems were encountered. This could only be achieved by careful and detailed preparation. It requires a primary system in a sound operational condition and experienced operators from the plant.
- The estimation of the secondary waste quantity is not easy; more waste (mainly ion exchange resins) was produced than originally estimated owing to higher than anticipated crud content.
- The decontamination had an important impact on the dismantling operations of the reactor internals:

  Firstly, a negative effect. Pollution of the reactor pool occurred during the unloading of the reactor internals, resulting in high turbidity and poor visibility. This pollution was due to the presence of insoluble ferrous oxalate and loose crud still present on the internals.

  Secondly, a positive effect. The internals were remarkably clean. This greatly facilitated the subsequent dismantling operations and even allowed the disposal of some activated pieces at the upper part of the reactor as low radioactive waste (dose rate <0.2 mSv/h) which would not have been possible without the decontamination.

As a general lesson for future plants, it would be very helpful to include at the design phase features to allow for future decontamination, so that later modifications (in a high dose rate field) can be avoided. Moreover, progress still has to be made in the process chemistry in order to minimize the secondary waste arisings.

Facility name: **Various Belgian facilities (nuclear fuel factory, NPP, phosphate industry)**

Requirement/problem: **Worker protection in decontamination**

During qualifying tests on a carbon dioxide blasting process, many tests were conducted on the removal of epoxy paint from concrete and radium contaminated phosphate crud layers in piping. For these tests, in order to avoid the production of unnecessary quantities of waste, a small polyethylene tent was built in each case. Owing to the small volume of air (approximately 15 cubic metres), the use of the CO_2

pellet blasting system (pellets at –80°C), quickly reduced the temperature inside the tent, which fell below 0°C within a few minutes. A major consequence of this significant temperature decrease (apart from the uncomfortable working conditions for the operators) was the cracking and failure of the PVC inflatable suits worn by the operators. This resulted in the loss of individual protection (clothes contamination and inhaled air) and the operators having to evacuate the work area. Another consequence of the temperature decrease was that the mobile ventilation system quickly froze owing to humidity in the air. The pre-filters and the high efficiency particulate air filters froze, the ventilation system was automatically shut down and the dynamic confinement lost.

Solution/lessons learned:

The following improvements were brought into the decontamination process:

— Using larger volume rigid containment systems to avoid a rapid temperature decrease and to decrease the volume of the secondary waste produced,
— Stopping CO_2 blasting every 30 minutes for a 10 minute period to allow the temperature in the containment to increase,
— Providing operators with special clothes and gloves to protect against the cold,
— Procuring a synthetic inflatable suit more resistant to low temperature ,
— Providing pre-filters and high efficiency particulate air filters with a pre-heating unit at the entry of the mobile ventilation system (to dry the air and increase the temperature of the air entering the filters).

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Nuclear Facilities: Report of a Technical Committee Meeting on the Decommissioning of Nuclear Facilities, IAEA-179, Vienna (1975).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Factors Relevant to the Decommissioning of Land-Based Nuclear Reactor Plants, Safety Series No. 52, IAEA, Vienna (1980).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, The Regulatory Process for the Decommissioning of Nuclear Facilities, Safety Series No. 105, IAEA, Vienna (1990).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Nuclear Facilities: Decontamination, Disassembly and Waste Management, Technical Reports Series No. 230, IAEA, Vienna (1983).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Decontamination of Nuclear Facilities to Permit Operation, Inspection, Maintenance, Modification or Plant Decommissioning, Technical Reports Series No. 249, IAEA, Vienna (1985).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Methodology and Technology of Decommissioning Nuclear Facilities, Technical Reports Series No. 267, IAEA, Vienna (1986).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Decontamination and Demolition of Concrete and Metal Structures During the Decommissioning of Nuclear Facilities, Technical Reports Series No. 286, IAEA, Vienna (1988).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Methods for Reducing Occupational Exposures During the Decommissioning of Nuclear Facilities, Technical Reports Series No. 278, IAEA, Vienna (1987).

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Factors Relevant to the Recycling or Reuse of Components Arising from the Decommissioning and Refurbishment of Nuclear Facilities, Technical Reports Series No. 293, IAEA, Vienna (1988).

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Monitoring Programmes for Unrestricted Release Related to Decommissioning of Nuclear Facilities, Technical Reports Series No. 334, IAEA, Vienna (1992).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Remotely Operated Handling Equipment in the Decommissioning of Nuclear Facilities, Technical Reports Series No. 348, IAEA, Vienna (1993).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, National Policies and Regulations for Decommissioning Nuclear Facilities, IAEA-TECDOC-714, Vienna (1993).

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Safe Enclosure of Shut Down Nuclear Installations, Technical Reports Series No. 375, IAEA, Vienna (1995).

[14] INTERNATIONAL ATOMIC ENERGY AGENCY, Design and Construction of Nuclear Power Plants to Facilitate Decommissioning, Technical Reports Series No. 382, IAEA, Vienna (1997).

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiological Characterization of Shut Down Nuclear Reactors for Decommissioning Purposes, Technical Reports Series No. 389, IAEA, Vienna (1998).

[16] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning Techniques for Research Reactors, Technical Reports Series No. 373, IAEA, Vienna (1994).
[17] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Facilities for Mining and Milling of Radioactive Ores and Closeout of Residues, Technical Reports Series No. 362, IAEA, Vienna (1994).
[18] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Nuclear Facilities Other Than Reactors, Technical Reports Series No. 386, IAEA, Vienna (1998).
[19] INTERNATIONAL ATOMIC ENERGY AGENCY, Decontamination and Decommissioning of Nuclear Facilities: Final Report of Three Research Co-ordination Meetings, IAEA-TECDOC-511, Vienna (1989).
[20] INTERNATIONAL ATOMIC ENERGY AGENCY, Decontamination and Decommissioning of Nuclear Facilities: Results of a Co-ordinated Research Programme, Phase II: 1989–1993, IAEA-TECDOC-716, Vienna (1993).
[21] EUROPEAN COMMISSION, A Review of the Situation of Decommissioning of Nuclear Installations in Europe, Rep. EUR 17622, Office for Official Publications of the European Communities, Luxembourg (1998).
[22] KOMATSU, J., Research and development for dismantlement of nuclear facilities, J. RANDEC, Nov. 1 (1991).
[23] YOKOTA, M., “Outline of the JPDR dismantling activities”, Decommissioning of Nuclear Facilities (2nd JAERI Workshop Tokai, 1991), internal report, Tokai Research Establishment, Tokai (1991).
[24] SAEKI, K., EZURE, H., “Decommissioning of nuclear facilities in Japan”, Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 29–40.
[25] YANAGIHARA, S., et al., “Data analysis and lessons learned in decommissioning Japan power demonstration reactor”, Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 127–140.
[26] MINISTRY OF ATOMIC ENERGY, State Conception of Radioactive Waste Management in the Russian Federation, Draft Version 4D, Rep. No. 30-1149, Moscow, 24 Dec. 1997.
[27] LAW OF THE RUSSIAN FEDERATION ON USE OF NUCLEAR POWER, Rep. No. 170-F3, Moscow, 21 Nov. 1995.
[28] LAW OF THE RUSSIAN FEDERATION ON RADIOACTIVE WASTE MANAGEMENT, version adopted by Governmental Duma, Moscow, 24 Nov. 1995.
[29] LAW OF THE RUSSIAN FEDERATION ON RADIATION SAFETY OF POPULATION, Rep. No. 3-F3, Moscow, 9 Jan. 1996.
[30] GOVERNMENTAL SANITARY EPIDEMIOLOGICAL CONTROL BODY, Norms of Radiation Safety (NRB-96), Hygienic Standards Rep. GN 2.6.1.054-96, Moscow (1996) (in Russian).
[31] MINISTRY OF HEALTH, The Basic Sanitary Rules of Operation with Radioactive Substances and other Emitters of Ionizing Radiation, Reps NRB-76/87 and OSP-72/87, Moscow (1988) (in Russian).
[32] MINISTRY OF HEALTH, Sanitary Rules of Radioactive Waste Management (SPORO-85), Moscow (1986) (in Russian).

[33] MOSCOW GOVERNMENT, Control Levels on Content of Radionuclides in the Environment of Moscow, Rep. No. 11, Moscow, 19 Dec. 1995 (in Russian).
[34] EUROPEAN COMMISSION, Demonstrating Compliance with Clearance Levels in Dismantling Nuclear Installations (and Application to the WAK Reprocessing Plant), Rep. EUR 17623, Office for Official Publications of the European Communities, Luxembourg (1997).
[35] LIN, S.-W., CHIOU, S.-T., "Establishment of clearance levels and regulation of solid radwaste in Taiwan", ICEM '97: Radioactive Waste Management and Environmental Remediation (Proc. 6th Int. Conf. Singapore, 1997), American Society of Mechanical Engineers, New York (1997)137–143.
[36] BURCLOVA, J., "Slovak decommissioning strategy and technology", ICEM '97: Radioactive Waste Management and Environmental Remediation (Proc. 6th Int. Conf. Singapore, 1997), American Society of Mechanical Engineers, New York (1997) 837–840.
[37] BRENNECKE, P., HOLLMANN, A., Anfall Radioaktiver Abfälle in der Bundesrepublik Deutschland — Abfallerhebung für das Jahr 1995, Federal Office for Radiation Protection (BfS), Fachbereich Nukleare Entsorgung und Transport, Rep. BfS-ET-25/97, Salzgitter (1997) (in German).
[38] NIEVES, L.A., TILBROOK, R.W., Potential radioactive scrap metal quantities from nuclear power plants worldwide, Radwaste Mag. **3** 1 (1996) 45–53.
39] EUROPEAN COMMISSION, Handbook on Decommissioning of Nuclear Installations, Rep. EUR 16211, Office for Official Publications of the European Communities, Luxembourg (1995).
[40] INTERNATIONAL ATOMIC ENERGY AGENCY, Experience in the Application of Exemption Principles, IAEA-TECDOC-807, Vienna (1995).
[41] MENON, S., "Clearance of materials from nuclear facilities — overview of current practices and proposed regulations", ICONE-5: Nuclear Engineering (Proc. 5th Int. Conf. Nice, 1997), American Society of Mechanical Engineers, New York (1997).
[42] SIMON, R.A., "The clearance of materials and buildings from decommissioning operations in Europe", Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 355–362.
[43] RUSSELL, P., "Development of EPA radiation site cleanup regulations", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).
[44] EUROPEAN COMMISSION, Decommissioning of Nuclear Installations in the European Union, Rep. EUR 18860, Office for Official Publications of the European Communities, Luxembourg (1999).
[45] INTERNATIONAL ATOMIC ENERGY AGENCY, Clearance Levels for Radionuclides in Solid Materials, Application of Exemption Principles, Interim Report for Comment, IAEA-TECDOC-855, Vienna (1996).
[46] EUROPEAN COMMISSION, Recommended Radiological Protection Criteria for the Recycling of Metals from the Dismantling of Nuclear Installations, Radiation Protection 89, Office for Official Publications of the European Communities, Luxembourg (1998).
[47] OECD NUCLEAR ENERGY AGENCY, Nuclear Decommissioning — Recycling and Reuse of Scrap Metals, OECD, Paris (1996).

[48] US FEDERAL REGISTER, 62FR39058-39095, 21 July 1994, US Govt Printing Office, Washington, DC (1994).

[49] US FEDERAL REGISTER, 58FR16268-16322, US Govt Printing Office, Washington, DC.

[50] WOLBARST, A.B., et al., Technical basis for EPA's proposed regulation on the cleanup of sites contaminated with radioactivity, Health Phys. **71** 5 (1966) 644–660.

[51] GIL, E., CARBONERAS, P., "Fundamentals for the release of very low activity materials. A practical case: The decommissioning of Vandellos 1 NPP", paper presented at Tech. Sem. on Low Level Radioactive Waste, Cordoba, 1997.

[52] EUROPEAN COMMISSION, Policies, Regulations and Recommendations for the Decommissioning of Nuclear Installations in the European Community, Rep. EUR 15355, Office for Official Publications of the European Communities, Luxembourg (1994).

[53] SCHALLER, G., et al., Beseitung radioaktiver Abfälle und Verwertung von Reststoffen und Anlagenteilen — Grundlagen, Konzepte, Ergebnisse, Federal Office for Radiation Protection (BfS), Fachbereich Kerntechnische Sicherheit, Rep. BfS-ISH-177/97, Salzgitter (1997) (in German).

[54] GRABENER, K.-H., "Melting and recycling of contaminated (alpha, beta and gamma) aluminum, copper and steel", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 456–467.

[55] SAPPOK, M., Results of melting large quantities of radioactive steel scrap, Nucl. Technol. **86** Aug. (1989) 188–191.

[56] SAPPOK, M., "Treatment of ferrous and non-ferrous waste from nuclear power plants", Waste Management '94 (Proc. Int. Symp. Tucson, 1994), Waste Management Symposia, Tucson, AZ (1994) 1627–1631.

[57] THIERFELDT, S., "Clearance of slightly radioactive material from radiological control in Germany", ICEM '95: Radioactive Waste Management and Environmental Remediation (Proc. Int. Conf. Berlin, 1995), American Society of Mechanical Engineers, New York (1995) 93–96.

[58] BRÖCKING, D., "German approach to VLLW management", Application of the Concepts of Exclusion, Exemption and Clearance (Proc. Specialists Mtg Vienna, 1997), IAEA, Vienna (1997).

[59] BRÖCKING, D., MATTING, A., "Regulatory control of the German radwaste program", TOPSEAL '96 (Proc. Conf. Stockholm, 1996), European Nuclear Society, Berne (1996).

[60] BRÖCKING, D., Aktuelle Entwicklung in den Bereichen Freigabe und Verbringung Radioaktiver Abfälle, KONTEC '95: Conditioning of Radioactive Operational and Decommissioning Waste (Proc. 2nd Symp. Hamburg, 1995), Kontec Gesellschaft für technische Kommunication mbH, Glinde (1995) 12–24.

[61] MOORE, K., Clearing paths to green field sites, Atom **428** May/June (1993).

[62] CLAMP, A., Decommissioning breaking up's not hard to do, Nucl. Energy, Fourth Quarter (1994) 6–11.

[63] HEIDER, K.J., MELLOR, R.A., Decommissioning Yankee Rowe, Radwaste Mag. **1** 4 (1994) 27–32.

[64] LIKAR, V.F., POPP, D.M., “Licensing experience for decommissioning Fort St. Vrain”, Waste Management ’93 (Proc. Int. Symp. Tucson, 1993), Waste Management Symposia, Tucson, AZ (1993) 1495–1499.

[65] LACKEY, M.B., KELLY, M.L., The Trojan large component removal project, Radwaste Mag. **4** 1 (1997) 11–17.

[66] GORDELLIER, S.C., PASSANT, F.H., “Decommissioning of Nuclear Electric’s gas cooled reactors: The development of a new strategy”, Decommissioning Policies for Nuclear Facilities (Proc. Int. Sem. Paris, 1991), OECD, Paris (1992).

[67] AULER, I., “Experience and current status of Niederaichbach power plant decommissioning project”, Managing Risks in Decommissioning, Decontamination and Reutilization Projects (Exec. Conf. Washington, DC, 1995), American Nuclear Society, La Grange Park, IL (1995).

[68] LIKAR, V.F., “Decommissioning progress at Fort St. Vrain”, Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 1–16.

[69] STURVI, M., DIRENZO, G., “Decommissioning activities at Latina NPP”, Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 71–78.

[70] MASSAUT, V., STEINER, H., STERNER, H., “Waste minimization during decommissioning: Practical experience from the EU pilot decommissioning projects BR3 Mol and KRB-A Gundremmingen and from the EWN plant decommissioning”, TOPSEAL ’96 (Proc. Conf. Stockholm, 1996), European Nuclear Society, Berne (1996).

[71] EUROPEAN COMMISSION, Economic Comparison of Management Modes for Contaminated Metal Scrap, Rep. EUR 11149, Office for Official Publications of the European Communities, Luxembourg (1987).

[72] US DEPARTMENT OF ENERGY, Beneficial Reuse ’97: Recycle and Reuse of Radioactive Scrap Metal (Proc. 5th Ann. Conf. Knoxville, 1997), USDOE, Washington, DC (1997).

[73] LOISELLE, V., A survey of existing and projected recyclable scrap metals in the DOE community”, Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[74] INTERNATIONAL ATOMIC ENERGY AGENCY, Minimization of Radioactive Waste from Nuclear Power Plants and the Back End of the Nuclear Fuel Cycle, Technical Reports Series No. 377, IAEA, Vienna (1995).

[75] BOING, L.E., et al., “Waste minimization and pollution prevention in decommissioning and decontamination operations at the Argonne National Laboratory — East Site”, paper presented at US Dept of Energy Pollution Prevention Conference XII, Chicago, 1996.

[76] MACKINNEY, J., “An assessment of the recycling of US Department of Energy radioactive scrap metals”, Waste Management ’94 (Proc. Int. Conf. Tucson, 1994), Waste Management Symposia, Tucson, AZ (1994).

[77] BOING, L.E., COFFEY, M.J., Waste Minimization Handbook, Vol. 1, Rep. ANL/D&D/M-96/1, Argonne Natl Lab., Argonne, IL (1995).

