TECHNICAL REPORTS SERIES NO. 446

Decommissioning of Research Reactors: Evolution, State of the Art, Open Issues

IAEA
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DECOMMISSIONING OF RESEARCH REACTORS: EVOLUTION, STATE OF THE ART, OPEN ISSUES

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2006

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A-1400 Vienna
Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
http://www.iaea.org/books

Printed by the IAEA in Austria
May 2006
STI/DOC/010/446

IAEA Library Cataloguing in Publication Data

Decommissioning of research reactors : evolution, state of the art, open issues. – Vienna : International Atomic Energy Agency, 2006.
p. ; 24 cm. — (Technical reports series, ISSN 0074–1914 ; 446)
STI/DOC/010/446
ISBN 92–0–112605–0
Includes bibliographical references.

1. Nuclear reactors — Decomissioning. I. International Atomic Energy Agency. II. Series: Technical reports Series (International Atomic Energy Agency) ; 446.

IAEAL 6–00436

FOREWORD

Many research reactors throughout the world date from the original nuclear research programmes in Member States. Consequently, dozens of old research reactors are candidates for near term decommissioning in parallel with progressive ageing and technical and economic obsolescence. Many of them are located in countries/institutions that, although familiar with the operation and management of their reactors, do not necessarily have adequate expertise and technologies for planning and implementing state of the art decommissioning projects. It is felt that IAEA reports may contribute to the awareness of technologies and know-how already tested successfully elsewhere.

This report addresses a subject area that was dealt with earlier by two IAEA publications, namely, Planning and Management for the Decommissioning of Research Reactors and Other Small Nuclear Facilities (Technical Reports Series No. 351) and Decommissioning Techniques for Research Reactors (Technical Reports Series No. 373). This publication updates those reports in view of the technological progress, experience gained and the progressive ageing of research reactors, many of which have already reached the permanent shutdown stage and should be decommissioned soon. It is intended to contribute to the systematic coverage of the entire range of activities that have been addressed by the IAEA's decommissioning work in past years. The perspective of the report is historical, in that relevant issues are identified as solved, pending, or emerging. Much of the information provided in this report will also be of use for the decommissioning of nuclear power plants and other nuclear facilities.

A Technical Committee Meeting on this subject was held in Vienna from 17 to 21 May 2004, at which the participants reviewed a draft report written by consultants from Canada, Germany, Israel, the Russian Federation and the United Kingdom. The IAEA officer responsible for this publication was M. Laraia of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION

The first IAEA report on the decommissioning of nuclear facilities [1] concluded that: “There are no insurmountable technical problems to decommissioning at any stage, but considerations with respect to policy, planning, timing, costs, waste disposal, safety criteria and regulatory aspects need further development.”

Since then much work has been done and substantial progress has been made — to the extent that decommissioning is now considered to be a generally mature industry. However, even a mature industry has to keep pace with evolving safety and environmental regulatory requirements, technological progress, and also with changes in political perceptions and expectations. In addition, there are still technical areas needing improvement, and the experience and know-how should be transferred to countries that are now facing ‘first of a kind’ decommissioning projects. Therefore the above challenge, as identified in 1975, remains generally valid. Only the emphasis is shifting, with rather less need for new developments and a growing demand for optimization, common approaches and effective sharing of experiences.

The future of research reactors is radically changing in a more economically competitive and safety conscious marketplace. To survive in today’s difficult environment, research reactors must be actively managed, planned, researched, financed and marketed. The IAEA is helping countries pursue viable utilization strategies. However, many ageing research reactors will not survive in this tough new environment and the IAEA is endeavouring to help in the shutdown process [2].

Taking account of work done to date on research reactor decommissioning, it is timely to provide an up to date basis for ongoing and foreseen activities in this field. An evaluation of the state of the art, latest trends and current issues is desirable. The approach taken in this report is to review, from a historical perspective, decommissioning projects either completed in recent years or under way, to assess progress, as well as remaining and new issues. The baseline is provided by two IAEA reports published in the early 1990s [3, 4], which this report is intended to supersede to a large extent with the support of more recent information. The intention is to facilitate timely, safe and efficient completion of decommissioning projects for research reactors by highlighting state of the art technologies and planning methodologies and suggesting ways to overcome expected issues.

Updates on the classification and status of research reactors are provided in Tables 1 and 2. This information originates from Ref. [4] and has been updated during the preparation of this report. The numbers in these tables, as

TABLE 1. STATISTICS OF RESEARCH REACTORS

Status	Number of research reactors
Operating	287
Shut down	114
Decommissioned	410
Under construction	10
Planned	10
Unknown	1
Total	832
Power (P)	
P = 1 kW	306
1 kW < P = 1 MW	245
1 MW < P = 5 MW	86
5 MW < P = 10 MW	52
10 MW < P	123
Unknown	20
Total	832
Age (A) of operating reactors	
A < 40 years	205
A = 40 years	76
Unknown	6
Total	287
Decommissioning status of shut down reactors	
1. Planned for decommissioning (shutdown)	
To unrestricted use	4
To safe enclosure	2
Unknown/undecided	18
2. In the process of decommissioning	
To unrestricted use	55
To safe enclosure	29
Unknown/undecided	44
3. Current status: Decommissioning completed	

TABLE 1. STATISTICS OF RESEARCH REACTORS (cont.)