[78] BRENNECKE, P., KUGEL, K., “Disposal-specific requirements on radioactive waste originating from decommissioning’’, Nuclear Decommissioning — The Strategic,

Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 201–208.
[79] NUCLEAR REGULATORY COMMISSION, Technology, Safety and Costs of Decommissioning Reference Nuclear Fuel Cycle Facilities — Classification of Decommissioning Wastes, Rep. NUREG/CR-4519, NRC, Washington, DC (1986).
[80] JONES, J.M., et al., “Decommissioning technology in the United Kingdom”, Decommissioning Policies for Nuclear Facilities (Proc. Int. Sem. Paris, 1991), OECD, Paris (1992) 97–104.
[81] SCHMALZ, G.D., Fort St. Vrain’s new career in the gas-fired sector, Nucl. Eng. Int. **42** 511 (1997) 32.
[82] RITTSCHER, D., Entsorgung der Brennelemente und Stillegungsabfälle aus den Kernkraftwerken Greifswald und Rheinsberg, Jahrestagung Kerntechnik (1996) 56–78 (in German).
[83] Yucca Mountain project almost shut down twice, Nucl. Remediation Week (10 Jan. 1997).
[84] EUROPEAN COMMISSION, The Situation of Spent Fuel Storage in Nuclear Reactors in the CIS and Central and Eastern Europe, Rep. EUR 16998, Office for Official Publications of the European Communities, Luxembourg (1996).
[85] EUROPEAN COMMISSION, An Overview of Radioactive Waste Management in Central and Eastern European Countries, Working Document of DG XI/C-3, Radioactive Waste Management Policy, Doc. No. XI/475/97, Office for Official Publications of the European Communities, Luxembourg (1997).
[86] It’s official: The US will take spent fuel, Nucl. News June (1996) 18.
[87] US DEPARTMENT OF ENERGY, Decontamination and Decommissioning Focus Area, Technology Summary, Rep. DOE/EM-0300, Aug. 1996, USDOE, Washington, DC (1996).
[88] SIMON, R., “The European Union’s R&D in the field of decommissioning”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 10–16.
[89] GAVRILOV, S., KREMNEV, V., Decommissioning of nuclear installations in Russia and other countries in the CIS, Nucl. Eng. and Des. **159** (1995) 105–115.
[90] BILKIN, B., et al., Development of Radiation Safety Technology and Equipment for Dismantling Nuclear Reactors, Bull. Nuclear Energy Information Centre No. 6, Moscow (1996) 7.
[91] BILKIN, B., et al., Radiation safety and dismantling technology, At. Tekh. Rubezhom **5** (1995) 3.
[92] KAY, J.M., et al., “The closure of Trawsfynydd power station — effects on staff and the local community and identifying a strategy for decommissioning”, Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 295–304.
[93] EUROPEAN COMMISSION, Council Directive 97/11/EC of 3 March 1997, amending Directive 85/337/EEC of 27 June 1985 on the Assessment of the Effects of Certain Public and Private Projects on the Environment (OJL 73/5 of 1997-03-14), Office for Official Publications of the European Communities, Luxembourg (1997).

[94] GRUMBLY, T.P., Site Technology Coordination, Memorandum to DOE Operations Office Managers, 1994-01-25, US Dept of Energy, Washington, DC (1994).

[95] NUCLEAR REGULATORY COMMISSION, NRC Revises Requirements for Decommissioning Nuclear Power Plants, NRC news release No. 96-106, 1996-07-30, NRC, Washington, DC (1996).

[96] GENERAL ACCOUNTING OFFICE, Usefulness of Information from Shippingport Decommissioning for Rancho Seco, Rep. GAO/RCED-90-171, Washington, DC (1990).

[97] MASSAUT, V., "Research and development in decontamination and dismantling techniques: The Belgian approach'', paper presented at IAEA Regional Training Course on Decommissioning of Research Reactors and Other Small Nuclear Facilities, Bucharest, 1997.

[98] NOKHAMZON, J.G., "CEA decommissioning experience", ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1689–1694.

[99] YAMAMOTO, T., "Decommissioning situation and R&D for the decommissioning of the commercial nuclear power station in Japan", ICONE-4: Nuclear Engineering (Proc. 4th JSME/ASME Joint Int. Conf. New Orleans, 1996), American Society of Mechanical Engineers, New York (1996) 107–110.

[100] WHITE, S.J., et al., "An overview of the AEA Technology decommissioning research and development programme", Decommissioning and Demolition 1990: Decommissioning Offshore, Onshore Demolition and Nuclear Works (Proc. Conf. Manchester, 1990), Thomas Telford, London (1990) 123.

[101] COLQUHOUN, A.P., "British Nuclear Fuel's decommissioning development programme and progress", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[102] BOSSART, S.J., KASPER, K.M., Improved D&D through innovative technology deployment, Radwaste Mag. **5** 1 (1998) 36–40.

[103] US DEPARTMENT OF ENERGY, Record of the Decontamination and Decommissioning Workshop: Defining Research Needs, Rep. DOE/METC-96, USDOE, Washington, DC (1996) 8–18.

[104] DUDA, J., KASPER, K.M., "Innovative technology performance — Demonstrations at Hanford's C reactor facility'', SPECTRUM '98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 245–250.

[105] OECD NUCLEAR ENERGY AGENCY, Low-Level Radioactive Waste Repositories: An Analysis of Costs, OECD, Paris (1999).

[106] OECD NUCLEAR ENERGY AGENCY, Decommissioning of Nuclear Facilities: An Analysis of the Variability of Decommissioning Cost Estimates, OECD, Paris (1991).

[107] OECD NUCLEAR ENERGY AGENCY, Future Financial Liabilities of Nuclear Activities, OECD, Paris (1996).

[108] STEVENS, G.H., YASUI, M., "Funding schemes in OECD countries for future decommissioning of nuclear facilities", Dismantling of Nuclear Facilities: Policies and Techniques (Proc. Conf. Avignon, 1992), Société française d'énergie nucléaire, Paris (1992).

[109] INTERNATIONAL ATOMIC ENERGY AGENCY, Review of Selected Cost Drivers for Decisions on Continued Operation of Older Nuclear Reactors, IAEA-TECDOC-1084, Vienna (1999).

[110] COLVIN, J.F., "US decommissioning strategy in today's regulatory, technical, political, and economic environment", Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 333–342.

[111] LA GUARDIA, T., "Decommissioning progress: USA", Decommissioning of Nuclear Facilities (Proc. 5th Int. Conf. London, 1997), IBC Technical Services, London (1997).

[112] LA GUARDIA, T., "Recent development in US policy", Decommissioning of Nuclear Facilities (Proc. 5th Int. Conf. London, 1997), IBC Technical Services, London (1997).

[113] MITTLER, M., LUKACS, G., Nationale und internationale Kostenaspekte bei Stillegung und Rückbau, Vortrag. — Stillegung und Rückbau kerntechnischer Anlagen/VDI-Tagung, Schwerin, 26–27 September 1996, VDI-Gesellschaft Energietechnik, Düsseldorf, VDI-Verlag, 1996 (in German).

[114] PETTERSSON, S., LONNERBERG, B., Decommissioning of Swedish nuclear power plants", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[115] ANDERSSON, S.O., et al., An Evaluation of Cost Estimates of Nuclear Power Reactor Decommissioning in Sweden, Germany and the United States, November 1995, SKI-report 95:65, Swedish Nuclear Power Inspectorate, Stockholm (1995).

[116] ANDERSSON, S.O., et al., "The adequacy of decommissioning provisions — A case study in Sweden", Decommissioning of Nuclear Facilities (Proc. 5th Int. Conf. London, 1997), IBC Technical Services, London (1997).

[117] OECD NUCLEAR ENERGY AGENCY, The NEA Co-operative Programme on Decommissioning: The First Ten Years 1985–1995, OECD, Paris (1996).

[118] NUCLEAR REGULATORY COMMISSION, Estimating Boiling Water Reactor Decommissioning Costs, Rep. NUREG/CR-6270, NRC, Washington, DC (1996).

[119] NUCLEAR REGULATORY COMMISSION, Estimating Pressurized Water Reactor Decommissioning Costs, Rep. NUREG/CR-6054, NRC, Washington, DC (1995).

[120] BOBELDIJK, V., A computerized cost estimating system for the decommissioning of contaminated facilities, Cost Eng. (US) **37** July (1995) 31–37.

[121] HARRISON, J., "Development of software to support decommissioning and waste management strategy planning", Decommissioning of Nuclear Facilities (Proc. 5th Int. Conf. London, 1997), IBC Technical Services, London (1997).

[122] ESSMAN, J., "Decommissioning issues and policy of German utilities", Decommissioning of Nuclear Facilities (Proc. 4th Int. Conf. London, 1995), IBC Technical Services, London (1995).

[123] HAWLEY, R., "Decommissioning of nuclear facilities", Decommissioning of Nuclear Facilities (Proc. 4th Int. Conf. London, 1995), IBC Technical Services, London (1995).

[124] FERTÉ, J., Decommissioning nuclear installations: Business as usual or playing with the Devil, Nucl. Energy **35** 5 (1995) 339–344.

[125] THIERFELDT, S., Stillegung und Rückbau kerntechnischer Anlagen — Erfahrungen und Perspektiven, German Federal Ministry for Education, Science, Research and Technology (BMBF), Bonn, Verlag Gebr. Tönnes, Düsseldorf (1993) (in German).

[126] UK GOVERNMENT WHITE PAPER, Review of Radioactive Waste Management Policy, Rep. CM 2919, Her Majesty's Stationery Office, London (1995).
[127] INTERNATIONAL ATOMIC ENERGY AGENCY, Planning and Management for the Decommissioning of Research Reactors and Other Small Nuclear Facilities, Technical Reports Series No. 351, IAEA, Vienna (1993).
[128] HEYDE, T., Projektplanung und Überwachung bei Stillegung und Rückbau/ Vortrag — Stillegung und Rückbau kerntechnischer Anlagen/VDI-Tagung, Schwerin (1996) (in German).
[129] CROSS, M.T., et al., "Development of decommissioning technologies for the Windscale advanced gas-cooled reactor'', Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).
[130] EUROPEAN COMMISSION, The BR3 Pressurized Water Reactor Pilot Dismantling Project, Rep. EUR 18229, Office for Official Publications of the European Communities, Luxembourg (1998).
[131] MASSAUT, V., "Lessons learned during the BR3 European pilot decommissioning project", Decommissioning Nuclear Facilities (Proc. 5th Int. Conf. London, 1997), IBC Technical Services, London (1997).
[132] FUJIKI, K., "Development programs on decommissioning technology for reactors and fuel cycle facilities in Japan", Decommissioning Policies for Nuclear Facilities (Proc. Int. Sem. Paris, 1991), OECD, Paris (1992) 111–120.
[133] MIMORI, T., et al., "The decommissioning program for JAERI's reprocessing test facility", Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 229–236.
[134] SUKEGAWA, T., et al., "Waste characterization in decommissioning the Japan power demonstration reactor by computer code systems", ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1779–1784.
[135] YANAGIHARA, S., et al., "Systems engineering approach to planning of nuclear power plant decommissioning", SPECTRUM '98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 269–274.
[136] TEUNCKENS, L., et al., "Decommissioning of the main process building of the former Eurochemic reprocessing plant'', Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).
[137] PULSFORD, S.K., et al., "System for tracking remediation exposure, activities and materials (STREAM): Innovative technology demonstration at Hanford's C reactor", SPECTRUM '98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 275–278.
[138] KERARON, Y., TANGUY, I., "Documentation as a support and memory of dismantling operations", Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 2, Société française d'énergie nucléaire, Paris (1998) 607–617.

[139] PFLUGRAD, K., et al., “Collection and sharing of data and experience from EC funded decommissioning projects”, Nuclear Decommissioning ’98 (Proc. Int. Conf. London, 1998), Professional Engineering Publishing, London (1998) 331–341.
[140] LEUSHACKE, D.F., RITTSCHER, D., Projektmanagement und Logistik bei der Stillegung und dem Rückbau der Kernkraftwerke der Energiewerke Nord GmbH (in German), Proceedings of the V. Stillegungskolloquium Hannover, 24–25 June 1997, German Federal Ministry for Education, Science, Research and Technology, Bonn (1997) 63.
[141] GRÜNDER, D., HARMANN, B., KAFFKA, E., “Documentation system for radioactive wastes arising from decommissioning of nuclear power plants”, KONTEC ’97: Conditioning of Radioactive Operational and Decommissioning Waste (Proc. 3rd Symp. Hamburg, 1997), Kontec Gesellschaft für technishce Kommunication mbH, Glinde (1997).
[142] GRÜNDER, D., WRINGER, W., “Data processing system for tracking and documenting radioactive wastes and residues”, ICEM ’97: Radioactive Waste Management and Environmental Remediation (Proc. 6th Int. Conf. Singapore, 1997), American Society of Mechanical Engineers, New York (1997).
[143] WATZEL, G., et al., Technik und Kosten bei der Stillegung von Kernkraftwerken nach Ende ihrer Einsatzdauer, VDI Verlag Reihe **15** 52 (1987) (in German).
[144] ADLER, J., PETRASCH, P., Decommissioning Cost of Light Water Nuclear Power Plants in Germany from 1977 to Date, Rep. EUR 14798, Office for Official Publications of the European Communities, Luxembourg (1993).
[145] PETRASCH, P., BACKER, A., BIRRINGER, K.J., Unterstützung bei der Stillegung kerntechnischer Anlagen durch EDV, Werkzeuge — Betriebserfahrung und neue Entwicklungen, Jahrestagung Kerntechnik Aachen, 1997 (in German).
[146] MANNERS, T.K., “Decommissioning a high activity handling cell to stage 3”, Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 109–118.
[147] WAHLEN, E., et al., “Decommissioning of the AVR experimental nuclear power plant”, Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 255–264.
[148] ANDREWS, P.J., et al., “Stage I decommissioning of the steam generating heavy water reactor — Current achievements”, Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 305–314.
[149] MINISTRY OF HEALTH, Sanitary Rules for Industrial and Municipal Special Laundries on Decontamination of Working Clothing and Other Individual Protection Means, Moscow (1989) (in Russian).
[150] FELLHAUER, C.R., BOING, L.E., ALDANA, J., Decontamination and Decommissioning of the Experimental Boiling Water Reactor (EBWR): Project Final Report, Rep. ANL/D&D/TM-96/4, Argonne Natl Laboratory, Argonne, IL (1997).
[151] CHEEVER, C.L., ROSE, R.W., Decontamination and Decommissioning of 61 Plutonium Gloveboxes in D-Wing, Building 212, ANL-East: Final Project Report, Rep. ANL/D&D/TM-96/3, Argonne Natl Laboratory, Argonne, IL (1996).

[152] NUCLEAR REGULATORY COMMISSION, Manual for Conducting Radiological Surveys in Support of License Termination, Rep. NUREG/CR-5849 (draft), NRC, Washington, DC (1992).

[153] US ENVIRONMENTAL PROTECTION AGENCY, US DEPARTMENT OF ENERGY, NUCLEAR REGULATORY COMMISSION, US DEPARTMENT OF DEFENSE, Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM), Rep. NUREG-1575, Rep. EPA 402-R-97-016, NRC, Washington, DC (1997).

[154] CORNELISSEN, R., et al., "Unrestricted reuse of decommissioned nuclear laboratories", Site Remediation (Topical Mtg Mol, 1996), Rep. BLG-721, SCK-CEN, Mol (1996) (available upon request).

[155] BORST, F.J., FISHER, M.J., "The Fort St. Vrain decommissioning: Final radiation survey", SPECTRUM '98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 269–274.

[156] FLEISCHER, C.C., et al., "Examination and long term assessment of nuclear power stations", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 591–602.

[157] EUROPEAN COMMISSION, Konsequenzen der Aufhebung der Unterdruckhaltung im Containment des Kernkraftwerks Lingen, Rep. EUR 13131, Office for Official Publications of the European Communities, Luxembourg (1991) (in German).

[158] BRYERS, J., et al., "Hunterston 'A' power station — A structured approach to long-term storage and preservation", Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 209–218.

[159] INTERNATIONAL ATOMIC ENERGY AGENCY, Classification of Radioactive Waste, Safety Series No. 111-G-1.1, IAEA, Vienna (1994).

[160] EUROPEAN COMMISSION, Radioactive Waste Categories — Current Position (98) in the EU Member States and in the Baltic and Central European Countries, Rep. EUR 18324, Office for Official Publications of the European Communities, Luxembourg (1998).

[161] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1990 Recommendations of the International Commission on Radiological Protection, Publication 60, Pergamon Press, Oxford and New York (1991).

[162] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANISATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996).

[163] EUROPEAN UNION, Council Directive 96/29 Euratom of 13 May 1996, Laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionising radiation, Off. J. Eur. Commun. L **159** 39 (1996).

[164] COMMISSARIAT A L'ENERGIE ATOMIQUE, ALARA and Decommissioning (1st Eur. ALARA Network Workshop Saclay, 1997), Office for Official Publications of the European Communities, Luxembourg (1997).

[165] INTERNATIONAL ATOMIC ENERGY AGENCY, The Principles of Radioactive Waste Management, Safety Series No. 111-F, IAEA, Vienna (1995).
[166] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Radiation Protection Principles to the Cleanup of Contaminated Areas, Interim Report for Comment, IAEA-TECDOC-987, Vienna (1997).
[167] BRENNECKE, P., RITTSCHER, D., Conditioning and disposal of decommissioning wastes, Kerntechnik **56** 6 (1991) 379–382.
[168] EUROPEAN COMMISSION, Recycling and Reuse of Radioactive Material in the Controlled Nuclear Sector, Rep. EUR 18041, Office for Official Publications of the European Communities, Luxembourg (1998).
[169] SIMPSON, K.A., ELDER, G.R., "Decontamination for free release", Treatment Technologies for Low and Intermediate Level Waste from Nuclear Applications, IAEA-TECDOC-929, IAEA, Vienna (1997) 147–152.
[170] RAUH, H.J., "Radiological aspects of recycling concrete debris from dismantling of nuclear installations", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 421–432.
[171] GARBAY, H., et al., "Technical elements for the determination of clearance levels for steel and concrete", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 565–578.
[172] EUROPEAN COMMISSION, Recycling of Activated/Contaminated Reinforcement Metal in Concrete, Rep. EUR 15045, Office for Official Publications of the European Communities, Luxembourg (1994).
[173] COMMISSION OF THE EUROPEAN COMMUNITIES, Impact radiologique dû au cuivre et à l'aluminium très faiblement radioactifs provenant du démantèlement d'installations nucléaires, Rep. EUR 13160, Office for Official Publications of the European Communities, Luxembourg (1991) (in French).
[174] EUROPEAN COMMISSION, Untersuchungen zur Rezyklierung von radioaktiv kontaminiertem Aluminium und Kupfer durch Schmelzprozesse, Rep. EUR 16512, Office for Official Publications of the European Communities, Luxembourg (1995) (in German).
[175] INTERNATIONAL ATOMIC ENERGY AGENCY, Principles for the Exemption of Radiation Sources and Practices from Regulatory Control, Safety Series No. 89, IAEA, Vienna (1988).
[176] EUROPEAN COMMISSION, High Resolution In Situ Gamma Spectrometer For Use on Contaminated Reactor Building Structures and Outdoor Grounds Under Decommissioning, Rep. EUR 18349, Office for Official Publications of the European Communities, Luxembourg (1998).
[177] EUROPEAN COMMISSION, Handbook on Measurements Methods and Strategies at Very Low Levels and Activities, Rep. EUR 17624, Office for Official Publications of the European Communities, Luxembourg (1998).
[178] MORRELL, D.M., MILLER, J.R., ALLEN, D.F., "The Rocky Flats environmental technology site beryllium characterization project'', SPECTRUM '98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste

Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 1165–1171.

[179] US DEPARTMENT OF ENERGY, Closing the Circle on the Splitting of the Atom, USDOE, Washington, DC (1995).

[180] EUROPEAN COMMISSION, Assessment of the Consequences of the Presence of Toxic Elements in Some Common Radioactive Waste Streams, Rep. EUR 18211, Office for Official Publications of the European Communities, Luxembourg (1998).

[181] EUROPEAN COMMISSION, Large Scale Demonstration of Dismantling Techniques under Realistic Conditions in the LIDO Biological Shield, Rep. EUR 17888, Office for Official Publications of the European Communities, Luxembourg (1998).

[182] EUROPEAN COMMISSION, Evaluation of Various Cutting Techniques Suitable for the Dismantling of Nuclear Components, Rep. EUR 17919, Office for Official Publications of the European Communities, Luxembourg (1998).

[183] US DEPARTMENT OF ENERGY, Decommissioning Handbook, Rep. DOE/EM-0142P, USDOE, Washington, DC (1994).

[184] COMMISSION OF THE EUROPEAN COMMUNITIES, Measurements of Secondary Emissions from Plasma Arc and Laser Cutting in Standard Experiments, Rep. EUR 14065, Office for Official Publications of the European Communities, Luxembourg (1992).

[185] RIMANDO, R.V., Jr., DOWD, A.S., Jr., "Demolishing a tritium-contaminated exhaust stack amid an operating nuclear area", X-Change '97: The Global D&D Marketplace (Proc. Conf. Miami, 1997), Hemispheric Center for Environmental Technology, Miami, FL (1998).

[186] QUADE, U., et al., "Packaging requirements for graphite and carbon from the decommissioning of the AVR in consideration of the German final disposal regulations", Technologies for Gas Cooled Reactor Decommissioning, Fuel Storage and Waste Disposal, IAEA-TECDOC-1043, IAEA, Vienna (1998) 275–286.

[187] HOLT, G., "The decommissioning of commercial Magnox gas cooled reactor power stations in the United Kingdom", Technologies for Gas Cooled Reactor Decommissioning, Fuel Storage and Waste Disposal, IAEA-TECDOC-1043, IAEA, Vienna (1998) 71–83.

[188] US DEPARTMENT OF ENERGY, Understanding Tritium During Decommissioning, Rep. DOE/SR-5000-513, USDOE, Washington, DC (1997).

[189] WALTON, G.R., et al., "Decontamination and decommissioning the TOKAMAK fusion test reactor", Decontamination and Decommissioning (Proc. Int. Symp Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[190] KRASZNAI, J.P., "UV/ozone treatment to decontaminate tritium contaminated surfaces", New Methods and Techniques for Decontamination in Maintenance or Decommissioning Operations, IAEA-TECDOC-1022, IAEA, Vienna (1998) 45–50.

[191] SEDOV, V.M., et al., Chemical Technology of Nuclear Power Reactor Coolants, Energoatomizdat, Moscow (1985) (in Russian).

[192] MARSDEN, B.J., DAVIES, M.A., "Decommissioning graphite cores containing significant amounts of stored energy", Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 265–274.

[193] MARSDEN, B.J., et al., "Evaluation of graphite safety issues for the British production piles at Windscale: Graphite sampling in preparation for the dismantling of Pile 1 and the further safe storage of Pile 2", Technologies for Gas Cooled Reactor Decommissioning, Fuel Storage and Waste Disposal, IAEA-TECDOC-1043, IAEA, Vienna (1998) 213–223.
[194] WICKHAM, A.J., et al., "Graphite core stability during 'care and maintenance' and 'safe storage' ", Technologies for Gas Cooled Reactor Decommissioning, Fuel Storage and Waste Disposal, IAEA-TECDOC-1043, IAEA, Vienna (1998) 225–232.
[195] MARSDEN, B.J., WICKHAM, A.J., "Graphite disposal options — A comparison of the approaches proposed by UK and Russian reactor operators", Nuclear Decommissioning '98 (Proc. Int. Conf. London, 1998), Professional Engineering Publishing, London (1998) 145–153.
[196] AMPELOGOVA, N.I., SIMANOVSKY, Y.M., TRAPESNIKOV, A.A., Decontamination in Nuclear Power Engineering, Energoizdat, Moscow (1982) (in Russian).
[197] EUROPEAN COMMISSION, The Community's Research and Development Programme on Decommissioning of Nuclear Installations (1989–93) — Annual Progress Report 1993, Rep. EUR 15854, Office for Official Publications of the European Communities, Luxembourg (1994).
[198] EUROPEAN COMMISSION, Destruction du sodium contaminé du circuit primaire du reacteur expérimental Rapsodie-installation Desora, Rep. EUR 16881, Office for Official Publications of the European Communities, Luxembourg (1996) (in French).
[199] ROGER, J., et al., "Transformation of sodium from the Rapsodie fast breeder reactor into sodium hydroxide", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1994) 156–163.
[200] MACHLACHLAN, A., Cadarache accident yields lessons for decommissioning, Nucleonics Week (28 July 1994) 12.
[201] MCINTYRE, A., The disposal of liquid metal coolants at PFR — A decommissioning challenge, Nucl. Eng. **38** 1 (1997) 9–11.
[202] KATHOL, W., RUDINGER, V., "Decommissioning the KNK compact sodium-cooled nuclear reactor facility", SPECTRUM '98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 251–260.
[203] PETERSON, E., "Remediation of Department of Energy sodium system component test facility", SPECTRUM '98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 99–103.
[204] AMERICAN NATIONAL STANDARDS INSTITUTE, Safe Use of Lasers, Rep. ANSI Z136.1-1993, New York (1993).
[205] US CODE OF FEDERAL REGULATIONS, General Requirements, Rep. 29 CFR 1910 132, subparts, I, O and P, US Govt Printing Office, Washington, DC (1998).
[206] US CODE OF FEDERAL REGULATIONS, Occupational Noise Exposure, Rep. 29 CFR 1910 95, US Govt Printing Office, Washington, DC (1998).
[207] TEUNCKENS, L., LEWANDOWSKI, P., "Progress report for the Eurochemic reprocessing plant of Dessel, Belgium", OECD Nuclear Energy Agency Co-operative

Programme on Decommissioning (23rd TAG Mtg Chester, 1997), OECD, Paris (1997) (restricted circulation).
[208] NUCLEAR ENGINEERING INTERNATIONAL, STATUS MEETINGS, Fire & Safety ’94: Fire Protection and Prevention in Nuclear Facilities (Proc. Conf. Barcelona, 1994), Status Meetings, Petersfield, UK (1994).
[209] EUROPEAN COMMISSION, Decommissioning Experience in Europe (Proc. Workshop Gundremmingen, 1995), Rep. EUR 16900 Office for Official Publications of the European Communities, Luxembourg (1995).
[210] ISHIKURA, T., Development of Decontamination and Decommissioning Techniques for Commercial NPPs in Japan, Nuclear Power Engineering, Tokyo (1996).
[211] NUCLEAR POWER ENGINEERING CORPORATION, Verification Tests on Decommissioning Technology for Commercial Nuclear Power Facilities, internal report, NUPEC, Tokyo (1997).
[212] AEA TECHNOLOGY, US DOE European Technologies Review, internal report, Rep. DG/TS/196(TN), Sept. 1996, AEA Technology, Harwell (1996).
[213] US DEPARTMENT OF ENERGY, Decommissioning Benchmarking Study, 1997, http://www.em.doe.gov/dd/bench.html.
[214] KRAUSE, D.R., et al., “Execution of large scale technology demonstrations within an active decontamination and decommissioning project”, Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 446.
[215] HYDE, J.M., “D&D technology needs to meet environmental management cleanup strategy”, Waste Management ’98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).
[216] BOSSART, S.J., SHAH, S.I., “New technologies for dismantlement of DOE’s surplus facilities”, Waste Management ’98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).
[217] US DEPARTMENT OF ENERGY, Decontamination and Decommissioning Focus Area, Annual Report 1997, Rep. DOE/FETC-98/1055, USDOE, Washington, DC (1998).
[218] US DEPARTMENT OF ENERGY, OFFICE OF ENVIRONMENTAL RESTORATION, Preferred Alternatives Matrices Decommissioning, June 1997, http://www.em.doe.gov/define/d_pam.htm.
[219] INTERNATIONAL ATOMIC ENERGY AGENCY, Characterization of Radioactive Waste Forms and Packages, Technical Reports Series No. 383, IAEA, Vienna (1997).
[220] ISHIKURA, T., et al., “Radioactivity measurement and assessment techniques for decommissioning of commercial nuclear power plants”, SPECTRUM ’94: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Atlanta, 1994), American Nuclear Society, La Grange Park, IL (1994) 374–379.
[221] NUCLEAR POWER ENGINEERING CORPORATION, Annual Report 1997, NUPEC, Tokyo (1997) 30–31.
[222] MESERVEY, R.H., et al., Idaho National Engineering Laboratory Decontamination and Decommissioning Technology Logic Diagram, Vol. 1, Rep. EGG-WTD-11104, Jan. 1994, Idaho National Engineering Laboratory, Idaho Falls, ID (1994).

[223] BRONSON, F.L., "Nuclear instrumentation tools for lower costs and higher reliability decommissioning of buildings and grounds", TOPSEAL '96 (Proc. Int. Conf. Stockholm, 1996), European Nuclear Society, Berne (1996).

[224] LUFF, C., et al., "Free release monitoring of pipes and ducts", Waste Management '97 (Proc. Int. Conf. Tucson, 1997), Waste Management Symposia, Tucson, AZ (1997).

[225] HUGHES, K.A., LIGHTFOOT, J.A., "Use of the RadScan™ 600 in the decommissioning of a highly active cell", Waste Management '97 (Proc. Int. Conf. Tucson, 1997), Waste Management Symposia, Tucson, AZ (1997).

[226] HUGHES, K.A., LIGHTFOOT, J.A., "Upgrading the RadScan™ 600 gamma scanner to produce dose maps in three dimensions", ICONE-5: Nuclear Engineering (Proc. 5th Int. Conf. Nice, 1997), American Society of Mechanical Engineers, New York (1997).

[227] BRITISH NUCLEAR FUELS, RadScan™ 700 Gamma Scanner, company brochure, BNFL, Warrington (1997).

[228] US DEPARTMENT OF ENERGY, Indoor Radiation Mapping Using the Laser Assisted Ranging and Data Systems (LARADS), Feb. 1998, http://www.bhi-erc.com/Creactor/final.htm.

[229] Groundhog makes the day for surveying contaminated land, Nucl. Eng. Int. **43** 524 (1998) 22.

[230] SCIENCE AND ENGINEERING ASSOCIATES, Alpha Measurement Capability in Pipes and Ducts with the Pipe Explorer™ System, company brochure, Science and Engineering Associates, Albuquerque, NM (1996).

[231] KENDRICK, D., CREMER, C.D., "Pipe Explorer™ overview — Applications and recent development'', SPECTRUM '96: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Seattle, 1996), American Nuclear Society, La Grange Park, IL (1996) 1038–1045.

[232] US DEPARTMENT OF ENERGY, Position-Sensitive Radiation Monitoring (Surface Contamination Monitoring), Feb. 1998, http://www.bhi-erc.com/Creactor/final.htm.

[233] BREGANI, F., "Decontamination for decommissioning purposes", Decommissioning of Nuclear Installations (Eur. Comm. Course Ispra, 1993), European Commission, Luxembourg (1993) (unpublished report).

[234] INTERNATIONAL ATOMIC ENERGY AGENCY, New Methods and Techniques for Decontamination in Maintenance or Decommissioning Operations, IAEA-TECDOC-1022, Vienna (1998).

[235] US NATIONAL RESEARCH COUNCIL, A Review of Decontamination and Decommissioning Technology Development Programs at the Department of Energy, National Academy Press, Washington, DC (1998).

[236] BOUDREAUX, J.F., et al., "Decision analysis science modeling for application and field selection applied to concrete decontamination technologies", SPECTRUM '96: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Seattle, 1996), American Nuclear Society, La Grange Park, IL (1996) 2011–2015.

[237] HEMISPHERIC CENTER FOR ENVIRONMENTAL TECHNOLOGY, Decision Analysis System for Selection of Appropriate Decontamination Technologies, Fiscal Year 1997, Year-end Report (1997), http://www.hcet.fiu.edu.

[238] OAK RIDGE NATIONAL LABORATORY, Demonstration Recommendations for Accelerated Testing of Concrete Decontamination Methods, Rep. ORNL/TM-13098, Dec. 1995, Oak Ridge, TN (1995).

[239] HIRABAYASHI, T., "Research and development of decontamination techniques at Japan power demonstration reactor decommissioning project", paper presented at IAEA Workshop on Planning and Management of Decommissioning WWER NPPs, Bratislava, 1997.

[240] ISHIKURA, T., et al., "Development of decontamination techniques for decommissioning commercial nuclear power plants", Nuclear Waste Management and Environmental Remediation (Proc. Int. Conf. Prague, 1993), Vol. 2, American Society of Mechanical Engineers, New York (1993) 295–300.

[241] HOSAKA, K., et al., "Decontamination technique for decommissioning waste", ICEM '95: Radioactive Waste Management and Environmental Remediation (Proc. 5th Int. Conf. Berlin, 1995), American Society of Mechanical Engineers, New York (1995) 1677–1681.

[242] ONOZAWA, T., et al., "Development of decontamination technique before dismantling for decommissioning of commercial nuclear power plants", ICEM '95: Radioactive Waste Management and Environmental Remediation (Proc. 5th Int. Conf. Berlin, 1995), American Society of Mechanical Engineers, New York (1995) 1687–1689.

[243] BORIOLI, E., et al., "Effectiveness of different decontamination techniques on metallic scraps arising from decommissioned power plants", New Methods and Techniques for Decontamination in Maintenance or Decommissioning Operations, IAEA-TECDOC-1022, IAEA, Vienna (1998) 139–148.

[244] VNIPIET, Decontamination Facilities and Equipment, Information Collection, VNIPIET, St. Petersburg (1992) (in Russian).

[245] NECHAEV, A.F., et al., "Decontamination and waste management in the course of research decommissioning", paper presented at First IAEA CRP on Decommissioning Techniques for Research Reactors, Mumbai, 1998.

[246] NECHAEV, A.F., et al., Decontamination and Waste Management in the Course of Research Reactors Decommissioning, Progress Report, St. Petersburg Institute of Technology, St. Petersburg (1998).

[247] INTERNATIONAL ATOMIC ENERGY AGENCY, Decontamination of Transport Casks and of Spent Fuel Storage Facilities, IAEA-TECDOC-556, Vienna (1990).

[248] DEMMER, R.L., et al., "A review of decontamination technologies under development and demonstration at the ICPP", Decommissioning, Decontamination, and Environmental Restoration of Contaminated Nuclear Sites (Proc. Conf. Washington, DC, 1994), American Nuclear Society, La Grange Park, IL (1994) 114–118.

[249] DEMMER, R.L., Testing and Comparison of Seventeen Decontamination Chemicals, Rep. INEL-96/0361, Sept. 1996, Idaho National Engineering Laboratory, Idaho Falls, ID (1996).

[250] MESERVEY, R.H., et al., Idaho National Engineering Laboratory Decontamination and Decommissioning Technology Logic Diagram, Vol. III, Rep. EGG-WTD-11104, Jan. 1994, Idaho National Engineering Laboratory, Idaho Falls, ID (1994).

[251] CHEN, L., et al., "A review of chemical decontamination systems for nuclear facilities", The Best D&D... Creative, Comprehensive and Cost-Effective (Proc. Topical Mtg Chicago, 1996), American Nuclear Society, La Grange Park, IL (1996) 87–94.

[252] JAPAN ATOMIC ENERGY RESEARCH INSTITUTE, Progress of JPDR Decommissioning Program — Twelfth Progress Report (October 1992 — March 1993), report for OECD Nuclear Energy Agency, JAERI, Tokyo (1993).
[253] JAPAN ATOMIC ENERGY RESEARCH INSTITUTE, Progress of JPDR Decommissioning Program — Thirteenth Progress Report (April 1993 — March 1994), report for OECD Nuclear Energy Agency, JAERI, Tokyo (1994).
[254] MOMMA, T., et al., "Flowing abrasive method for system decontamination in the Japan power demonstration reactor", ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995).
[255] COURTOIS, C., "Decontamination techniques for dismantling", Decommissioning Policies for Nuclear Facilities (OECD/NEA Int. Sem. Paris, 1991), OECD, Paris (1992) 67–76.
[256] ROGER, J., "Stage 2: Dismantling of reactor case of the experimental FBR Rapsodie", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).
[257] ONUMA, T., AKIMOTO, H., Chemical Decontamination of Stainless Steel, Hitachi Plant Engineering Construction, Tokyo (1991).
[258] ONUMA, T., AKIMOTO, H., Chemical Decontamination Method for Radioactive Metal Waste, Hitachi Plant Engineering Construction, Tokyo (1991).
[259] HANULIK, J., RIPPIN, D.W.T., "Chemical decontamination for decommissioning with application of DECOHA technology on metal, concrete and brickwork", NUCLEAR DECOM '92: Decommissioning of Radioactive Facilities (Proc. Int. Conf. London, 1992), Mechanical Engineering Publications, London (1992).
[260] ROLLOR, M.A., et al., "Industrial-scale decontamination using the DECOHA process at Chernobyl: Technology and program for radioactive waste management and environmental restoration", Waste Management '97 (Proc. Int. Conf. Tucson, 1997), Waste Management Symposia, Tucson, AZ (1997) 569–573.
[261] HANULIK, J., Decontamination of Surfaces Contaminated by Radioactivity, Eidgenössische Technische Hochschule, Zurich (1991).
[262] DOILNITZYN, V.A., et al., The Estimation of the Efficiency of Precipitating Regeneration Method for Spent Decontamination Solutions used in DECOHA Technology, St. Petersburg Institute of Technology, St. Petersburg (1995) (in Russian).
[263] NAUGHTON, M.D., WOOD, C.J., EPRI Program: Nuclear Power Plant Decommissioning Technology, EPRI report, Electric Power Research Institute, Palo Alto, CA (1997).
[264] BRADBURY, D., et al., "The EPRI DfD process: Decontamination for decommissioning", Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 463.
[265] WOOD, C.J., BRADBURY, D., ELDER, G.R., "The EPRI DfD process: Decontamination for decommissioning", SPECTRUM '98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 64–67.

[266] MASSAUT, V., KLEIN, M., LEFEBVRE, A., “Pilot dismantling of the BR3 pressurized water reactor”, ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1719–1724.

[267] MASSAUT, V., et al., “Pilot dismantling of the BR3 pressurized water reactor’’, Decommissioning Experience in Europe (Proc. Eur. Comm. Workshop, 1996), Rep. EUR 16900, Office for Official Publications of the European Communities, Luxembourg (1996).