Status	Number of research reactors
To unrestricted use	207
To safe enclosure	26
Unknown/undecided	4
4. Status of decommissioning:	
Unknown	45
Total	434

TABLE 2. CLASSIFICATION OF RESEARCH REACTORS

Type of reactor	Number of reactors	Subtotals
Pool type		
TRIGA	74	
SLOWPOKE/MNSR	19	
Others	160	253
Tank type		
Heavy water	48	
ARGONAUT	29	
Pressurized	22	
Others	90	189
Homogeneous liquid	45	
Homogeneous solid	44	
Fast	37	
Graphite	44	170
Others		
Zero power[a]	185	
Miscellaneous	28	
Unknown	7	220
Total		832

[a] Including critical and subcritical assemblies, prompt burst and pulsing reactors.

well as on the attached CD-ROM, may differ from those in other IAEA publications, e.g. Ref. [5]. This is because the database used here is based, among other sources, on miscellaneous publications and private communications that may differ from official information provided to the IAEA.

2. SCOPE

This report builds on earlier IAEA publications dealing with the decommissioning of research reactors [3, 4]. An update is provided, including technological progress and experience gained. This report takes into account the progressive ageing of research reactors, many of which have already reached the stage of permanent shutdown and may be decommissioned in the near future. The intention is to contribute to the systematic coverage of the entire range of decommissioning aspects that have been addressed by the IAEA's decommissioning activities over many years.

3. OBJECTIVE

The objective of this publication is to provide up to date documentation of decommissioning experiences and to disseminate information based on experience and lessons learned in the planning and implementation of the decommissioning of research reactors. It is intended for personnel already working in the nuclear field but not necessarily currently working in decommissioning. As such, it is not a technical textbook but rather a historical reflection on past experiences and considerations for the future. This approach is intended to assist those involved in research reactor decommissioning projects to apply and focus on the wide variety of information on decommissioning that is already available. The information presented will be of interest to operating organizations of research reactors, particularly those reactors approaching the decommissioning stage, decommissioning contractors, decision makers at the government level and regulatory bodies.

4. STRUCTURE

Following introductory sections, the major topics addressed in Section 5 are the history and current status of research reactor decommissioning (the 'until now' component). The topics dealt with are the global picture, reasons for decommissioning, factors affecting national policy and strategy, management and planning, decommissioning and waste management techniques, information exchange, and costs and funding. Section 6 deals with the same topics and uses the same general structure as Section 5 but addresses pending issues (the ‘from now on’ component). Section 7 gives a summary of conclusions and recommendations for further work. The report is complemented by a CD-ROM which contains comprehensive lists of the status and decommissioning strategies adopted for research reactors worldwide and introduced in Annex I. Annex II describes the lessons learned from selected decommissioning projects.

5. HISTORY AND CURRENT STATUS

This section considers decommissioning from a historical perspective, with emphasis on the current status in terms of managerial and technical aspects relating to strategies, methods and techniques.

5.1. THE GLOBAL PICTURE TODAY

Research reactors play a significant role in the field of nuclear science and technology. Since early prototypes were designed and put into operation in the 1940s, the number of research reactors worldwide has increased rapidly as a result of developments in the nuclear industry in general and nuclear power programmes in particular. Research reactors have also contributed substantially in the area of non-power applications such as radioisotope production in nuclear medicine, agriculture and industry; neutron beam research; neutron activation analysis; material development and neutron radiography; and training. Several hundred research reactors have been built and operated worldwide [2].

The picture has changed considerably over the past 5–10 years with the reduced demand for many of the aforementioned programmes [6], maturity of the nuclear industry, increased competitiveness of the radioisotope market, increased competition for R&D funds, escalating operation and maintenance costs of ageing reactors, or changes in regulatory and/or government policy [7]. A number of examples are given in Section 5.2. The number of redundant reactors has gradually increased to the point that the number of shut down/ decommissioned reactors now far exceeds that of operational ones. This trend has been clearly visible for a number of years and there are no signs of its reversal. This inevitably calls for more attention to be given to decontamination and dismantling of these older research reactors. Over 70 research reactors operating today are already 40 years old and will become likely candidates for decommissioning in the near term. Many of these reactors are located in Member States where appropriate decommissioning experience may not be readily available. It should also be noted that research reactors are situated in a large number of countries, making their decommissioning a real international issue.

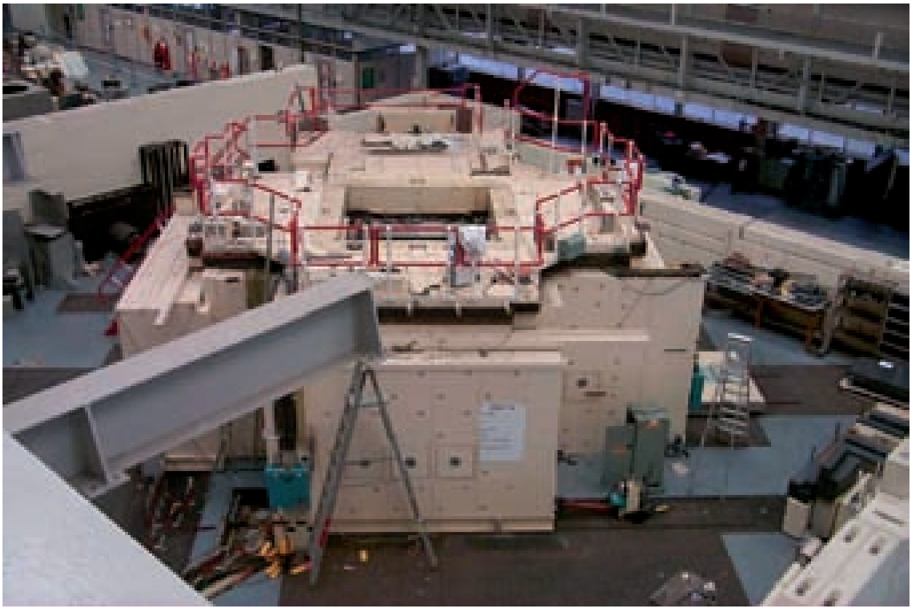
About 830 research reactors have been constructed worldwide to date, with some 20 more under construction or planned. Of these, about 290 are in operation and about 520 are shut down and at various stages of decommissioning. Approximately 25% of research reactors currently in operation around the world are over 40 years old. There are also several dozen research reactors that have not yet completed the decommissioning process (Table 1). The attached CD-ROM presents a detailed list of research reactors and gives the current status of each. The extent of decommissioning activities is expected to increase as more nuclear installations are taken out of service and fully dismantled.

The IAEA also monitors the progress of developments in decommissioning. For example, in 1998 it and consultants reviewed developments and produced a working document entitled Internal Report on Priorities for the IAEA Programme on Decontamination and Decommissioning of Nuclear Installations. In 2000 the IAEA conducted an internal performance, planning and assessment study (PPAS) on research reactors and low energy accelerators. The results of both working documents are reflected in this report.

One important consequence of the growth in decommissioning activities has been the experience gained from the decommissioning of larger nuclear facilities [8, 9]. Such projects include the total dismantling of large prototype facilities, which provided an opportunity to demonstrate that decommissioning could be performed in a safe and cost effective manner and also resulted in the further development and optimization of decommissioning techniques. In some cases, novel first use techniques have now become routine.

Following closure of a research reactor the overall decommissioning task is to remove the facility from regulatory control, which usually includes dismantling and the removal and disposal of all radioactive materials. As one example, Fig. 1 shows the Nestor reactor, Winfrith, UK, before and after total dismantling. Generally, the objective is to restore the facility or nuclear site to a condition suitable for unrestricted use. In cases where the plan for a site involves the remaining presence of radioactive materials above site clearance levels, the end state condition will be one of restricted use or in special cases in situ disposal (entombment). Recent examples of entombment or restricted use

(a)



(b)

FIG. 1. The NESTOR reactor, Winfrith, UK (a) before and (b) after decommissioning.

include, respectively, the RG-1M reactor in the Russian Federation [10] and the FR-2 reactor in Germany [11], which is currently being used as a museum (Fig. 2).

The IAEA previously defined three stages of decommissioning as the basis for assessing strategies. In recent years the IAEA has recommended a revised approach, based on the following definition of decommissioning: "the administrative and technical actions taken to allow the removal of some or all of the regulatory control from a facility" [12].

In this context, the IAEA now recommends three generic strategies or pathways, immediate dismantling, safe enclosure, and entombment, as further discussed in Section 6 [12]. Variations are possible, normally resulting from a combination of the above-mentioned strategies. The large decommissioning programme of the former USSR offers examples of typical decommissioning strategies for reactors as follows [10]:

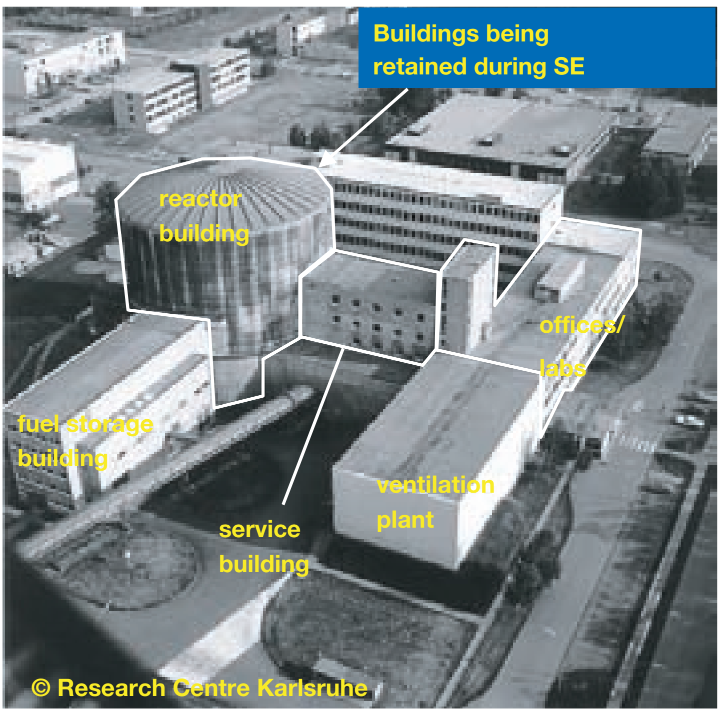


FIG. 2. The FR-2 reactor at the Research Centre Karlsruhe, buildings in safe enclosure (SE).