[268] ROSSET, R., et al., “Complexing properties of the main organic acids used in decontamination solutions and reactions involved in their degradation or elimination”, Chemistry in Water Reactors: Operating Experience and New Developments (Proc. Int. Conf. Nice, 1994), Vol. 1, Société française d’énergie nucléaire, Paris (1994) 195–202.

[269] MAJERSKÝ, D., SOLČÁNYI, M., PRAŽSKÁ, M., “Recent trends in the area of the decontamination of nuclear power plants in the Slovak Republic and in the Czech Republic”, Nuclear Waste Management and Environmental Remediation (Proc. Int. Conf. Prague, 1993), American Society of Mechanical Engineers, New York (1993) 301–306.

[270] SEDOV, V.M., et al., NPP decontamination, At. Ehnerg. **65** 6 (1988) 399–403 (in Russian).

[271] PRIESMEYER, U., HACKEL, W., “Treatment and recycling of nuclear scrap in decommissioning KRBA and VAK”, KONTEC ’97: Conditioning of Radioactive Operational and Decommissioning Waste (Proc. 3rd Symp. Hamburg, 1997), Kontec Gesellschaft für technische Kommunikation mbH, Glinde (1997) 1012–1019.

[272] VORONIK, N.I., et al., “Decontamination as a part of decommissioning and maintenance work at nuclear installations”, New Methods and Techniques for Decontamination in Maintenance or Decommissioning Operations, IAEA-TECDOC-1022, IAEA, Vienna (1988) 9–26.

[273] INTERNATIONAL ATOMIC ENERGY AGENCY, Improved Cement Solidification of Low and Intermediate Level Radioactive Wastes, Technical Reports Series No. 350, IAEA, Vienna (1993).

[274] KAISER, R., et al., “Decontamination of electrochemical parts by the SONATOL process: II — Results”, Waste Management ’98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).

[275] CHANY, P., et al., “Application of COGEMA decommissioning experience to preparation of UP1 final shutdown operations at Marcoule”, Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 1, Société française d’énergie nucléaire, Paris (1998) 239–252.

[276] XIAN WEN REN, YUAN ZHANG, “Loop cleanup with REDOX decontamination technique”, New Methods and Techniques for Decontamination in Maintenance or Decommissioning Operations, IAEA-TECDOC-1022, IAEA, Vienna (1998) 51–63.

[277] WOOD, C., Towards full system decontamination in the USA: Review of progress, Nucl. Eng. Int. **38** 469 (1993) 36–37.

[278] ELECTRIC POWER RESEARCH INSTITUTE, Effects of LOMI Decontamination and Preoxidation Processes on Stainless Steel-Clad Low-Alloy Steel, Rep. EPRI-NP-6730, Palo Alto, CA (1990).

[279] Searching for new decontamination solutions, Nucl. Eng. Int. **39** 475 (1994) 25.
[280] MOORTHY, P.N., et al., "Evaluation of LOMI and citrate formulations for the decontamination of the cleanup system surfaces of Tarapur atomic power station BWRs", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).
[281] SCHUNK, J., "Decontamination work at Paks Nuclear Power Plant Ltd", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).
[282] MANAS, L., et al., "Decommissioning of the JEN-1 experimental reactor", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 85–100.
[283] MANAS, L., et al., "Dismantling of the JEN-1 reactor", Decommissioning Experience in Europe (Proc. Eur. Comm. Workshop, 1996), Rep. EUR 16900, Office for Official Publications of the European Communities, Luxembourg (1996).
[284] SVANTESSON, I., et al., Oskarshamn 1 RPV — Cleaning it out before venturing in, Nucl. Eng. Int. **39** 484 (1994) 28–33.
[285] MASSAUT, V., et al., "Pilot dismantling of the BR3 pressurized water reactor", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 19–31.
[286] KLEIN, M., et al., "Decontamination for dismantling: Full system decontamination and thorough decontamination of dismantled pieces", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).
[287] DADOUMONT, J., MASSAUT, V., KLEIN, M., "Pilot dismantling of the BR3 pressurized water reactor", ASRR-V: Research Reactor (Proc. 5th Asian Symp. Taejon, 1996), Korea Atomic Energy Research Institute, Seoul (1996).
[288] KLEIN, M., RAHIER, A., "Thorough decontamination of metallic pieces with cerium process", SPECTRUM '96: Nuclear and Hazardous Waste Managment (Proc. Int. Topical Mtg Seattle, 1996), American Nuclear Society, La Grange Park, IL (1996) 1728–1734.
[289] MASSAUT, V., LEFEBVRE, A., "The BR3 PWR pilot dismantling project: Experience in segmenting highly radioactive internals", paper presented at Nuclear Technology '95, Nuremberg, 1995.
[290] MASSAUT, V., "The BR3 pilot decommissioning project", Radwaste and Decommissioning (Summer School Cambridge, 1998), IBC Technical Services, London (1998).
[291] DEMEULEMEESTER, A., et al., "The BR-3 PWR decommissioning project: Present status and lessons learned", Waste Management '98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).
[292] MASSAUT, V., TEUNCKENS, L., "Experience and developments from the decommissioning of the BR-3 nuclear power plant and the former Eurochemic reprocessing plant in Belgium", Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 1, Société française d'énergie nucléaire, Paris (1998) 191–204.

[293] EICKELPASCH, N., et al., "Remote dismantling experience at VAK", Decommissioning Experience in Europe (Proc. Eur. Comm. Workshop, 1996), Rep. EUR 16900, Office for Official Publications of the European Communities, Luxembourg (1996).
[294] WILLE, H., "Assessment for decontamination procedures for VVER-PWRs for waste minimization", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 386–396.
[295] BERTHOLDT, H.O., WATSON, S.L., "HP/CORD D UV — A new decontamination process for decommissioning of nuclear stations", SPECTRUM '98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 116–123.
[296] JONES, G.D., LYALL, D.J., "Nuclear submarine prototype post-core removal decommissioning and life extension", Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 119–126.
[297] CHAO, G., et al., "A chemical decontamination process for solid waste treatment", ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1823–1826.
[298] BRAY, L.A., et al., Decontamination Testing of Radioactive-Contaminated Stainless Steel Coupons Using a Ce(IV) Solution, Pacific Northwest Lab., Richland, WA (1992).
[299] ANDERSSON, O., et al., "The Ågesta steam generator decommissioning project", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).
[300] DUBOURG, M., "In situ hard chemical decontamination of the tube bundle from a removed PWR steam generator", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 374–385.
[301] LINDBERG, M., et al., "Free release decontamination of SG tubing from a VVER (Greifswald)", ICONE-5: Nuclear Engineering (Proc. 5th Int. Conf. Nice, 1997), American Society of Mechanical Engineers, New York (1997).
[302] KURATH, D.E., et al., "Decontamination of stainless steel using cerium (IV): Material recycle and reuse", Beneficial Reuse '97: Recycle and Reuse of Radioactive Scrap Metal (Proc. 5th Ann. Conf. Knoxville, 1997), US Dept of Energy, Washington, DC (1997).
[303] SANDERS, M.J., et al., "Decontamination of buildings, hot cells and similar facilities", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).
[304] FAURY, M., et al., "Foams for nuclear decontamination purposes: Achievements and prospects", Waste Management '98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).
[305] GAMBERINI, D., "Decommissioning experience at BNFL, Sellafield", Decommissioning Experience in Europe (Proc. Eur. Comm. Workshop, 1996), Rep. EUR 16900, Office for Official Publications of the European Communities, Luxembourg (1996).

[306] COSTES, J.R., et al., “Automatic decontamination foam spray device: Application to system pipes in the G2 and G3 reactors at Marcoule”, Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 368–369.

[307] COSTES, J.R., COCHAUX, C., “New techniques available for decontamination”, Decommissioning, Decontamination and Reutilization (Proc. Topical Mtg Washington, DC, 1996), American Nuclear Society, La Grange Park, IL (1996) 442–443.

[308] CALI, V., “Decontamination of plutonium contaminated materials using functionalized reagents as foam”, Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[309] COSTES, J.R., SAHUT, C., “Foam decontamination of large nuclear components before dismantling”, New Methods and Techniques for Decontamination in Maintenance or Decommissioning Operations, IAEA-TECDOC-1022, Vienna (1998) 65–80.

[310] COMMISSION OF THE EUROPEAN COMMUNITIES, Nouvelles techniques de décontamination: Gels chimiques, électrolyse au tampon et abrasifs, Rep. EUR 13497, Office for Official Publications of the European Communities, Luxembourg (1991) (in French).

[311] JUAN, A., ROUDIL, S., “Innovative decontamination processes applied to an actual decommissioning operation”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 370–373.

[312] POSS, G., et al., “Decontamination technique using a chemical agent dispersed as fog”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 356–364.

[313] WILLS, K.J., “The reaction of chlorine trifluoride and uranyl fluoride: A critical literature review and kinetics analysis”, Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 487.

[314] SHOEMAKER, H.D., KASPER, K.M., LUPICHUK, W., “Improved chemical decontamination methods for D&D”, SPECTRUM ’98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 112–115.

[315] BONEM, M.W., BORAH, R.E., “Removal of contaminants from equipment and debris and waste minimization using the Techxtract® technology”, Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 359.

[316] NICOLOSI, J.F., “Meeting decontamination and regulatory challenges in decommissioning a facility for reutilization — A case study’’, Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 243.

[317] US DEPARTMENT OF ENERGY, Lead “TechXtract” Chemical Decontamination, Technology Demonstration Fact Sheet, May 1998, http://www.bhi-erc.com/Creactor/facts.htm.

[318] HANULIK, J., "DECOFOR and DECONCRETE: New metal and concrete decontamination process for decommissioning", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[319] CARLSEN, H., et al., "Decommissioning of the Riso hot cell facility", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 135–143.

[320] ZIMON, A.D., PIKALOV, V.K., Decontamination, IzdAT, Moscow (1994) (in Russian).

[321] LAFRATE, P., et al., "Los Alamos Laboratory phase separator pit decommissioning project", Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 222.

[322] SEXTON, R.J., et al., "Decontamination and dismantlement of gloveboxes in Building 371 at the Rocky Flats environmental technology site", Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 207.

[323] DARYOKO, M., "Decontamination of radioisotope production facility", New Methods and Techniques for Decontamination in Maintenance or Decommissioning Operations, IAEA-TECDOC-1022, IAEA, Vienna (1998) 129–138.

[324] GUGAN, M.A., et al., "Decommissioning of a mixed oxide fuel fabrication plant at Winfrith technology centre", Waste Management (Proc. Joint Int. Conf. Seoul, 1991), American Society of Mechanical Engineers, New York (1991) 595–598.

[325] BUCK, S., SANDERS, M.J., PENGELLY, M.G.A., "Challenges and solutions for the decommissioning of production scale plutonium facilities'', NUCLEAR DECOM '92: Decommissioning of Radioactive Facilities (Proc. Int. Conf. London, 1992), Mechanical Engineering Publications, London (1992) 119–130.

[326] BOND, R.D., JORDAN, P.R., A Modular Solution to Temporary Containment Problems, Rep. AEAT-0501, AEA Technology, Harwell (1996).

[327] COMMISSION OF THE EUROPEAN COMMUNITIES, Decontamination with Pasty Pickling Agents Forming a Strippable Foil, Rep. EUR 13498, Office for Official Publications of the European Communities, Luxembourg (1991).

[328] PAVELEK, et al., Decontamination of TMI-2, Nucl. Technol. **86** Aug. (1989) 142.

[329] US DEPARTMENT OF ENERGY, Fernald Plant 1 Large Scale Technology Demonstration Project: Spray Vacuum Cleaning Technology, Nov. 1997, USDOE, Washington, DC (1997).

[330] TEUNCKENS, L., WALTHERY, R., DRESSELAERS, B., "Decontamination of metal components to clearance levels by means of abrasive blasting'', Experience in the Application of Exemption Principles, IAEA-TECDOC-807, IAEA, Vienna (1995) 193–200.

[331] PETITET, X., "Pilot dismantling of the FBR fuel reprocessing CO facility AT1", Decommissioning Experience in Europe (Proc. Eur. Comm. Workshop, 1996), Rep. EUR 16900, Office for Official Publications of the European Communities, Luxembourg (1996).

[332] PETITET, X., "Pilot dismantling of the AT1 FBR reprocessing facility at La Hague", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 60–71.

[333] BORNER, P., et al., "Decommissioning of the HOBEG fuel element fabrication plant in Germany", Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nclear Society, La Grange Park, IL (1997) 412.

[334] CHRIST, B.G., SCHMIDT, D., "D&D techniques applied during decommissioning of waste storage facilities at NPP Rheinsberg", Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 416.

[335] TACHIBANA, M., et al., "Decontamination on concrete surfaces in decommissioning of the Japan power demonstration reactor", Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1811–1816.

[336] KAMEO, Y., et al., "Development of advanced decontamination techniques for decommissioning", Waste Management '98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).

[337] GRIECO, S.A., et al., Removal and treatment of radioactive contaminants, Nuc. Plant J. **13** 4 (1995).

[338] SEXTON, R.J., ZACHARY, M., "Decontamination and its role in the Fort St. Vrain decommissioning", SPECTRUM '96: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Seattle, 1996), American Nuclear Society, La Grange Park, IL (1996) 1815–1820.

[339] US DEPARTMENT OF ENERGY, CP-5 Large Scale Demonstration Project, Advance Recyclable Media System Decontamination, Technology Demonstration Summary Sheet, USDOE, Washington, DC (1997).

[340] AEA TECHNOLOGY ENGINEERING SERVICES, Sponge Abrasive Decontamination Information Package, company brochure, AEA Technology Engineering Services, Pittsburgh, PA.

[341] BEINSTEIN, R.M., Compilation of Sponge Jet Use in Radiological Decontamination Applications, internal report, 30 Sept. 1997 Sponge-Jet, Eliot, ME (1997).

[342] ARCHIBALD, K.E., CO_2 Pellet Blasting Studies, Rep. INEL/EXT-97-00117, Jan. 1997, Idaho National Engineering Laboratory, Idaho Falls, ID (1997).

[343] EG&G IDAHO, Cryogenic Cutting System Demonstration, http://www.pnl.gov/WEBTECH/bwid/cryojet.htm.

[344] SCOTT, S.M., et al., "Decontamination of the jet vacuum vessel using the CO_2 pellet blasting (cold jet) technique", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[345] GILLIS, P., "Radwaste cost savings and mixed waste volume reduction achieved with CO_2 decontamination — Actual utility history", Waste Management '94 (Proc. Int. Conf. Tucson, 1994), Waste Management Symposia, Tucson, AZ (1994).

[346] AKIYAMA, T., et al., "Decontamination and modification of alpha-gamma hot cell in the materials monitoring facility", Nuclear Engineering (Proc. 3rd JSME/ASME Joint

Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1829–1834.

[347] FISHER, P.W., FOSTER, C.A., “Centrifugal cryoblaster for decommissioning and decontamination”, Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[348] VANKERCKHOVEN, P., Carbon dioxide blasting in Europe (an innovative way for decommissioning), Nucl. Eng. Int. **40** 488 (1995) 43–45.

[349] Canada: Freon-free washing, Nucleonics Week, 4 May (1995).

[350] RAMACHANDRAN, N., “Technology used in the cleanup of a difficult-to-remediate facility”, SPECTRUM ’96: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Seattle, 1996), American Nuclear Society, La Grange Park, IL (1996) 1974–1976.

[351] BARTHOLOMEW, P., MILLER, K., The decommissioning of the UKAEA’s SGHWR ponds, Nucl. Eng. **38** 1 (1997) 23–25.

[352] McINTYRE, P.J., “Decommissioning of Berkeley power station”, Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 1, Société française d’énergie nucléaire, Paris (1998) 170–178.

[353] BRANDT, C., et al., “Abrasive water suspension jets for nuclear decommissioning — Final investigations for the first application”, American Waterjet Conference (Proc. 9th Conf. Dearborn, 1997), 2 vols, Waterjet Technology Association, St. Louis (1997) 657–671.

[354] EUROPEAN COMMISSION, Abrasive Water Jet Cutting Technique from the Stage of Laboratory into Real Application, Rep. EUR 15241, Office for Official Publications of the European Communities, Luxembourg (1995).

[355] BOND, R., MAKAI, J., “Removal of compensator coating at Paks nuclear power plant, Hungary”, Jetting Technology (Proc. 13th Int. Conf. Cagliari, 1996), (GEE, C., Ed.), Mechanical Engineering Publications, London (1996).

[356] MASSAUT, V., TEUNCKENS, L., “The waste flow management during decommissioning: The Belgian approach”, SPECTRUM ’98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998).

[357] US DEPARTMENT OF ENERGY, Concrete Grinder, June 1998, http://www.bhi-erc.com/Creactor/final.htm.

[358] US DEPARTMENT OF ENERGY, Concrete Shaver, June 1998, http://www.bhi-erc.com/Creactor/facts.htm.

[359] US DEPARTMENT OF ENERGY, Centrifugal Shot Blast System, Rep. DOE/EM-0346, Feb. 1998, http://em-52.em.doe/ifd/d&d/itsrs/centr/begining.htm.

[360] DORR, K.A., et al., “Decontamination and decommissioning of Building 889 at the Rocky Flats environmental technology site, Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 201.

[361] VALENCIA, L., “The experience gained from the decommissioning of the Niederaichbach nuclear power plant”, Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1725–1732.

[362] BOSSART, S.J., "Technology demonstrations in the decontamination and decommissioning focus area", The Best D&D... Creative, Comprehensive and Cost-Effective (Proc. Topical Mtg Chicago, 1996), American Nuclear Society, La Grange Park, IL (1996) 73–77.

[363] US DEPARTMENT OF ENERGY, ROTOPEEN Scaler and VAC-PAC® System, Rep. DOE/EM-0343, Feb. 1998, http://em-52.em.doe.gov/ifd/d&d/itsrs/roto/begining.htm.

[364] LIKAR, F.V., HOWARD, G.T., Decommissioning of Fort St. Vrain, Radwaste Mag. **2** 5 (1995) 54–60.

[365] US DEPARTMENT OF ENERGY, Rotary Peening with Captive Shot, Rep. DOE/EM-0344, Feb. 1998, http://em-52.em.doe.gov/ifd/d&d/itsrs/rotpen/begining.htm.

[366] US DEPARTMENT OF ENERGY, Concrete Spaller, Dec. 1998, http://em-52em.doe.gov/ifd/ddfa/itsrs/spaller2/spaller.pdf.

[367] AULER, I., "Lessons learned from dismantling of Niederaichbach power plant", Decommissioning Experience in Europe (Proc. Eur. Comm. Workshop, 1996), Rep. EUR 16900, Office for Official Publications of the European Communities, Luxembourg (1996).

[368] LEUCHTE, H.W., et al., "Development and optimization of an easy-to-process electrolyte for electrochemical decontamination of stainless steel components", Decommissioning of Nuclear Installations (Proc. Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 336–345.

[369] BROWN, M.H., "Development of telerobotic decommissioning systems", Decommissioning Experience in Europe (Proc. Eur. Commun. Workshop, 1996), Rep. EUR 16900, Office for Official Publications of the European Communities, Luxembourg (1996).

[370] EUROPEAN COMMISSION, Telerobotic Monitoring, Decontamination and Size-Reduction System, Final Report, Rep. EUR 16903, Office for Official Publications of the European Communities, Luxembourg (1996).

[371] EICKELPASCH, N., et al., "Techniques for the dismantling of the NPPs Gundremmingen, Unit A (KRB) and Versuchsatomkraftwerk Kahl (VAK)", The Best D&D... Creative, Comprehensive and Cost-Effective (Proc. Topical Mtg Chicago, 1996), American Nuclear Society, La Grange Park, IL (1996) 200–208.

[372] COSTES, J.R., et al., "Development of an electroetching decontamination facility and application to alpha-bearing waste from the 'RM2' installation", Decommissioning of Nuclear Installations (Proc. Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 365–367.

[373] AMPELOGOVA, N.I., et al., Development of Electrochemical Decontamination Methods in Nuclear Engineering: Review, CSRIatominform, Moscow (1987) (in Russian).

[374] STEINER, H., "The KRB-A boiling water reactor pilot dismantling project", Decommissioning of Nuclear Installations (Eur. Comm. Course Ispra, 1993), European Commission, Luxembourg (1993) (unpublished report).

[375] EICKELPASCH, N., et al., "Overview on the decommissioning of the KRB nuclear plant, Unit A, with special consideration of waste minimization and scrap recycling", Practical Decommissioning Experience with Nuclear Installations in the European Community (Proc. 3rd Sem. Gunzburg, 1992), Rep. EUR 14879, Office for Official Publications of the European Communities, Luxembourg (1993).

[376] EICKELPASCH, N., et al., "Pilot dismantling of the KRB A boiling water reactor", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 47–59.
[377] STEINER, H., et al., "Pilot dismantling of the KRB boiling water reactor", Decommissioning Experience in Europe (Proc. Eur. Comm. Workshop, 1996), Rep. EUR 16900, Office for Official Publications of the European Communities, Luxembourg (1996).
[378] WEI, T.U., et al., "Experience with electrodecontamination to reduce the surface contaminated metal at INER", ICONE-4: Nuclear Enginnering (Proc. 4th JSME/ASME Joint Int. Conf. New Orleans, 1996), American Society of Mechanical Engineers, New York (1996) 145–156.
[379] WEDMAN, D.E., et al., "Electrochemical decontamination system for actinide processing gloveboxes", Waste Management '98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).
[380] YASUNAKA, H., KOZAKI, T., GORAI, T., "Decontamination technology for decommissioning of nuclear facilities", Residual Radioactivity and Recycling Criteria (Proc. Workshop St. Michaels, 1989), Rep. EPA 520/1-90-013, US Environmental Protection Agency, Washington, DC (1989) 62–89.
[381] BRANDAU, E., SOLLY, F., PHILP, D., "Electrolytical decontamination — An old process with new approaches", KONTEC '97: Conditioning of Radioactive Operational and Decommissioning Waste (Proc. 3rd Symp. Hamburg, 1997), Kontec Gesellschaft für technische Kommunikation mbH, Glinde (1997) 944–946.
[382] BREGANI, F., et al., "Decontamination of complex components using ultrasounds and flowing chemicals", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 317–325.
[383] PINACCI, P., et al., "Decontamination of complex components using ultrasounds and aggressive chemicals", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).
[384] GORODINSKY, S.M., GOLDSHTAIN, D.S., Decontamination of Polymeric Materials, 2nd edn, Energoizdat, Moscow (1981) (in Russian).
[385] DESROSIERS, A.E., et al., "Ultrasonic cleaning of effluent gas filters", Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 495.
[386] FLESHER, D.J., MILLER, R.D., "Light aided decontamination 1996 (LAD)", Surface Cleaning, Cutting and Welding with Light: A "NOW" Technology, Rep. WHC-SA-3110-S, Westinghouse Hanford, Richland, WA (1996).
[387] US DEPARTMENT OF ENERGY, Starboldt™ Flashlamp Decontamination, CP-5 Large-Scale Demonstration Project, Technology Demonstration Summary Sheet, USDOE, Washington, DC (1997).
[388] CASE, R.P., FREIWALD, D.A., PEEBLES, H.C., "Laser ablation of containments from concrete and metal surfaces", SPECTRUM '98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 124–131.

[389] COSTES, J.R., et al., "Decontamination by ultraviolet laser: The Lexdin Prototype", SPECTRUM '96: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Seattle, 1996), American Nuclear Society, La Grange Park, IL (1996) 1760–1764.

[390] MYODO, M., et al., "Outline and progress of the JRTF decommissioning program", Waste Management '98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).

[391] MORISHITA, Y., et al., "Current R&D status of decommissioning technologies for nuclear fuel cycle facilities in PNC", ICONE-5: Nuclear Engineering (Proc. Int. Conf. Nice, 1997), American Society of Mechanical Engineers, New York (1997).

[392] WHITE, T.L., et al., "Phase II microwave concrete decontamination results", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[393] CORLETO, P., et al., "Microwave system for removal of concrete surface layers", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 326–335.

[394] FLEISCHER, C.C., "Concrete dismantling experience at LIDO", Decommissioning Experience in Europe (Proc. Eur. Comm. Workshop, 1996), Rep. EUR 16900, Office for Official Publications of the European Communities, Luxembourg (1996).

[395] COMMISSION OF THE EUROPEAN COMMUNITIES, Décontamination du béton par fusion superficielle à l'aide d'un nouveau brûleur associé à un plasma, Rep. EUR 12489, Office for Official Publications of the European Communities, Luxembourg (1989) (in French).

[396] HAMILTON, M.A., et al., "Biodecontamination: Costs benefit analysis of a novel approach for decontamination of massive concrete structures", Nuclear Decommissioning '98 (Proc. Int. Conf. London, 1998), Professional Engineering Publishing, London (1998) 123–130.

[397] HAMILTON, M.A., et al., "Biodecontamination of concrete", SPECTRUM '96: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Seattle, 1996), American Nuclear Society, La Grange Park, IL (1996) 1977–1983.

[398] JOHNSON, L., et al., "Biodecontamination of concrete surfaces: Occupational and environmental benefits", Waste Management '97 (Proc. Int. Conf. Tucson, 1997), Waste Management Symposia, Tucson, AZ (1997).

[399] ROGERS, R.D., et al., "Microbially influenced degradation: A new innovative technology for the decontamination of radioactively contaminated concrete", Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 469.

[400] LOMASNEY, H.L., LOMASNEY, C.A., "Electrokinetic applications for environmental restoration, waste volume reduction, and contaminant systems", ICONE-4: Nuclear Engineering (Proc. 4th JSME/ASME Joint Int. Conf. New Orleans, 1996), American Society of Mechanical Engineers, New York (1996) 157–162.

[401] MORGAN, I.L., et al., "Electrokinetic decontamination of concrete", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994) US Dept of Energy, Washington, DC (1994).

[402] HARRIS, M.T., DE PAOLI, D.W., ALLY, M.R., “Modeling the electrokinetic decontamination of concrete”, Separation Science and Technology for Energy Applications (Proc. 9th Symp. Gatlinburg, 1995), Marcel Dekker, New York (1997).

[403] SOBOLEV, I.A., et al., “Thermochemical decontamination of metallic surfaces”, Waste Management ’97 (Proc. Int. Conf. Tucson, 1997), Waste Management Symposia, Tucson, AZ (1997).

[404] KARLINA, O.K., et al., “Decontamination of different materials by using exothermic metallic compositions”, KONTEC ’97: Conditioning of Radioactive Operational and Decommissioning Waste (Proc. 3rd Symp. Hamburg, 1997), Kontec Gesellschaft für technische Kommunikation mbH, Glinde (1997) 526–529.

[405] KARLINA, O.K., OVCHINNIKOV, A.B., PETROV, A.I., “Radioactive contaminated asphalt concrete surfaces decontamination”, Radiological Security of Modern Civilization: Socio-Cultural Approaches, Information Technologies, Economic Structures (1st Int. Scientific Practical Conf. Moscow, 1995), Enomar, Moscow (1995) 219–223.

[406] BABAIN, V., et al., “Supercritical fluid extraction of uranium, plutonium and neptunium oxides”, Supercritical Fluid Materials and Natural Products Processing (Proc. 5th Mtg Nice, 1998), 2 vols, Institut National Polytechnique de Lorraine, Nancy (1998) 791–796.

[407] MURZIN, A., et al., “Supercritical fluid extraction of uranium, transuranics and rare earth elements from solid surfaces”, Supercritical Fluid Materials and Natural Products Processing (Proc. 5th Mtg Nice, 1998), 2 vols, Institut National Polytechnique de Lorraine, Nancy (1998) 155–160.

[408] SHADRIN, A., et al., “Decontamination of real world contaminated stainless steel using supercritical CO_2”, SPECTRUM ’98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 94–99.

[409] BUNDY, R.D., et al., “Gas phase decontamination of gaseous diffusion process equipment”, Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[410] INTERNATIONAL ATOMIC ENERGY AGENCY, Technologies for Remediation of Radioactively Contaminated Sites, IAEA-TECDOC-1086, Vienna (in preparation).

[411] EUROPEAN COMMISSION, Optimal Management Routes for the Restoration of Territories Contaminated During and After the Chernobyl Accident, Rep. EUR 17627, Office for Official Publications of the European Communities, Luxembourg (1997).

[412] SOBOLEV, I.A., et al., “The use of biotechnology in the treatment of radioactive waste”, Radiological Security of Modern Civilization: Socio-Cultural Approaches, Information Technologies, Economic Structures (1st Int. Scientific Practical Conf. Moscow, 1995), Enomar, Moscow (1995) 203–206.

[413] SANDFORD, W., et al., “Decommissioning nuclear piping systems: Selecting the right cutting technique”, SPECTRUM ’98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 154–157.

[414] PILOT, G., et al., “Evaluation of steel cutting techniques”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 218–226.

[415] DUFAYET, J.P., et al., "Underwater thermal cutting techniques and associated remote-controlled manipulator systems", Decommissioning of Nuclear Installations, (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 227–238.
[416] ISHIGURE, K., et al., "Verification tests of decommissioning technology for commercial nuclear power facilities in Japan", SPECTRUM '90: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Knoxville, 1990), American Nuclear Society, La Grange Park, IL (1990) 378–383.
[417] MIWA, T., et al., "Progress of verification tests on decommissioning technology for commercial nuclear power plants in Japan", SPECTRUM '92: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Boise, 1992), American Nuclear Society, La Grange Park, IL (1992) 1349–1354.
[418] BACH, F.W., LINDMAIER, J., "State of the art of thermal and hydraulic cutting techniques for decommissioning tasks in the nuclear industry", Waste Management '98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).
[419] GESTERMANN, G., FOCKE, J., SANDER, H., "Cutting and conditioning of large components from boiling water reactors by hydraulic shears", KONTEC '97: Conditioning of Radioactive Operational and Decommissioning Waste (Proc. 3rd Symp. Hamburg, 1997), Kontec Gesellschaft für technische Kommunikation mbH, Glinde (1997) 430–431.
[420] SCHWALD, P., et al., Erfahrungen aus dem Abbau des KKN unter besonderer Berücksichtigung der Entlassung der Anlage aus der atomrechtlichen Bindung, IV. Stillegungskolloquium Hannover, Nov. 1995, Tagungsband, BMBF, Bonn (in German).
[421] STEINER, H., Zerlege- und Dekontaminationsverfahren bei der Stillegung der Siedewasserreaktoren KRB-A und VAK Kahl, V. Stillegungskolloquium Hannover, June 1997, Tagungsband, BMBF, Bonn (in German).
[422] HENDRICH, K., et al., Fernbediente Demontage der WAK — Konzepte und Erfahrungen, V. Stillegungskolloquium Hannover, June 1997, Tagungsband, BMBF, Bonn (in German).
[423] WARREN, S., et al., "Technology application for surplus facility decommissioning under US Department of Energy's environmental restoration program", Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1683–1688.
[424] LUNDBY, J.E., Decommissioning of a Uranium Reprocessing Plant — Practical Experiences, Final Report Research Project NKS/KAN-1.2, Rep. NEI-DK-1747, TemaNord **594** (1994).
[425] HAFERKAMP, D., Techniken zur Zerlegung von aktivierten und hochkontaminierten Reaktorbauteilen, III. Stillegungskolloquium Hannover, Greifswald, Sept. 1993, Tagungsband (in German).
[426] HAFERKAMP, D., Gesichtspunkte zur Auswahl von Zerlegeverfahren für die Demontage von Reaktorbehältern und deren Einbauten, IV. Stillegungskolloquium Hannover, Nov. 1995, Tagungsband, BMBF, Bonn (in German).
[427] US DEPARTMENT OF ENERGY, Self Contained Pipe Cutting Shear, Feb. 1998, http://www.bhi-erc.com/Creactor/final.htm.

[428] ARNOLD, H.-U., KALWA, H., “Testing of segmenting and remote dismantling techniques on the pressure vessel and internals of the VAK experimental BWR”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 509–518.
[429] ARNOLD, H-V., “Selected German experiences with dismantling techniques”, Nuclear Decommissioning ’98 (Proc. Int. Conf. London, 1998), Professional Engineering Publishing, London (1998) 131–143.
[430] EICKELPASCH, N., et al., “Decommissioning projects in KRB A and VAK”, Waste Management ’98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).
[431] BROWN, M.H., ASQUITH, J.D., “Cost reduction in size reduction — The benefits of robotic technology”, X-Change ’97: The Global D&D Marketplace (Proc. Conf. Miami, 1997), Hemispheric Center for Environmental Technology, Miami, FL (1998).
[432] SMITH, D., Hands-on glovebox decommissioning, Nucl Eng. **38** 5 (1997).
[433] PILOT, G., et al., “Dismantling: Comparative tests on five cutting tools”, ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1751–1756.
[434] EUROPEAN COMMISSION, Improving Underwater Thermal Cutting Techniques and Associated Remote-Control Systems, Rep. EUR 16607, Office for Official Publications of the European Communities, Luxembourg (1995).
[435] DEMEULEMEESTER, M.E., MASSAUT, V., LEFEBVRE, A., “The use of mechanical cutting techniques in the decommissioning of highly radioactive reactor internals”, ICONE-5: Nuclear Engineering (Proc. 5th Int. Conf. Nice, 1997), American Society of Mechanical Engineers, New York (1997).
[436] MASSAUT, V., et al., “The design, construction and deployment of a large underwater bandsaw for decommissioned LWR internals dismantling”, Remote Techniques for Hazardous Environments (Proc. Int. Conf. Leicestershire, 1996), Thomas Telford, London (1996).
[437] YANAGIHARA, S., SEIKI, Y., NAKAMURA, H., Dismantling techniques for reactor vessel structures, Nucl. Technol. **86** Aug. (1989).
[438] FUJIKI, K., et al., “Techniques and experiences in decommissioning of Japan power demonstration reactor”, Dismantling of Nuclear Facilities (Proc. Int. Conf. Avignon, 1992), Société française d’énergie nucléaire, Paris (1992) 219–232.
[439] MASSAUT, V., “Remote handling experience in the BR3 dismantling project”, paper presented at IEEE Int. Conf. on Robotics and Automation, Leuven, 1998.
[440] US DEPARTMENT OF ENERGY, High Speed Clamshell Pipe Cutter, Mar. 1998, http://www.bhi-erc.com/Creactor/facts.htm.
[441] JAPAN ATOMIC ENERGY RESEARCH INSTITUTE, Reactor Decommissioning Technology Development and Actual Dismantling of JPDR, Tokai Research Establishment, Tokai (1990).
[442] MOMMA, T., “Dismantling of piping by shaped explosives and the rotary disk knife”, Decommissioning of Nuclear Facilities (2nd JAERI Workshop, 1991), internal report, Tokai Research Establishment, Tokai (1991).

[443] HOSHI, T., et al., “Decommissioning experience of the Japan power demonstration reactor”, NUCLEAR DECOM ’92 (Proc. Int. Conf. London, 1992), Mechanical Engineering Publications, London (1992) 157–162.
[444] DEMANT, W., et al., Stand der Stillegungsaktivitäten des Mehrzweck-forschungsreaktors (MZFR) Karlsruhe, IV. Stillegungskolloquium Hannover, Nov. 1995, Tagungsband, BMBF, Bonn (in German).
[445] SLOAN, P., “Pilot dismantling of the Windscale advanced gas-cooled reactor”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 19–31.
[446] VALENCIA, L., PRECHTL, E., “Back to the ‘green field’ — The experience and the results gained from the decommissioning of the Niederaichbach power plant (KKN)”, The Best D&D... Creative, Comprehensive and Cost-Effective (Proc. Topical Mtg Chicago, 1996), American Nuclear Society, La Grange Park, IL (1996) 192–198.
[447] LIKAR, V.F., “Decommissioning of Fort St. Vrain”, ICONE-4: Nuclear Engineering (Proc. 4th JSME/ASME Joint Int. Conf. New Orleans, 1996), American Society of Mechanical Engineers, New York (1996) 81–88.
[448] BOING, L.E., et al., An Evaluation of Alternative Reactor Vessel Cutting Technologies for the Experimental Boiling Water Reactor at Argonne National Laboratory, Rep. ANL-89/31, Argonne Natl Laboratory, Argonne, IL (1989).
[449] CRAIG, K.A., BOING, L.E., “An evaluation of alternative concrete cutting techniques for massive concrete structures’’, Decommissioning, Decontamination, and Environmental Restoration at Contaminated Nuclear Sites (Proc. Conf. Washington, DC, 1994), American Nuclear Society, La Grange Park, IL (1994) 133–137.
[450] MANDRY, G.J., BECKER, C.L., “Demolition of the waste evaporator facility at Oak Ridge National Laboratory”, Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 229.
[451] BRAZIER, P., “The decommissioning of the NRX stack”, Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).
[452] CROSS, M.T., et al., “Progress in the development of tooling and dismantling methodologies for the Windscale advanced gas-cooled reactor (WAGR)”, Waste Management ’98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).
[453] US DEPARTMENT OF ENERGY, Liquid Nitrogen-Cooled Diamond-Wire Concrete Cutter, May 1998 (draft), http://www.bhi-erc.com/Creactor/facts.htm.
[454] HASEGAWA, H., et al., “Application of the wire sawing method to the decommissioning of nuclear power plant — Cutting test with turbine pedestal of thermal power plant”, ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1757–1762.
[455] MIYAO, H., et al., “Cutting techniques of reinforced concrete by wire sawing”, ICONE-5: Nuclear Engineering (Proc. 5th Int. Conf. Nice, 1997), American Society of Mechanical Engineers, New York (1997).