(a) The 2.5 MW(th) heavy water research reactor TVR. This was partially dismantled and portions of the site have been classified for 'restricted use' (Fig. 3).
(b) The 3 MW(th) heterogeneous WWR-2 reactor. This was dismantled 10 years after shutdown. The reactor building was demolished and the active liquid wastes, some of the solid waste and the irradiated reactor fuel were placed in suitable on-site storage facilities.
(c) Two training reactor facilities, VM-A and VM-4, situated at Paldiski (Estonia). These were placed in a condition of safe enclosure with three radiation protection barriers: a hermetically sealed primary coolant system; a hermetically sealed reactor compartment; and additional enclosures specifically constructed to withstand certain external events and impacts. These reactors do not require any maintenance, active control or power supplies. Periodic radiation measurements inside the shelter and routine air sampling are carried out through special penetrations in the walls of the enclosures
(d) The AM uranium–graphite water cooled reactor in Obninsk. This reactor was put into a substantial period of surveillance and maintenance in April 2002 [10, 13].

FIG. 3. The TVR reactor, Moscow: basement after dismantling of the cooling circuit.

Another feature of the worldwide scene has been the creation and expansion of a commercial market for decommissioning, which includes a multitude of contractors, specialist companies, consulting companies and other decommissioning oriented firms. This is in contrast to the mainly in-house strategic and technological approach prevailing in most countries in the 1980s and early 1990s. However, it should be noted that the current socioeconomic situation in many Member States does not yet allow full development of a competitive decommissioning market and the in-house approach remains a requirement or necessity due to such factors as loss of jobs and the costs of imported, proprietary technologies [14].

More recently, major advances have been made in decommissioning technologies, such as in electronics, computing and remote operations, which have contributed to significant improvements in decontamination and dismantling techniques. At the same time the regulatory environment has evolved, often requiring a more detailed assessment of proposals, stakeholder involvement and increased requirements for environmental impact considerations prior to the granting of approval for decommissioning activities. Also, there tends to be more detailed scrutiny of many individual decontamination and dismantling tasks.

Consensus is that more needs to be done to address the problem of the growing number of research reactors coming to the end of their operational lives and the large number of extended shut down, but not decommissioned, reactors, in order to ensure safe decommissioning. In many cases [15] these shut down facilities were essentially put into a 'do nothing' strategy. Major concerns in these cases include the perceived lack of attention to decommissioning by operating organizations, regulatory bodies and decision makers, the lack of funding and infrastructures, inadequate management, potential understaffing and the inadequate exchange of information between national stakeholders or IAEA Member States. Recent developments have focused on the need to definitively plan for decommissioning activities to follow shutdown operations in a timely fashion. A recent example is the shutdown and planned decommissioning of AECL's Whiteshell Laboratory, where emphasis was placed on completing a detailed environmental assessment and developing, planning and scheduling the decommissioning in parallel with facility shutdown operations [16]. In parallel with early planning for decommissioning, a growing percentage of research reactors today opt for immediate rather than deferred dismantling.

5.2. REASONS FOR DECOMMISSIONING

In the nuclear industry there are many reasons for facility shutdown and subsequent decommissioning. For research reactors these may include obsolete technology or process, lack of business need or support for continued operation, licensing and regulatory changes, incidents and accidents, legal and political operational constraints, change of site use and stakeholder pressure. While the decision making process leading to either plant closure or continued operation will be plant specific, guidance on the overall approach can be obtained through consideration of relevant practical examples, some of which are outlined below.

Numerous research reactors in the United States of America, originally supporting nuclear research and defence tasks, have fulfilled their mission and are now faced with the option of refurbishment and continued operation or shutdown and decommissioning, since some of these specific requirements are obsolete. The Oak Ridge Research Reactor (ORR) and the High Flux Isotope Reactor (HFIR) were both temporarily shut down in 1987. In the case of the 30 year old ORR, whilst the costs for safety and environmental upgrades were reasonable, the need for that particular research programme was obsolete and the decision was made to permanently shut down the facility. In contrast, the support for HFIR operations came from neutron scattering and radioisotope users, so continued operation was recommended [17].

Two German research reactors, FRG-1 and FRG-2, were of the same type and operated by the same organization. However, use of FRG-2 was limited to tests of power reactor components such as pressure vessel steel, fuel, cladding materials, etc. As the need for such tests had passed after 30 years of operation, the reactor was shut down in 1993. For the older 47 year old FRG-1 the neutron flux was increased and other measures were used to significantly increase its use. The operating organization now believes that FRG-1 can be operated until 2010, resulting in over 50 years of operation. This clearly demonstrates that where there is a need for the future use of a reactor, the design and age related problems can be fixed so that the reactor can be operated for a longer period of time [17].

The HIFAR research reactor in Australia began operation in 1958. Although originally designed exclusively for materials testing, it was modified over the years to allow for medical radioisotope production, neutron scattering research and irradiations services. It was decided to decommission HIFAR because of the construction of a replacement research reactor with enhanced capabilities [18].

An example of change of land use leading to decommissioning is the JASON reactor at the Royal Naval College, Greenwich, London, which was decommissioned to (then) IAEA Stage 3 status (unrestricted release) in 1999 in order to meet a military requirement to evacuate the site by the new millennium [19].

A further example is in the Russian Federation, where RF Minatom and the municipal government of Moscow decided to decommission nine research reactors of various types located at the Kurchatov Institute and MEPhI, Moscow. This included such unique facilities as a homogeneous liquid reactor, pulsed reactor, high temperature fast reactor, and was done despite continued programmatic needs and the possibility of technical upgrades. This decision was primarily made as a result of public pressure specifically opposing the operation of nuclear facilities in the city [20].

5.3. FACTORS AFFECTING NATIONAL POLICY AND STRATEGY

5.3.1. Regulatory framework

Nuclear regulatory bodies are generally concerned about aspects of decommissioning that involve nuclear and radiation safety. In particular, it is customary for the regulatory body to give special attention to safety assessments, waste management evaluations and risk evaluations for decommissioning activities.

In some Member States existing regulations do not specifically address decommissioning. A few years ago, deriving decommissioning regulations from those in force for construction or operation of nuclear facilities was the rule in most countries, often resulting in ambiguities, convoluted approaches and administrative delays [21]. This situation, however, is rapidly changing. If decommissioning regulations do not exist it is important for the operating organization to establish an early dialogue with the regulatory body. As decommissioning activities become more frequent, there is a tendency among Member States to develop decommissioning oriented guidance and/or regulations. For example, the decommissioning of the BR-3 reactor in Belgium was initiated in the early 1990s and carried out until 2001 in a regulatory regime of licence 'modifications'. This required a constant dialogue with the regulatory body. Eventually, decommissioning oriented regulations were enacted in 2001 [22].

Legislation and regulations governing research reactors vary considerably from country to country. In recent years the decommissioning of research reactors has been the subject of increased regulatory scrutiny. Early decommissioning planning is now recommended by IAEA standards [12]. It should be noted that new facilities are now generally required to address decommissioning aspects in order to receive authorization to operate. Although many existing research reactor operating organizations have not yet addressed decommissioning to any significant extent during operation, there are significant exceptions such as BR-2 in Belgium and the training university reactor in Hungary [23].

The regulatory process for decommissioning may differ from that required for reactor operation. For example, special regulatory arrangements may be required for waste management because of the increased volumes and types of waste generated during commissioning. Also, new regulatory issues may arise concerning removal of used fuel from the reactor or site.

The regulatory body may require decommissioning to be carried out in discrete, approved phases; and it ultimately approves release of the facility or site, as appropriate (for either restricted or unrestricted use). Approval of decommissioning projects by the regulatory body is now required by most national legislation, even for smaller reactors and critical assemblies.

Of special concern are the clearance/release criteria for unrestricted use of materials, buildings and sites. Various levels have historically been adopted in Member States. In some cases an ALARA approach has been pursued. It is noteworthy that the need to adopt internationally harmonized clearance criteria for materials and waste has been widely recognized over the past few years (e.g. to facilitate movement of materials across boundaries). This has led to international positions [24], even though differing national limits persist.

Another safety related area receiving growing attention is the transition period between operation and decommissioning. This area tended to be disregarded in the past in that attention was somehow focused on either operation or decommissioning, leaving a gap in-between. Guidance provided recently by IAEA publications [25, 26] addresses the specifics of the transition phase, including the cultural change needed for both operating organizations and regulatory bodies to adjust to the decommissioning mindset.

One important point is the need for the regulatory body and the decommissioning organization to reach agreement where the legislation is ambiguous. For example, in the UK there is a requirement that delicensing cannot be granted until it has been demonstrated that “there has ceased to be any danger from ionizing radiations from anything on the site or, as the case may be, on that part thereof”. A consultative document has recently been published as part of a process to quantify the meaning of this phrase [27]. This document proposes that ‘no danger’ could mean “a residual risk of no greater than one in a million chance of death per year from radiological exposure arising from any human made radioactivity left on the delicensed area of a nuclear licensed site”.

European Union countries are required to submit information relevant to safety and radiation protection for decommissioning facilities under Article 37 of the EURATOM Treaty. Two recent examples concern the decommissioning of Risø research reactors and other nuclear facilities in Denmark [28] and the FMRB in Brauschweig, Germany [29].

A general regulatory trend today is to encourage the completion of decommissioning of research reactors as soon as possible after final shutdown. While the same trend is true for larger facilities it is more relevant to research reactors, given the limited resources normally required for their decommissioning [12, 30]. In particular for research reactors, an additional argument for immediate dismantling is that the decommissioning waste volumes are generally much smaller than for nuclear power plants and can be easily accommodated in storage facilities if disposal repositories are not available. It should be noted that, in addition to safety considerations, the choice of strategy is influenced by political and other realities.

5.3.2. Resource aspects

One of the most significant considerations in selecting an appropriate decommissioning strategy is funding. Funding considerations include both estimated costs and the availability of financial resources.

Guidelines for preparing cost estimates and for project financing can be found in Ref. [31]. These guidelines have been applied for the decommissioning cost assessment of the Risø reactors [32]. Detailed planning should help to minimize total decommissioning costs by ensuring that the most appropriate strategy is selected. The funding of decommissioning strategy option studies is very important to ensure that a full range of viable decommissioning strategies is identified. The ‘do nothing’ strategy, which has been observed in the past, often occurs by default.

Historically, a clear tendency towards the establishment of decommissioning funding legislation has become evident in many countries over the last decade or so, such as in countries like the USA, which have significant private sectors [33]. For many State owned facilities, no funding provisions are made in the course of the reactor operation and funds are allocated by the Government only after permanent shutdown.

5.3.3. Reutilization of facilities

The usual objective of decommissioning in the past was to achieve the release of the nuclear site with no subsequent uses foreseen in the near term. A more recent development is the realization that the land and facilities associated with the decommissioned reactor may be of value, and consideration of site reuse could be beneficial and therefore be incorporated into the decommissioning plan. For example, immediate dismantling may be desirable in order to deploy existing resources for a different use. Reactor staff may be usefully re-employed at the converted facility. Also, much ancillary equipment, such as hot cells and cranes, may be used for other purposes. For these and other reasons it is not uncommon for reactor operating organizations to implement immediate and selective decommissioning policies in order to convert the facilities for reuse.