[456] VALENCIA, L., PRECHTL, E., Die Demontage und Beseitigung des Kernkraftwerks Niederaichbach (KKN), IV. Stillegungskolloquium Hannover, Nov. 1995, Tagungsband, BMBF, Bonn (in German).

[457] GRABENSTÄTTER, K., Die Beseitigung des Heissdampfreaktors (HDR), II. Stillegungskolloquium Hannover, Nov. 1992, Tagungsband (in German).

[458] NAKAMURA, H., et al., Cutting technique and system for biological shield, Nucl. Technol. **86** Aug. (1989).

[459] TANAKA, H., YAMASHITA, Y., "Dismantling of the biological shield concrete by diamond sawing/coring technique", Decommissioning of Nuclear Facilities (2nd JAERI Workshop, 1991), internal report, Tokai Research Establishment, Tokai (1991).

[460] YANAGIHARA, S., "Experience of dismantling and technology development in the Japan power demonstration reactor decommissioning program", Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 1, Société française d'énergie nucléaire, Paris (1998) 170–178.

[461] MIYAZAWA, M., et al., "Technical verification test for dismantling the surface layer of biological shield by using large circular saw and wedge technique", SPECTRUM '90: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Knoxville, 1990), American Nuclear Society, La Grange Park, IL (1990).

[462] ENGLAND, M.R., et al., Decommissioning and delicensing of the Universities research reactor, Nucl. Energy **36** 6 (1997) 411–416.

[463] ISHIDA, M., et al., "Dismantling the Japan power demonstration reactor's biological shield by controlled blasting", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[464] KOZAWA, K., et al., "Progress of the Japan power demonstration reactor (JPDR) dismantling activities — Dismantling of the biological shield", ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1707–1712.

[465] FREUND, H.-U., FLEISCHER, C.C., "Demonstration of explosive dismantling techniques on KKN Niederaichbach and LIDO biological shields", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 101–118.

[466] INNS, A., LANGLEY, K., "Decommissioning three minor nuclear facilities at Harwell to green field sites", Decommissioning of Nuclear Facilities (Proc. 5th Int. Conf. London, 1997), IBC Technical Services, London (1997).

[467] KLEIN, M., et al., "Contaminated and activated concrete: Characterization, decontamination and demolition techniques", SPECTRUM '98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998).

[468] ROUSSEAU, A., KLEIN, M., Techniques avancées de demolition et de fragmentation de bétons armés, Rapport de Synthèse (in French), Convention IRSIA Rep. No. 0147, CSTC-WTCB, July 1994, internal report, Institut pour l'encouragement de la recherche scientifique dans l'industrie et l'agriculture, Brussels (1994).

[469] IMBARD, G., et al., "Cutting of CO_2 primary circuit pipes of G2/G3 using explosive charges", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg,

1994), Office for Official Publications of the European Communities, Luxembourg (1995) 199–206.

[470] PAZIENZA, G., “Investigations of explosives and techniques for cutting and decontamination of metallic nuclear components”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 207–217.

[471] FLEISCHER, C.C., “Controlled use of explosive techniques in the decommissioning of nuclear facilities’’, Decommissioning and Demolition 1990: Decommissioning Offshore, Onshore Demolition and Nuclear Works (Proc. Conf. Manchester, 1990), Thomas Telford, London (1990) 58.

[472] BINNER, W., Early dismantling of retired reactor pressure vessels, Trans. Am. Nucl. Soc. **71** (1994) 659-661.

[473] WHITE, S.J., PARKER, R., “Development of a plasma arc torch and control/monitoring technique for the internal cutting of small bore pipework”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 239–255.

[474] TRATT, J.H., “The Windscale advanced gas-cooled reactor (WAGR) decommissioning project”, Decommissioning Experience in Europe (Proc. Eur. Comm. Workshop, 1996), Rep. EUR 16900, Office for Official Publications of the European Communities, Luxembourg (1996).

[475] HARDEY, G., “Decommissioning of the dry granulation plant using machine assistance”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 127–134.

[476] HICKEY, H.B., “Experience in developing processes and equipment for the dismantling of the Windscale gas cooled reactor”, Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 2, Société française d’énergie nucléaire, Paris (1998) 497–507.

[477] PILOT, G., et al., “Underwater dismantling thermal cutting tools measurement of secondary wastes”, ICONE-4: Nuclear Engineering (Proc. 4th JSME/ASME Joint Int. Conf. New Orleans, 1996), American Society of Mechanical Engineers, New York (1996) 163–172.

[478] JAPAN ATOMIC ENERGY RESEARCH INSTITUTE, JPDR Workshop, internal report, 3 vols, Feb. 1988, JAERI, Tokyo (1988).

[479] MIKI, I., SHIMURA, T., “Dismantling of the JPDR internals by the underwater plasma arc cutting technique”, Decommissioning of Nuclear Facilities (2nd JAERI Workshop, 1991), internal report, Tokai Research Establishment, Tokai (1991).

[480] YANAGIHARA, S., et al., “The Japan power demonstration reactor decommissioning program — Experience and data analysis on dismantling procedures”, Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[481] ELECTRIC POWER RESEARCH INSTITUTE, The Cleanup of Three Mile Island Unit 2 — A Technical History: 1979 to 1990, Rep. EPRI - NP-6931, EPRI, Palo Alto, CA (1990).

[482] COMMISSION OF THE EUROPEAN COMMUNITIES, Dross and Ultrafine Particulate Formation in Underwater Plasma Arc Cutting, Rep. EUR 13798, Office for Official Publications of the European Communities, Luxembourg (1991).

[483] BACH, W., LINDEMAIER, J., “State of the art of thermal and hydraulic cutting techniques for decommissioning tasks in nuclear industry”, Waste Management ’98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).

[484] GEZELMAN, J., Oxygasoline torch cuts demolition time of nuclear test facility, Weld. J. Apr. (1993) 81–83.

[485] BACH, F.-W., “Technologies for cutting and demolishing of research reactors”, paper presented at IAEA Regional Training Course on Decommissioning of Research Reactors and Other Small Nuclear Facilities, Bucharest, 1997.

[486] ISHIGURE, K., et al., “Development of decommissioning technology for commercial nuclear power plants in Japan”, Decommissioning Policies for Nuclear Facilities (Proc. OECD/NEA Int. Sem. Paris, 1991), OECD, Paris (1992) 77–86.

[487] CHILD, C.L., “Removal of the Yankee pressure vessel — Diary of a work in progress”, ICONE-4: Nuclear Engineering (Proc. 4th JSME/ASME Joint Int. Conf. New Orleans, 1996), American Society of Mechanical Engineers, New York (1996) 95–100.

[488] US DEPARTMENT OF ENERGY, Fernald Plant 1 Large Scale Technology Demonstration Project, Oxy-Gasoline Cutting Torch, Feb. 1997, USDOE, Washington, DC (1997).

[489] SNEDAKER, W.H., KRAUSE, D.R., PETERS, M.S., “Dismantlement using the innovative oxy-gasoline cutting torch”, SPECTRUM ’98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 158–165.

[490] UOZUMI, H., et al., “Technical verification test for reactor pressure vessel cutting by using G&G method (arc gouging + gas cutting method)’’, SPECTRUM ’90: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Knoxville, 1990), American Nuclear Society, La Grange Park, IL (1990) 384–386.

[491] KAWAHARA, W., et al., “Technical verification test for reactor pressure vessel cutting by using G&G method (arc gouging + gas cutting method)”, ICONE-1: Nuclear Engineering (Proc. 1st JSME/ASME Joint Int. Conf. Tokyo, 1991), Japan Society of Mechanical Engineers, Tokyo (1991).

[492] BISHOP, A., “Ventilation and filtration techniques for handling aerosols produced by thermal cutting operations”, Decommissioning of Nuclear Installations (Proc. Int. Conf. Brussels, 1989), Office for Official Publications of the European Communities, Luxembourg (1990) 627–638.

[493] SATOH, F., YOKOTA, M., “Dismantling of the biological shield concrete by the abrasive water jet cutting technique”, Decommissioning of Nuclear Facilities (2nd JAERI Workshop, 1991), internal report, Tokai Research Establishment, Tokai (1991).

[494] YOKOTA, I., et al., “Dismantling the Japan power demonstration reactor’s biological shield using abrasive water jet cutting system”, Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[495] LOUIS, H., et al., “Abrasive water jet cutting”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 169–180.

[496] MURPHIE, W.E., "An overview of the United States' decommissioning programme with selected examples of current technology and environmental compliance", NUCLEAR DECOM '92 (Proc. Int. Conf. London, 1992), Mechanical Engineering Publications, London (1992) 9–16.

[497] EICKELPASCH, N., et al., WASS-Schneiden bei der Stillegung des VAK, Atw. Atomwirtsch. Atomtech. **43** 5 (1998).

[498] BRANDT, C., et al., "Further developments of abrasive water jets for decommissioning applications", Decommissioning Experience in Europe (Proc. Eur. Comm. Workshop, 1996), Rep. EUR 16900, Office for Official Publications of the European Communities, Luxembourg (1996).

[499] ELCO INTERNATIONAL, Darda Hydraulic Rock Concrete Splitter, Dec. 1996, http://www.elco.com.

[500] MCGOUGH, M.S., Electric discharge and metal disintegration machining makes the cut, Weld. J. July (1989) 36–39.

[501] LITKA, T.J., "Electrical discharge and metal disintegration machining for nuclear vessel sample removal", Pressure Vessels and Piping Conference (Proc. Conf. Minneapolis, 1994), PVP-Vol. 278, American Society of Mechanical Engineers, New York (1994) 133–135.

[502] LITKA, T.J., "An overview of reactor vessel internals segmentation for nuclear plant decommissioning", American Power (Proc. Conf. Chicago, 1994), Illinois Institute of Technology, Chicago, IL (1994) 1448–1451.

[503] CHILD, C.L., MCGOUGH, M.S., SMITH, G., Segmentation of the Yankee reactor internals, Nucl. Plant J. Sept./Oct. (1995).

[504] YOKOTA, M., ISHIKAWA, H., Underwater arc saw get to work on the vessel at Japan's JPDR, Nucl. Eng. Int. **35** 434 (1990) 35–36.

[505] TACHIBANA, M., et al., "Dismantling of the reactor pressure vessel by the underwater arc saw cutting technique", Decommissioning of Nuclear Facilities (2nd JAERI Workshop, 1991) internal report, Tokai Research Establishment, Tokai (1991).

[506] ZAWTECH, ZAWCAD Cryogenic Liquid Jet System, company brochure, Zawtech, Duluth, GA (1998).

[507] COMMISSION OF THE EUROPEAN COMMUNITIES, Investigation of Specific Applications of Laser Cutting for Dismantling of Nuclear Power Plants, Rep. EUR 12947, Office for Official Publications of the European Communities, Luxembourg, (1990).

[508] MEGAW, J.H.P.C., et al., "Assessment of CO laser technology as an improved dismantling tool", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 181–189.

[509] ALFILLE, J.P,. et al., "Underwater laser cutting of metal structures", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 190–198.

[510] TAKANO, G., et al., "Development of cutting technique of reactor core internals by CO laser", ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1775–1778.

[511] EUROPEAN COMMISSION, Assessment of State-of-the-Art CO Laser Technologies as an Improved Dismantling Tool, Rep. EUR 15649, Office for Official Publications of the European Communities, Luxembourg (1994).

[512] MATSUMOTO, O., et al., "Cutting technique for reactor internals by laser beam", SPECTRUM '90: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Knoxville, 1990), American Nuclear Society, La Grange Park, IL (1990) 387–389.

[513] MIYA, K., et al., "Development of laser cutting technique to reactor core internals", Dismantling of Nuclear Facilities (Proc. Int. Conf. Avignon, 1992), Société française d'énergie nucléaire, Paris (1992).

[514] YASUDA, K., et al., "Study on material processing of chemical iodine laser", ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1769–1774.

[515] TSURUMAKI, K., et al., "Development of remote dismantling of components in nuclear reactor with laser transmitted through optical fiber", ICONE-5: Nuclear Engineering (Proc. 5th Int. Conf. Nice, 1997), American Society of Mechanical Engineers, New York (1997).

[516] EUROPEAN COMMISSION, Application des procédés lasers CO_2 et YAG à la découpe dans l'air et sous eau de structures métalliques, Rep. EUR 16854, Office for Official Publications of the European Communities, Luxembourg (1996) (in French).

[517] ALFILLE, J.P., PILOT E., "Thick cutting of metallic material for nuclear dismantling applications with pulsed YAG laser", ICONE-5: Nuclear Engineering (Proc. 5th Int. Conf. Nice, 1997), American Society of Mechanical Engineers, New York (1997).

[518] SHAH, S.N., HARDY, R.B., KNEFF, D.W., "Remote laser processing of radioactive components at the energy Technology Engineering Centre (ETEC)", Waste Management '98: (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).

[519] COMMISSION OF THE EUROPEAN COMMUNITIES, Télé-usinage par laser pour site nucléaire en cours de déclassement (Programme ROLD), Rep. EUR 14497, Office for Official Publications of the European Communities, Luxembourg (1993) (in French).

[520] WITTRIDGE, S., "Solid low level waste and minimization in the nuclear industry: Supercompaction — Volume reduction process and experience", paper presented at British Nuclear Energy Society Sem., 18 May 1995.

[521] HEKI, H., et al., "Decommissioning waste processing system", SPECTRUM '90: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Knoxville, 1990), American Nuclear Society, La Grange Park, IL (1990) 285–287.

[522] OLEINIK, M.S., TROFIMOV, V.V., SHUISKY, D.B., "Conditioning of heat insulation waste contaminated by radionuclides", Radiation Safety Management '97 (Proc. Int. Symp. Taejon, 1997), Korea Electric Power Research Institute, Seoul (1997) 93–102.

[523] GUSYNIN, V.D., et al., "Recovery of metal radioactive waste", Radiation Safety Management '97 (Proc. Int. Symp. Taejon, 1997), Korea Electric Power Research Institute, Seoul (1997) 75–80.

[524] ISMAGILOV, Z.R., et al., "Development of new treatment technology for mixed organic radioactive waste", Radiation Safety Management '97 (Proc. Int. Symp. Taejon, 1997), Korea Electric Power Research Institute, Seoul (1997) 346–355.

[525] SOBOLEV, I.A., et al., SIA ‘Radon’ Experience in Radioactive Waste Vitrification, Enomar, Moscow (1996) (in Russian).
[526] BEREGKO, B.I., et al., Radioactive metal wastes utilisation by remelting, Mater. Technol. Questions, **2** 8 (1995) 74–77 (in Russian).
[527] SOBOLEV, I.A., “Management of non-nuclear radioactive wastes in the Russian Federation”, The 50th Anniversary of Russian Nuclear Science and Engineering (Proc. Jubilee Scientific Practical Conf. Moscow, 1995), (BABAEV, N.S., Ed.) Minatom, Moscow (1996) 210–221 (in Russian).
[528] POLJAKOV, A.S., “Management of irradiated nuclear materials and radioactive wastes”, The 50th Anniversary of Russian Nuclear Science and Engineering (Proc. Jubilee Scientific Practical Conf. Moscow, 1995), (BABAEV, N.S., Ed.) Minatom, Moscow (1996) 222–245 (in Russian).
[529] CLEMENTS, D.W., “Decontamination and melting of low level waste — A complete environmental package”, Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 371–380.
[530] AULER, L., ROJAHN, T., PAUL, R., “Management of residual materials from dismantled reactor pressure vessels”, KONTEC ’97: Conditioning of Radioactive Operational and Decommissioning Waste (Proc. 3rd Symp. Hamburg, 1997), Kontec Gesellschaft für technische Kommunikation mbH, Glinde (1997) 962–967.
[531] COMMISSION OF THE EUROPEAN COMMUNITIES, Cast-Iron Containers out of Low Radioactive Steel, Rep. EUR 12795, Office for Official Publications of the European Communities, Luxembourg (1990).
[532] COMMISSION OF THE EUROPEAN COMMUNITIES, Large Packages for Reactor Decommissioning Waste, Rep. EUR 13345, Office for Official Publications of the European Communities, Luxembourg (1991).
[533] ESTEBAN-DUQUE, A., et al., “Characterization and conditioning of radioactive graphite from nuclear reactor”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 144–155.
[534] COMMISSION OF THE EUROPEAN COMMUNITIES, Conditionnement pour le stockage définitif des briques de graphite radioactif provenant du déclassement des réacteurs, Rep. EUR 12815, Office for Official Publications of the European Communities, Luxembourg (1990) (in French).
[535] MENON, S., “Minimisation of waste arising from decommissioning”, Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 1, Société française d’énergie nucléaire, Paris (1998) 367–377.
[536] GREPPO, J.F., SIXOU, Y., “SOCODEI melting recycling and incineration facilities”, Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 1, Société française d’énergie nucléaire, Paris (1998) 403–414.
[537] NESTER, A.T., et al., “Radioactive metals management in Russia: Status and outlook”, ICEM ’97: Radioactive Waste Management and Environmental Remediation (Proc. 7th Int. Conf. Singapore, 1997), American Society of Mechanical Engineers, New York (1997) 835–838.

[538] MOTL, G.P., BURNS, D.D., “Waste container fabrication from recycled DOE metal”, Waste Management ’94 (Proc. Int. Conf. Tucson, 1994), Waste Management Symposia, Tucson, AZ (1994).

[539] HACKWORTH, J.M., Jr., et al., “Managing scrap metal for off-site shipment”, Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 15.

[540] SYPHERS, V.A., LEVERSQUE, R.G., “Results of chemical decontamination of scrap metal at the Portsmouth uranium enrichment facility”, Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997, American Nuclear Society, La Grange Park, IL (1997) 17.

[541] JANSSENS, A., “Different policy options for the recycling of contaminated scrap metal”, ALARA and Decommissioning (1st Eur. ALARA Network Workshop Saclay, 1997), Office for Official Publications of the European Communities, Luxembourg (1997).

[542] ROLLOR, M.A., et al., “Decontamination and recycling of radioactively contaminated lead (Pb)”, EPRI International Low Level Waste Conference (Proc. Int. Conf. Palo Alto, 1994), Electric Power Research Institute, Palo Alto, CA (1995) 8.1–8.15.