An example of this is the 10 MW(th) Astra reactor at the Austrian Research Centre in Seibersdorf, which started decommissioning in 1999 and is planning to be finished by 2006. The former reactor hall will be used as a storage facility for low level radioactive waste. Several more examples, including research reactors, are given in Ref. [34].

When there is no compelling requirement to reuse the land or facilities, a strategy of deferred dismantling is often selected. In particular, this strategy is sometimes selected when the research reactor to be decommissioned is located with other facilities on a common site. In such a case a decommissioning process that extends over several decades may pose no problems. In fact, it is not uncommon for such facilities to serve an educational and historical purpose; the FR-2 reactor situated at the Karlsruhe research centre in Germany is currently being used as a museum [11]. It is more common, however, for deferred dismantling to occur by default, usually due to a lack of funds.

The following references describe further cases where reuse and delicensing have already been achieved at research reactors and other types of nuclear installation. In some instances [35] licensees are reaching the stage where applications are being prepared for the reuse and delicensing of all or part of a site. The release of the Swiss underground experimental reactor at Lucens from nuclear monitoring and the reuse of parts of the underground cavities for cultural institutions are mentioned in Refs [34, 36]. The Polish reactor EVA was partly delicensed from the year 2000 onwards. The reactor building was transferred to a new owner and the construction of a dry spent fuel storage facility inside the reactor shaft is to be prepared [37].

5.3.4. Waste management

The availability and capability of radioactive waste management facilities is extremely important to the selection of an appropriate decommissioning strategy. Because of their experimental nature it is not unusual for a wide variety of radionuclides or physical-chemical forms to be found in the solid and liquid wastes of particular research reactors. While this waste may require special and sometimes rather complicated waste treatment technologies, it is now more common for appropriate equipment for treating and conditioning such wastes to be available. Special considerations may be warranted for certain types of wastes such as beryllium, tritiated water [10] and graphite [38].

Some Member States have one or more research reactors, but do not yet have an approved low level waste repository. Interim storage space for dry active wastes on-site may be limited, and acceptance criteria may not be available for the storage of some unique types of waste. In such cases immediate dismantling may not be a viable strategy.

5.3.5. Stakeholder acceptance

In the past, decommissioning of nuclear facilities was usually dealt with by institutional parties, typically nuclear operating organizations and regulatory bodies. Addressing the information and communication requirements for all stakeholders involved and interested in a decommissioning project has become significant in the last decade. The public has become increasingly interested in decommissioning plans. This interest has resulted in enhanced scrutiny and review of projects, particularly by safety and environmental regulatory bodies with direct responsibility for granting project approvals, and also by government officials who require detailed information to keep abreast of the broader interests and issues raised by their constituents [9, 39].

Effective communication is important to ensure stakeholder acceptance of a particular strategy. It is particularly important to respond to the concerns expressed by the various individuals and interest groups. The stakeholders for a decommissioning project can be divided as follows into three distinct groups in relation to specific areas of interest:

(a) Safety and environmental regulatory bodies: This group has a distinct and formal role in the development of a project from strategy selection through to the delivery of a project end state. Accordingly, this requires very detailed project information, and assessment of individual project activities on the basis of potential impacts on workers and public safety and on environmental safety. The recent trend towards significant public interest has further sensitized the regulatory groups to ensuring that project planning has adequately addressed issues and that appropriate justification exists for granting project approval. As stakeholders, regulatory groups have a special relationship with the project proponent.
(b) Government and political figures: This group represents the public at the local and national levels and needs to be well informed of the

decommissioning activity in relation to the public issues which may be raised. This group needs to have adequate information to be able to respond to public enquiries and to higher government levels, and needs to be well informed of the project's public communication mechanisms.

(c) The public: This group includes all groups and individuals who have an interest in the project (site staff, unions, site redevelopers, shareholders, local area residents, regional and national interest groups). The information requirements for this wide ranging group may be varied, requiring a variety of communication mechanisms. Staff and local residents are primarily concerned with economic and job impacts and safety and environmental considerations. Formal interest groups, local and/or national, may have specific issues of interest, such as national availability or provision of waste disposal facilities.

A detailed communication strategy and appropriate mechanisms need to be considered for each specific interest group in accordance with their areas of interest.

Public acceptance of nuclear activities in their vicinity generally ranges from suspicious acceptance to outright opposition. Experience has shown that efforts to educate the public on nuclear matters are only moderately successful in achieving public acceptance. However, experience has also shown that bringing the various interest groups together in a common forum where they are kept well informed and where they can make inputs to planning and proposed actions can be very effective in improving public acceptance of a proposed action. One case of special interest in this regard is the JASON decommissioning project. JASON was a low energy training reactor located in the King William Building (KWB) at the Royal Naval College (RNC), Greenwich, London. The KWB is part of a scheduled ancient monument. The works proposed for decommissioning were designed to avoid or minimize potential impacts on the KWB and the RNC site and were discussed with English Heritage. An application for scheduled monument clearance was made for the works and approved by the Department of Culture, Media and Sport. Regular liaison meetings were held with the London Borough of Greenwich, London Heritage and other stakeholders and, although not strictly required, an environmental report was produced [40].