[543] MENON, S., “Recycling of metal scrap from nuclear installations”, ALARA and Decommissioning (1st Eur. ALARA Network Workshop Saclay, 1997), Office for Official Publications of the European Communities, Luxembourg (1997).

[544] MILLER, C., BYRNE, M.J., “Recycling of Diablo Canyon’s contaminated metal at Manufacturing Sciences Corporation”, Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 11–14.

[545] SCHIFFER, K., MICKLINGHOFF, M., Kernkraftwerk Würgassen: Erste Phase des Rückbaus (in German), Proceedings of the V. Stillegungskolloquium Hannover, June 1997, German Federal Ministry for Education, Science and Technology, Bonn (1997) 78.

[546] RÖHL, N., RIDDER, D., HAFERKAMP, D., Die Herstellung der sicher eingeschlossenen Anlage für den THTR-300 (in German), Proceedings of the Jahrestagung Kerntechnik (Annual Meeting on Nuclear Technology), May 1997, Aachen, Germany, INFORUM Verlag, Bonn (1997) 519.

[547] BERG, H.P., BRENNECKE, P., GÖRTZ, R., Reststoffverwertung und Abfallbeseitigung (in German), Atw. Int. Z. Kernenergie **40** 4 (1995) 252.

[548] WESTERMANN, H., GESTERMANN, G., “Cutting of metal parts in a modernized waste/residual material conditioning facility in the GNS plant at Duisburg”, KONTEC ’97: Conditioning of Radioactive Operational and Decommissioning Waste (Proc. 3rd Symp. Hamburg, 1997), Kontec Gesellschaft für technische Kommunikation mbH, Glinde (1997) 505–508.

[549] SAPPOK, M., LEDEBRINK, F.W., “Conditioning of uranium contaminated metals from recontruction of the Siemens Brennelementewerk Hanau — Results of the 300 t melting campaign”, KONTEC ’95: Conditioning of Radioactive Operational and Decommissioning Waste (Proc. 2nd Symp. Hamburg, 1995), Kontec Gesellschaft für technische Kommunikation mbH, Glinde (1995) 270–280.

[550] SAPPOK, M., LEDEBRINK, F.W., "Uranium-contaminated steel melting in Germany — Part II", Melting and Recycling of Metallic Materials from Decommissioning (3rd Eur. Sem. Nyköping, 1997), Office for Official Publications of the European Communities, Luxembourg (1998).
[551] SAPPOK, M., KREH, R., "Activity distribution in the melt of radioactively contaminated metal scrap", Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 1, Société française d'énergie nucléaire, Paris (1998) 391–401.
[552] CLEMENTS, D.W., Decontamination and melting of low level waste, Radwaste Mag. **4** 2 (1997) 36–41.
[553] ANDERSSON, L., "Melting for recycling by free release at Studsvik", Melting and Recycling of Metallic Materials from Decommissioning (3rd Eur. Sem. Nyköping, 1997), Office for Official Publications of the European Communities, Luxembourg (1998).
[554] ANDERSSON, L., "Melting and recycling of materials from nuclear installations", Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 1, Société française d'énergie nucléaire, Paris (1998) 415–420.
[555] FEAUGAS, J., et al., "Experience with melting beta and gamma contaminated metals", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 433–444.
[556] FRANQUARD, D., TACHON, M., POIRIER, M.C., "Waste arising from dismantling operations: Melting contaminated scrap iron", IPRA 9: Radiation Protection (Proc. Int. Cong. Vienna, 1996), 3 vols, International Radiation Protection Association, Washington, DC (1996) 298–300.
[557] NAKAMURA, H., et al., "R&D on melting of radioactive metal wastes at JAERI", ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1785–1790.
[558] ISHIKURA, T., et al., "Development of techniques on metal and concrete recycling", X-Change '97: The Global D&D Marketplace (Proc. Conf. Miami, 1997), Hemispheric Center for Environmental Technology, Miami, FL (1998).
[559] UMEMURA, A., et al., "Radioactive tracer test to develop a recycling system for operating reactor scrap metal", Scientific Basis of Nuclear Waste Management (Proc. 18th Int. Symp. Kyoto, 1994), 2 vols (MURAKAMI, T., EWING, R.C., Eds), Materials Research Society, Warrendale, PA (1995).
[560] HARTWIG, P., et al., "Recycling of AECL's contaminated stainless steel fuel baskets at Manufacturing Sciences Corporation", Waste Management '97 (Proc. Int. Conf. Tucson, 1997), Waste Management Symposia, Tucson, AZ (1997).
[561] EUROPEAN COMMISSION, Technical Seminar on Melting and Recycling of Metallic Waste Materials from Decommissioning of Nuclear Installations (Tech. Sem. Krefeld, 1993), Rep. EUR 15691, Office for Official Publications of the European Communities, Luxembourg (1994).
[562] NESTER, A.T., et al., "Radioactive metal waste recycling and utilization", Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 2, Société française d'énergie nucléaire, Paris (1998) 631–641.

[563] STEINWARZ, W., SAPPOK, M., “SURF — The melting facility for Chernobyl using CARLA experience’’, ICONE-5: Nuclear Engineering (Proc. 5th Int. Conf. Nice, 1997), American Society of Mechanical Engineers, New York (1997).

[564] QUADE, U., SELGAS, F., “Experience on project management and first results of cutting and melting fuel element racks from a Spanish nuclear power plant”, Melting and Recycling of Metallic Materials from Decommissioning (Proc. 3rd Eur. Sem. Nyköping, 1997), Office for Official Publications of the European Communities, Luxembourg (1998).

[565] OMORI, H., et al., “Feasibility study on recycling of dismantled metal by induction cold crucible melting method”, ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1791–1796.

[566] SUZUKI, M., et al., “Promising technology for the melting of dismantled metal by an induction cold crucible”, Waste Management ’98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).

[567] QUADE, U., KADEN, S., Recycling radioaktiver Reststoffe durch Schmelzen, Sonderdruck aus der Zeitschrift Atw. Atomwirtsch. Atomtech. **40** 4 (1995) (in German).

[568] SAPPOK, M., Recycling radioactive scrap metal by producing concrete shielding with steel granules, Trans. Am. Nucl. Soc. **75** (1996) 462–463.

[569] EUROPEAN COMMISSION, Grosstechnisches Einschmelzen von radioaktiven metallischen Stillegungs-Abfällen, Rep. EUR 14960, Office for Official Publications of the European Communities, Luxembourg (1994) (in German).

[570] EUROPEAN COMMISSION, Grosstechnisches Schmelzen von tritiumhaltigem Stahl aus kerntechnischen Anlagen, Rep. EUR 16009, Office for Official Publications of the European Communities, Luxembourg (1995) (in German).

[571] HOLLAND, D., et al., “Behaviour and removal of tritium in the industrial-scale melting of steel from nuclear installations”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 445–455.

[572] HAAS, E.W., et al., “Laboratory development of methods for decontamination of ferrous and non-ferrous metals by melting”, KONTEC ’95: Conditioning of Radioactive Operational and Decommissioning Wastes (Proc. 2nd Symp. Hamburg, 1995), Kontec Gesellschaft für technische Kommunikation mbH, Glinde (1995) 367–385.

[573] CORNELISSEN, H.A.W., PEEZE BINKHORST, I.A.G.M., “Development of a process for separating radioactive concrete constituents, including pilot plant testing”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 401–410.

[574] PEEZE BINKHORST, I.A.G.M., CORNELISSEN, H.A.W., “Technology for reuse of contaminated concrete constituents”, New Methods and Techniques for Decontamination in Maintenance or Decommissioning Operations, IAEA-TECDOC-1022, IAEA, Vienna (1998) 149–160.

[575] JOHNSON, J.O., et al., “Contaminated concrete recycling system’’, X-Change ’97: The Global D&D Marketplace (Proc. Conf. Miami, 1997), Hemispheric Center for Environmental Technology, Miami, FL (1998).

[576] PARKER, F.L., et al., "Economic, risk, and efficacy analysis of recycling radioactively contaminated concrete", Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 3–10.

[577] YASHIRO, Y., NISHIDE, J., ARIKAWA, K., "Development of concrete aggregate recycling system by using microwaves", ICONE-6: Nuclear Engineering (Proc. 6th Int. Conf. San Diego, 1997), American Society of Mechanical Engineers, New York (1997).

[578] MASSAUT, V., et al., "Decommissioning of nuclear laboratories and other facilities supporting operation of research reactors", paper presented at IAEA Regional Training Course on Decommissioning of Research Reactors and Other Small Nuclear Facilities, Bucharest, 1997.

[579] BOING, L.E., Beneficial reuse of decommissioned former nuclear facilities, Radwaste Mag. **5** 4 (1998) 44–49.

[580] KOPS, J., VAN DER LUGT, G., "Digging up radioactive waste: A recapitulation", Remediation and Restoration of Radioactive-contaminated Sites in Europe, (Proc. Int. Symp. Antwerp, 1993), Vol. II, Office for Official Publications of the European Communities, Luxembourg (1993) 693–712.

[581] INTERNATIONAL RADIOLOGICAL PROTECTION ASSOCIATION, Radiological Protection (Proc. 17th IRPA Reg. Cong. Portsmouth, 1994), (NIMMO-SCOTT, W., GOLDING, D.J., Eds), Nuclear Technology Publishing, Ashford (1994).

[582] DONDERS, R.E., et al., "Managing LLRW from decommissioning of nuclear facilities — A Canadian perspective", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[583] RITTSCHER, D., Das Stillegungs–und Rückbau — Projekt Greifswald, VEI-Tagung "Stillegung und Rückbau kerntechnischer Anlagen", VDI-Berichte 1268 (1996) (in German).

[584] LOESCHHORN, V., FRANK, C., STERNER, H., "Decommissioning and dismantling of the nuclear power plant in Greifswald", Planning and Management of Decommissioning for WWER NPPs (IAEA Reg. Workshop Greifswald, 1996), unpublished report, IAEA, Vienna (1996).

[585] EMPRESA NACIONAL DE RESIDUOS RADIACTIVOS, Vandellos 1 NPP Decommissioning Project — Progress Report, internal report, ENRESA, Madrid (1997).

[586] BOSSART, S.J., "Innovative technologies for asbestos removal, treatment and recycle", Beneficial Reuse '97 (Proc. Conf. Knoxville, 1997), US Dept of Energy, Washington, DC (1997).

[587] BOSSART, S.J., KASPER, K.M., Innovative technologies for asbestos removal and treatment, Radwaste Mag. **5** 1 (1998) 10–18.

[588] EUROPEAN COMMISSION, TELEMAN Telerobotics Research Conference and ERNET Workshop, (Conf. Noordwijkerhout, 1995), Office for Official Publications of the European Communities, Luxembourg (1995).

[589] ROBERTSON, B., A preview of the European Commission TELEMAN programme for telerobotics research, IEEE Robotics and Automation Mag. **4** 4 (1997).

[590] KYRIAKOPULOS, K.J., LIMA, P.A., Robotics and automation in Europe: Projects founded by the European Union, IEEE Robotics and Automation Mag. **4** 4 (1997).

[591] US DEPARTMENT OF ENERGY, Office of Science and Technology, Robotics Technology Crosscutting Program, Technology Summary, Rep. DOE/EM-0299, Aug. 1996, USDOE, Washington, DC (1996).
[592] COLQUHOUN, A.P., "Some remote decommissioning applications and progress within the Sellafield decommissioning programme", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).
[593] CHAMEAUD, H., et al., "Underwater qualification of the RD500 manipulator", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 525–531.
[594] CLEMENTS, D.W., "Proven experience plus initiative equates to safe, cost-effective decommissioning with added value", Waste Management '98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).
[595] HAMEL, W.R., et al., "Dual-arm manipulation module for use in decontamination and decommissioning operations", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).
[596] HYDE, J.M., et al., "Standardized tooling delivery systems for decommissioning of US Department of Energy nuclear facilities", Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 179–187.
[597] HENLEY, D.R., LITKA, T.J., A Survey of Commercially Available Manipulators, End-Effectors, and Delivery Systems for Reactor Decommissioning Activities, Rep. ANL/D&D/TM-95/1, Argonne Natl Laboratory, Argonne, IL (1996).
[598] BACHMANN, M., et al., "Handling devices for the dismantling of nuclear installations — Cooperation of university and operator", Decommissioning Experience in Europe (Proc. Eur. Comm. Workshop, 1996), Rep. EUR 16900, Office for Official Publications of the European Communities, Luxembourg (1996).
[599] Underwater remote techniques used to dismantle reactor internals, Nucl. Waste News 18 July (1996).
[600] FRITZ, P., et al., "Remote dismantling at the spent fuel reprocessing plant, Karlsruhe", KONTEC '97: Conditioning of Radioactive Operational and Decommissioning Waste (Proc. 3rd Symp. Hamburg, 1997), Kontec Gesellschaft für technische Kommunikation mbH, Glinde (1997) 968–976.
[601] BIRRINGER, K.J., et al., "First step of remote dismantling of the Wiederaufarbeitungsanlage Karlsruhe (WAK)", SPECTRUM '94: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Atlanta, 1994), American Nuclear Society, La Grange Park, IL (1994) 1570–1575.
[602] GRANDJEAN, J.P., LAMBERT, F., STREIFF, G., La robotique en démantèlement, Rev. Gen. Nucl. **3** (1995) 183–191 (in French).
[603] MASSON, Y., et al., "EVEREST: A virtual reality interface to program a teleoperated mission", Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 2, Société française d'énergie nucléaire, Paris (1998) 591–601.
[604] VARLEY, J., Windscale: Getting down to the core, Nucl. Eng. Int. **42** 520 (1997) 26–28.

[605] PARR, M.R., “Decommissioning of the B212 caesium extraction plant”, Nuclear Decommissioning ’98 (Proc. Int. Conf. London, 1998), Professional Engineering Publishing, London (1998) 181–190.
[606] COLE, G.V., “The decontamination and decommissioning of the internals of the DIDO high activity handling cell using a NEATER based telerobotic system”, Decommissioning Experience in Europe (Proc. Eur. Comm. Workshop, 1996), Rep. EUR 16900, Office for Official Publications of the European Communities, Luxembourg (1996).
[607] WALTERS, C.L., WRIGHT, E.M., LENG, J.L., “Remote dismantling of nuclear facilities in the United Kingdom: Experience to date”, Waste Management ’92 (Proc. Int. Conf. Tucson, 1992), Vol. 1, Waste Management Symposia, Tucson, AZ (1992) 723–727.
[608] LOUGHBOROUGH, D., et al., “Decommissioning of a hot laboratory and cyclotron complex to green field”, Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 343–354.
[609] ASQUITH, J., LOUGHBOROUGH, D., Manipulator carves up hot cells, Atom **429** (1993) 16–19.
[610] TRATT, J.H., WORTHINGTON, P.W., “Adaptation and testing of a remotely controlled underwater vehicle”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 519–524.
[611] UK ROBOTICS, MAGNOX ELECTRIC, Keeping control when cutting through a reactor vessel, Nucl. Eng. Int. **42** 518 (1997) 41–42.
[612] BLACK, D.B., et al., “Deployment of remote dismantling systems at the CP-5 reactor”, Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 364–370.
[613] US DEPARTMENT OF ENERGY, ROSIE — Mobile Robot Worksystem for Decommissioning and Dismantling Operations, final report, Rep. DOE/MC/33207-5634, USDOE, Washington, DC (1998).
[614] CATALAN, M., “The Wall Walker™: An innovative and proven D&D robot”, Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 433–438.
[615] US DEPARTMENT OF ENERGY, 2-D Linear Motion System (2-D LMS), Mar. 1998, http://www.bhi-erc/Creactor/final.htm.
[616] PULSFORD, S.K., et al., “Results of 2-D Wall Walker™ — Innovative technology demonstrated at Hanford’s C Reactor”, SPECTRUM ’98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 173–177.
[617] FULLER, B.R., Bringing robotics technology down to earth, Radwaste Mag. **4** 2 (1997) 36.
[618] EICKELPASCH, N., STEINER, H., PRIESMEYER, U., “Remote techniques for the underwater dismantling of reactor internals at the nuclear power plant Gundremmingen

Unit A", Remote Techniques for Hazardous Environments (Proc. Int. Conf. Leicestershire, 1996), Thomas Telford, London (1996).
[619] MULLER, K., GENGENBACH, U., "Adaptation and testing of selected tools on the long range teleoperated manipulator system EMIR", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 500–508.
[620] ISHIBASHI, Y., et al., "The development of remote dismantling and removal of large components in reprocessing plant", ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1803–1808.
[621] FUJII, Y., USUI, H., SHINOHARA, Y., Development of multi-functional telerobotic systems for reactor dismantlement, J. Nucl. Sci. Technol. **29** 9 (1992).
[622] FOURNIER, R., et al., "MAESTRO hydraulic manipulator and its TAO-2000 control system", Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 2, Société française d'énergie nucléaire, Paris (1998) 579–589.
[623] EUROPEAN COMMISSION, Robotic System for Dismantling the Process Cell of a Reprocessing Plant, Rep. EUR 16551, Office for Official Publications of the European Communities, Luxembourg (1995).
[624] BOSSU, R., et al., "Dismantling of a nuclear reprocessing plant with fixation of the radioactive contamination", Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 532-547.
[625] ESPALLARDO, J.A., WATSON, C., Remote solution to waste removal, Atom **437** (1995) 27–30.
[626] ESPALLARDO, J.A., WATSON, C.J.H., "Radwaste vault clearance at Vandellos 1 Reactor", Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 237–244.
[627] US DEPARTMENT OF ENERGY, Technical Basis for Radiological Release of Grand Junction Office Building 2, Vol. 1: Dose Assessment, Rep. GJO-97-12-FOS, July 1997, USDOE, Washington, DC (1997).
[628] US DEPARTMENT OF ENERGY, Pipe Explorer™ System, Innovative Technology Summary Report, Rep. DOE/EM-0306, Apr. 1996, http://www.wpi.org/doe/focus/old/docs/techrpt.htm.
[629] RAWOOL-SULLIVAN, M., Alpha Contamination Monitoring for Decontamination and Decommissioning, Rep. LALP-94-145, Los Alamos National Laboratory, Los Alamos, NM (1994).
[630] FOGLE, R.F., et al., The visual and radiological inspection of a pipeline using a teleoperated pipe crawler, Radwaste Mag. **3** 4 (1996) 42.
[631] US DEPARTMENT OF ENERGY, Pipe Crawler® Internal Piping Characterization System, Rep. DOE/EM-0355, Feb. 1998, http://em-52.em.doe.gov/ifd/d&d/itsrs/crawl/begining.htm.
[632] DUDA, J., et al., "Field demonstration of improved D&D technologies at Hanford C reactor", Waste Management '98 (Proc. Int. Conf. Tucson, 1998), Waste Management Symposia, Tucson, AZ (1998).