Two examples of national approaches to the stakeholders' dialogue are given below.

The Swedish RISCOM model provides for a transparent public participation process. The RISCOM model for transparency was developed as a pilot project funded by the Swedish Nuclear Power Inspectorate and the Swedish Radiation Protection Authority. The overall objective was to support transparency in decision making processes in the radioactive waste programmes of the participating organizations, and also of the European Union, by means of a greater degree of public participation. In the old view (sometimes known as 'decide–announce–defend'), transparency often meant explaining technical solutions to stakeholders and the public. The task was to convince them that solutions proposed by implementers and accepted by regulatory bodies were safe. It was recognized that decisions would improve in quality if it were made clear to the public and the decision makers how the two elements interacted [41].

Two noteworthy nuclear reactor decommissioning 'stakeholder dialogues' took place in the UK, the British Nuclear Group (BNG) (ex-BNFL) 'Magnox Decommissioning Dialogue' and the UK Ministry of Defence (Navy) Nuclear Submarine Decommissioning 'Project ISOLUS Dialogue'. Although these are not directly related to research reactors, they are quoted here as significant examples of methodologies which would be applicable to a wide range of decommissioning projects for high energy research reactors.

The aim of the Magnox Decommissioning Dialogue was to bring together a range of stakeholders to identify and explore the various decommissioning strategies and their implications for future Magnox decommissioning projects. It was funded by BNG and facilitated by The Environment Council (TEC), which is an independent UK charity. TEC brought together people from BNG, British Energy, the government (e.g. the Department of Trade and Industry (DTI) and local government representatives), regulatory bodies (e.g. The Nuclear Installations Inspectorate (NII) and Environment Agency), professional organizations (e.g. INucE), academics, trade unions, non-governmental organizations (e.g. Friends of the Earth and Campaign for Nuclear Disarmament) and the community (e.g. concerned residents and local activist groups). The dialogue considered potential Magnox decommissioning strategies in a spirit of openness and transparency by generating a common understanding of issues, problems and solutions; mutual understanding of all stakeholder viewpoints; identifying where consensus existed and where it didn't, why; developing links with other dialogues and proactively engaging with other initiatives; and considering and exploring the strategies for Magnox decommissioning in the light of government policy by the use of the strategic action planning process [42].

The aim of the Project ISOLUS (Interim Storage of Laid Up Submarines) Dialogue was to undertake both an initial and an ongoing public consultation exercise as part of the wider UK MoD(N) review of its nuclear submarine decommissioning strategy to identify the most suitable future land storage solution and location for the cutting up of decommissioned nuclear submarines. Lancaster University was contracted by the MoD(N) to carry out a series of independent national consultations through ‘stakeholder workshops’ and ‘citizens’ panels’. This consultation showed strong public support for storing radioactive material from decommissioned nuclear submarines on land and acceptance that consultation was a positive step. The initial consultation produced some 65 recommendations, the vast majority of which were accepted by the MoD(N). Further consultation was implemented through a series of ‘focus groups’ [43].

5.3.6. Safeguards

Safeguards are a set of activities by which the IAEA seeks to verify that a State is living up to its international undertakings not to use nuclear programmes for nuclear weapons purposes [44]. The safeguards system is based on the assessment of the correctness and completeness of the State’s declarations to the IAEA concerning nuclear material and nuclear related activities. In relation to these arrangements, reactor operating organizations are now encouraged to use nuclear fuel that is less than 20% enriched [45].

Regardless of fuel enrichment, however, the administrative and financial burden relating to nuclear fuel is not insignificant. The requirements associated with the control and reporting of spent fuel, as well as associated nuclear material, vary among Member States. Regardless of the regulatory or political requirements it is generally accepted that early removal of such materials of interest may be a priority in any decommissioning strategy. The existence of any material of regulatory interest on an otherwise decommissioned site may result in significant ongoing expenses for safety and security reasons.

5.3.7. Expertise

It is now increasingly recognized that whenever a facility ceases operation many of the existing staff are no longer needed. The demographics of the existing staff may be a factor in considering a decommissioning strategy. Experience indicates that a strategy involving deferred actions will lead to the loss of experienced personnel. There is also a resulting socioeconomic impact on the surrounding community, and facility closure may alter the economic viability of that community. Socioeconomic impacts are of particular interest to facility staff and local area residents.

Unlike deferred dismantling, a strategy that involves immediate dismantling takes advantage of the expertise of existing staff. Conversely the availability of skilled human resources for deferred or future projects is a serious concern.

5.4. MANAGEMENT AND PLANNING

Decommissioning plays a special role within the overall nuclear industry. It should be noted that, because of the natural life cycle of nuclear facilities, decommissioning was the last component of a nuclear programme that attracted attention in most countries. Even today there is a perception in certain environments that decommissioning is an easily manageable activity which can be implemented at any time and needing no advance planning. This inaccurate perception was established in the years of a flourishing nuclear industry when the focus was on construction and operation of nuclear reactors, and planning for shutdown and decommissioning was relegated to a distant (yet unknown) future.