[633] DUMBRECK, A.A., PERROTT, E.H., SCHEIWILLER, P.M., "3-D TV: An application in nuclear power plant decommissioning", Remote Techniques for Nuclear Plant (Proc. Conf. Stratford-upon-Avon, 1993), British Nuclear Energy Society, London (1993) 293–297.

[634] LUBAWY, J.L., et al., "As-built modeling of industrial environments", Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 2, Société française d'énergie nucléaire, Paris (1998) 603–606.

[635] LE GOALLER, C., COSTES, J.-R., "Onsite nuclear video imaging", papers presented at Waste Management '98, Tucson, 1998.

[636] LE GOALLER, C., COSTES, J.-R., "In situ nuclear video imaging", Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 2, Société française d'énergie nucléaire, Paris (1998) 519–527.

[637] EUROPEAN COMMISSION, The Development and Improvement of the ALADIN Gamma Camera to Localise Gamma Activity in Nuclear Installations, Rep. EUR 18230, Office for Official Publications of the European Communities, Luxembourg (1998).

[638] EUROPEAN COMMISSION, Further Development and Operation of an Automated Large-Scale Radioactivity Measurement Facility for Low-Level Decommissioning Waste, Rep. EUR 15444, Office for Official Publications of the European Communities, Luxembourg (1994).

[639] HENNEBORN, A.C., BORLAND, M.W., "Gamma ray imaging in decontamination and decommissioning", X-Change '97: The Global D&D Marketplace (Proc. Conf. Miami, 1997), Hemispheric Center for Environmental Technology, Miami, FL (1998).

[640] US DEPARTMENT OF ENERGY, Gamma Ray Imaging System (PSC/BNFL Radscan™ 600), Feb. 1998, http://www.bhi-erc.com/Creactor/final.htm.

[641] US DEPARTMENT OF ENERGY, GammaCam™ Radiation Imaging System, Rep. DOE/EM-0345, Feb. 1998, http://em-52.em.doe.gov/ifd/d&d/itsrs/gamma/begining.htm.

[642] VOLKOVICH, A.G., et al., Application of gamma-visor for reactors survey, At. Ehnerg. **79**, Nov. (1995) (in Russian).

[643] VOLKOVICH, A.G., et al., Gamma-visor — An automatic imaging system for gamma radioactive objects, Prib. Tekh. Ehksp. **3** (1996) 131–135 (in Russian).

[644] SUDARKIN, A.N., et al., High-energy radiation visualizer (HERV): A new system for imaging in x-ray and gamma-ray emission regions, IEEE Trans. Nucl. Sci. **43** 4 (1996) 2427–2433.

[645] HUGHES, K.A., et al., "Radscan™ 600 gamma ray imaging as the basis for a strategic approach to decommissioning", Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 307–311.

[646] ASQUITH, J.D., "Hands on versus remote techniques in waste management and decommissioning", Waste Management '94 (Proc. Int. Conf. Tucson, 1994), Vol. 3, Waste Management Symposia, Tucson, AZ (1994) 2309–2313.

[647] STURTEVANT, W.C., et al., "Remote dismantlement by novel adaptations of conventional equipment", Waste Management '93 (Proc. Int. Conf. Tucson, 1993), Waste Management Symposia, Tucson, AZ (1993) 1505–1510.

[648] COLEMAN, S.H., "A system for decommissioning reactor vessel internals", Decommissioning, Decontamination and Reutilization of Commercial and Government

Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 426–432.
[649] CROSS, M.T., HOLT, G., "Gas-cooled reactor decommissioning in the UK", ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1695–1700.
[650] EUROPEAN COMMISSION, Manufacturing and Testing of a Robotic System (TRR) for the Removal of Tubes from a Latina Magnox Steam Generator with Subsequent Melting and Radiological Characterization, Rep. EUR 16976, Office for Official Publications of the European Communities, Luxembourg (1996).
[651] GRANDJEAN, J.P., ALFILLE, J.P., "Remote laser cutting for decommissioning — The CLAUDIN project", Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 2, Société française d'énergie nucléaire, Paris (1998) 563–570.
[652] PENTEK, WALL WALKER™ 2-D Linear Motion System, company brochure, Rev. 1, Aug. 1997, Pentek, Coraopolis, PA (1997).
[653] MARSHALL, R.A., et al., "Remote mechanical methods for decontaminating concrete walls", X-Change '97: The Global D&D Marketplace (Proc. Conf. Miami, 1997), Hemispheric Center for Environmental Technology, Miami, FL (1998).
[654] PENTEK, MOOSE™ Decontamination Robot Supports D&D Operations for the DOE in Columbus, Ohio, company brochure, Oct. 1995, Pentek, Coraopolis, PA (1995).
[655] KAFKA, T.M., MARKELL, C.G., WHITE, L.R., "Recent developments in the use of chemical absorbing membranes for radionuclide separation", International Low Level Waste Conference (Proc. Int. Conf. New Orleans, 1996), Electric Power Research Institute, Palo Alto, CA (1996) 113–115.
[656] RODRIGUEZ, A., "Vandellos 1 NPP Decommissioning Project Technical Advisory Group Meeting Number 20", Decommissioning (OECD/NEA Co-operative Programme Stockholm, 1996), internal report, Empresa Nacional de Residuos Radiactivos, Madrid (1996).
[657] PILOT, G., POURPRIX, M., "Prefiltering devices for gaseous effluents from dismantling operations", Decommissioning of Nuclear Installations (Proc. Int. Conf. Brussels, 1989), Office for Official Publications of the European Communities, Luxembourg (1990) 639–648.
[658] COMMISSION OF THE EUROPEAN COMMUNITIES, Analysis of Results Obtained with Different Cutting Techniques and Associated Filtration Systems for the Dismantling of Radioactive Metallic Components, Rep. EUR 14213, Office for Official Publications of the European Communities, Luxembourg (1993).
[659] EUROPEAN COMMISSION, Underwater Dismantling Using Divers to Install Remotely Controlled Equipment, Rep. EUR 16977, Office for Official Publications of the European Communities, Luxembourg (1996).
[660] ROTTNER, B., "Underwater cutting at ISPRA 1", Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 2, Société française d'énergie nucléaire, Paris (1998) 571–578.
[661] US DEPARTMENT OF ENERGY, Advanced Worker Protection System, Innovative Technology Summary Report, Rep. DOE/EM-0307, Apr. 1996, http://www.em.doe.gov/plumesfa/intech/advwork/index.html.

[662] US DEPARTMENT OF ENERGY, Protective Clothing Based on Permselective Membrane and Carbon Adsorption, Technology Development Data Sheet, Nov. 1997, Federal Energy Technology Center, Pittsburgh, PA (1997).

[663] US DEPARTMENT OF ENERGY, Sealed-Seam Sack Suits, Mar. 1998, http://www.bhi-erc.com/ Creactor/final.htm.

[664] US DEPARTMENT OF ENERGY, FRHAM-TEX™ Cool Suit, Rep. DOE/EM-0353, Feb. 1998, http://em-52.em.doe.gov/ifd/d&d/itsrs/frham/begining.htm.

[665] US DEPARTMENT OF ENERGY, NuFab™ Anti-Contamination Suit, Rep. DOE/EM-0354, Feb. 1998, http://em-52.em.doe.gov/ifd/itsrs/nufab/begining.htm.

[666] US DEPARTMENT OF ENERGY, Wireless Remote Radiation Monitoring System, Technology Demonstration Fact Sheet, USDOE, Washington, DC (1997).

[667] US DEPARTMENT OF ENERGY, Heat Stress Monitoring System (HSMS), Mar. 1998, http://www.bhi-erc.com/Creactor/final.htm.

[668] PULSFORD, S.K., et al., "Results of heat stress monitoring system — Innovative technology demonstrated at Hanford's C reactor", SPECTRUM '98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 178–181.

[669] US DEPARTMENT OF ENERGY, Fernald Plant 1 Large Scale Technology Demonstration Project: Personal Ice Cooling System, Sept. 1997, USDOE, Washington, DC (1997).

[670] BOSSART, S.J., SHOEMAKER, H.D., KASPER, K.M., "Improved technologies to alleviate worker heat stress", SPECTRUM '98: Int. Conf. on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management (Proc. Int. Conf. Denver, 1998), American Nuclear Society, La Grange Park, IL (1998) 1159–1164.

[671] US DEPARTMENT OF ENERGY, Aerosol Fog System for Fixing Radioactive Contamination, Technology Deployment Fact Sheet, Feb. 1999, http://www.hanford.gov/techmgmt/factsheets/deploys/fogger/htm.

[672] HUMISTON, T.J., "Decommissioning of gloveboxes from Building 707 at the Rocky Flats environmental technology site", Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 212–218.

[673] CLOSS, J.W., "Decommissioning experience: One-piece removal and transport of a LWR pressure vessel and internals", Nuclear Waste Management and Environmental Remediation (Proc. Int. Conf. Prague, 1993), American Society of Mechanical Engineers, New York (1996) 105–110.

[674] Yankee Atomic Electric set to remove vessel, Environ. Remed. Technol. 3 April (1996) 65–66.

[675] WESTINGHOUSE HANFORD, Shippingport Station Decommissioning Project Lifting, Barge Loading and Transportation of the Shippingport Reactor Pressure Vessel Package, topical report, Rep. DOE/SSDP-0079, Nov. 1989, Westinghouse Hanford, Richland, WA (1989).

[676] CRUICKSHANK, H., et al., "Fast track steam generator disposal at Salem generation station", Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 619–624.

[677] HEATON, T., FLOYD, D., "Economical disposition of surplus equipment from Department of Energy sites", Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 625–637.

[678] HICKEY, H.B., TAYLOR, E., MILLIGAN, P.T., "Disposal of the WAGR heat exchangers'', The Best of D&D... Creative, Comprehensive and Cost-Effective (Proc. Topical Mtg Chicago, 1996), American Nuclear Society, La Grange Park, IL (1996) 173–185.

[679] MORGAN, R.D., et al., "Low density cellular concrete (LDCC) injection", The Best of D&D... Creative, Comprehensive and Cost-Effective (Proc. Topical Mtg Chicago, 1996), American Nuclear Society, La Grange Park, IL (1996).

[680] MILLER, R.L., et al., "Engineering studies for the surplus production reactor decommissioning project at the Hanford site", Decontamination and Decommissioning (Proc. Int. Symp. Knoxville, 1994), US Dept of Energy, Washington, DC (1994).

[681] LACY, N.H., et al., "Steam generator and pressurizer radwaste package design features", The Best of D&D... Creative, Comprehensive and Cost-Effective (Proc. Topical Mtg Chicago, 1996), American Nuclear Society, La Grange Park, IL (1996).

[682] ZUCHOWSKI, L.A., "Large component cradle design and grouting technologies", paper presented at Conf. on Decommissioning, Captiva Island, 1996.

[683] EIBEN, K., FRITZ, P., "The WAK decommissioning and dismantling program", SPECTRUM '96: Nuclear and Hazardous Waste Management (Proc. Int. Topical Mtg Seattle, 1996), American Nuclear Society, La Grange Park, IL (1996).

[684] OECD NUCLEAR ENERGY AGENCY, NEA Data Bank, http://www.nea.fr.

[685] MASSAUT, V., et al., "Optimization and decommissioning: Challenge and limits", ALARA and Decommissioning (1st Eur. ALARA Network Workshop Saclay, 1997), Office for Official Publications of the European Communities, Luxembourg (1997).

[686] US DEPARTMENT OF ENERGY, RESRAD-BUILD: A Model to Estimate Dose for Contaminated Structures, Dec. 1997 (draft), http://www.bhi-erc.com/ Creactor/facts.htm.

[687] RIMSKI-KORSAKOV, A.A., ROSCHIN, A.S., YAVSHITS, S.G., "The code system COROUT: Radioactive inventory calculations for decommissioning studies'', International Benchmark Calculations of Radioactive Inventory for Fission Reactor Decommissioning, Rep. INDC(NDS)-355, IAEA, Vienna (1996) 89–94.

[688] GRANDJEAN, J.P., VALENTIN, P., "3-D simulation for decommissioning — The CITADIN project: Results and outlook", Dismantling of Nuclear Facilities — Projects Feed Back Experience (Proc. Int. Conf. Avignon, 1998), Vol. 2, Société française d'énergie nucléaire, Paris (1998) 509–518.

[689] WULLER, C.E., et al., "Computer mapping and visualization of facilities for planning of D&D operations", ICEM '95: Radioactive Waste Management and Environmental Remediation (Proc. 5th Int. Conf. Berlin, 1995), Vol. 2, American Society of Mechanical Engineers, New York (1995) 1749–1753.

[690] RACKY, B., "Cost benefit by kinematic CAD simulation for the project planning", KONTEC '97: Conditioning of Radioactive Operational and Decommissioning Waste (Proc. 3rd Symp. Hamburg, 1997), Kontec Gesellschaft für technische Kommunikation mbH, Glinde (1997) 981–983.

[691] TANAKA, K., et al., "Computer-aided decommissioning engineering system with 3D-CAD for JAERI's reprocessing test facility", ICONE-3: Nuclear Engineering (Proc. 3rd

Int. Conf. Kyoto, 1995), American Society of Mechanical Engineers, New York (1995) 1799–1801.

[692] TACHIBANA, M., SHIMADA, T., YANAGIHARA, S., “Computer simulation systems for analyzing optimum dismantling procedures on nuclear facilities”, Radioactive Waste Management and Environmental Restoration (Proc. Int. Conf. Singapore, 1997), American Society of Mechanical Engineers, New York (1997) 831–834.

[693] HIGH, N.M., et al., “Automated data interpretation and report generation for final status surveys at nuclear facilities”, Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 443–445.

[694] HEMISPHERIC CENTER FOR ENVIRONMENTAL TECHNOLOGY, Decision Analysis Science Modeling for Application and Fielding Selection Applied to Concrete Decontamination Technologies, final report, Hemispheric Center for Environmental Technology, Miami, FL (1997).

[695] ZEIGHMI, E.A., et al., “LEADIS — A computer decision system for identifying potentially contaminated nuclear material use sites”, Decommissioning, Decontamination and Reutilization of Commercial and Government Facilities (Proc. Topical Mtg Knoxville, 1997), American Nuclear Society, La Grange Park, IL (1997) 135–144.

[696] SLOAN, P., “Pilot dismantling of the Windscale advanced gas cooled reactor”, Decommissioning of Nuclear Installations (Proc. 3rd Int. Conf. Luxembourg, 1994), Office for Official Publications of the European Communities, Luxembourg (1995) 19–31 .

[697] ANDREWS, P.J., et al., “Stage 1 decommissioning of the steam generating heavy water reactor — Current achievements”, Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 305–314.

[698] MANNERS, T.K., “Decommissioning of a highly active handling cell”, Nuclear Decommissioning — The Strategic, Practical, and Environmental Considerations (Proc. Int. Conf. London, 1995), Mechanical Engineering Publications, London (1995) 109–118.

[699] BRANT, A.W., HOEGEWERF, P.M., “Decommissioning of post-irradiation examination caves, Berkeley Nuclear Laboratories”, European Nuclear Conference ’90 (Proc. Conf. Lyon, 1990), Verlag TÜV Rheinland, Cologne (1990).

[700] WALL, G., “Decommissioning needs and programmes at AWE”, Decommissioning of Nuclear Facilities (Proc. Int. Conf. London, 1995), IBC Technical Services, London (1995).

[701] WARREN, S., BULLER, J., DORRIES, J., “Technology application for surplus facility decommissioning under US Department of Energy’s environmental restoration program”, ICONE-3: Nuclear Engineering (Proc. 3rd JSME/ASME Joint Int. Conf. Kyoto, 1995), Vol. 4, American Society of Mechanical Engineers, New York (1995) 1683–1688.

[702] CHEEVER, C.L., ROSE, R.W., Decontamination and Decommissioning of 61 Plutonium Glove Boxes in D-Wing, Building 212, ANL-East, Final Project Report, Rep. ANL/D&D/TM-96/3, Sept. 1996, Argonne Natl Laboratory, Argonne, IL (1996).

[703] FELLHAUER, C., "Case study: Experimental boiling water reactor decommissioning", paper presented at IAEA Interregional Training Course on Decontamination and Decommissioning of Research Reactors and Other Small Nuclear Facilities, Argonne, 1998.
[704] MASSAUT, V., "Lessons learned during the BR-3 European pilot decommissioning project", Decommissioning of Nuclear Facilities (Proc. Int. Conf. London, 1997), IBC Technical Services, London (1997).

CONTRIBUTORS TO DRAFTING AND REVIEW

Bailo, M.	Ente Nazionale Energia Elettrica, Italy
Boing, L.E.	Argonne National Laboratory, United States of America
Brotherton, C.	British Nuclear Fuels Ltd, United Kingdom
Destrait, L.	Compagnie générale des matières nucléaires, France
Gazit, M.	Atomic Energy Commission, Israel
Hladky, E.	DECOM, Slovakia
Halaszovich, S.R.	Jülich Research Centre, Germany
Inoue, T.	Nuclear Power Engineering Corporation, Japan
Laraia, M.	International Atomic Energy Agency
Lefebvre, A.	Tractebel, Belgium
Löschhorn, V.	Energiewerke Nord GmbH, Germany
Lund, I.	Radiation Protection Institute, Sweden
Madrid, F.	Empresa Nacional de Residuos Radiactivos, Spain
Massaut, V.	Studiecentrum voor Kernenergie/Centre d'étude de l'énergie nucléaire, Belgium
Medvedev, S.	St. Petersburg State Institute of Technology, Russian Federation
Mittler, M.	Hamburgische Electrizitätswerke Aktiengesellschaft, Germany
Ortenzi, V.	Agenzia Nazionale per la Protezione dell'Ambiente, Italy
Park, W.J.	Permanent Mission of the Republic of Korea to the United Nations (Vienna)
Pflugrad, K.	European Commission
Ranganathan, K.	Bhabha Atomic Research Centre, India
Saishu, S.	Nuclear Power Engineering Corporation, Japan
Thierfeldt, S.	Brenk Systemplanung, Germany
Vankerckhoven, P.	European Commission
Wareing, M.	AEA Technology, United Kingdom

Consultants Meetings

Vienna, Austria: 20–24 January 1997; 8–12 June 1998;
25–29 January 1999

Technical Committee Meeting

Vienna, Austria: 10–14 November 1997