Specific attention to the subject of research reactor decommissioning is considered necessary because of the unique aspects of research reactor facilities when compared to other nuclear facilities. Significant aspects of research reactors making decommissioning activities distinctly different from other nuclear facilities may include [46]:

(a) A broad spectrum of research reactor types, including prototype reactors;
(b) Use of high enriched uranium (HEU) in many research reactors;
(c) Use of many types of fuel, including experimental and exotic fuel;
(d) Absence of self-shielding properties;
(e) Insufficient funding of operating and shut down facilities (a general consideration for research activities: in times of economic difficulties research is often the first sector to be sacrificed);
(f) A broad range and specificity of experimental work carried out in research reactors (e.g. impact of government policy, direction of national programmes);
(g) Proximity of some research reactors to the public domain.

In particular, attention to and planning for eventual decommissioning of research reactors has been generally poor in most countries during the lifetimes of their reactors (i.e. while these reactors were being designed, constructed, operated and shut down). Plans for decommissioning were at best ‘a rough conceptual plan’ in most countries, and proper infrastructure was either missing or inadequate. This included the lack of decommissioning oriented regulations, record keeping, waste management and disposal sites, expertise, training and technologies. All of these aspects did not receive proper attention and planning, with the inaccurate perception that decommissioning could be accomplished quite readily with minimal planning and available resources. Complacency in decommissioning planning and implementation has resulted in undue delays, lack of funding and other resources, and ultimately ended up with extra costs.

Another important consequence of poor planning for the decommissioning of research reactors was the tendency to approach each decommissioning project as a first of the kind project, even when experience was already available elsewhere. With time it became clear that experience was being gathered not only from active decommissioning projects but also from major decontamination and refurbishment of operating reactors. This is in turn was reflected in early and more accurate planning for decommissioning.

As for any decommissioning project, management and planning aspects are of key importance for the decommissioning of research reactors. The following section highlights the various developments and achievements in this area.

5.4.1. Selection of the decommissioning strategy

5.4.1.1. Decommissioning stages

In the past the IAEA defined three stages of decommissioning as a basis for assessing strategies (stage 1, storage with surveillance; stage 2, restricted site use; and stage 3, unrestricted site use). These stages are discussed in many references, e.g. [1, 3].

Some organizations still prepare decommissioning plans in accordance with these old IAEA stages. However, the definition of these stages was not completely clear. The end point of each stage was even less clear [47]. In recent years the IAEA has recommended a revised approach, based on the following definition of decommissioning: "The administrative and technical actions taken to allow the removal of some or all of the regulatory control from a facility" [12].

The IAEA identifies three strategies or pathways that lead to the end result. These are 'immediate dismantling', 'deferred dismantling (safe enclosure)' and 'entombment'.

Immediate dismantling is the strategy by which the equipment, structures and parts of a nuclear facility containing radioactive contaminants are removed or decontaminated to a level that permits the facility to be released for unrestricted use or with restrictions imposed by the regulatory body, and activities begin shortly after permanent termination of operations. It implies prompt and complete decommissioning and involves the removal and processing of all radioactive material from the facility to another new or existing nuclear facility for either long term storage or disposal.

Deferred dismantling (sometimes called safe storage or safe enclosure) is the strategy by which parts of a nuclear facility containing radioactive contaminants are either processed or placed into such a condition that they can be safely stored and maintained until they can subsequently be decontaminated and/or dismantled to levels that permit the facility to be released for other use [48].

Entombment is the strategy by which radioactive contaminants are encased in a structurally long lived material until the radioactivity decays to a level permitting unrestricted release or release with restrictions imposed by the regulatory body. Because radioactive material will remain on the site this essentially means that the facility will eventually be designated as a near surface waste disposal site. Entombment might be the most logical strategy for some countries with very small nuclear programmes, e.g. including just one research reactor [47, 49].

5.4.1.2. Strategy studies

Decommissioning can be an expensive process. It is becoming increasingly important to clearly demonstrate that the proposed decommissioning plan is the best value for money, environmentally and socially acceptable and safe. This is most readily achieved by conducting a professional and comprehensive evaluation of realistic strategies, leading to selection of the preferred strategy. A trend towards immediate dismantling prevails in several countries, particularly for small and medium size research reactors for which there is less justification for a safe enclosure period. The preference in general seems to be based on a range of considerations, notably the availability of know-how and experienced staff from the operational phase and the certainty of funding. Nevertheless there will still be cases in which one of the other strategies — deferred dismantling or entombment — may be appropriate. Immediate dismantling is the strategy preferred by the IAEA [47, 50].

In the past, most regulatory systems accepted for review one proposed decommissioning strategy. The current trend in many countries is that operating organizations submit a range of possible decommissioning strategies and justify the adoption of the preferred strategy. For example, in Germany the applicant for a decommissioning licence has to evaluate alternative technical strategies for the decommissioning of a nuclear facility. These strategies and the reasons why one of them is preferred have to be specified in the application documents for a decommissioning licence.

Under current UK statutory regulations the range of potential decommissioning strategies has to be detailed in an environmental impact assessment (EIA), which is required as part of the regulatory approval process for nuclear reactor decommissioning. These regulations, which came into force in 1999, prohibit the commencement of any decommissioning project in the UK without the consent of the Health and Safety Executive (HSE) (effectively the NII). The regulations require the licensee to produce an environmental statement; detail what information must be included in the statement; enable the licensee to seek prior information/opinion from the HSE; and requires the HSE and other consulting bodies, such as the Environment Agency, to assist in the preparation of an environmental impact statement (EIS) if requested. The regulations also describe how the HSE proceeds with an application, outlines how publicity matters are handled and details how decisions made by the HSE are promulgated.

The information required by UK Law in an EIS is very detailed and includes a description of the project; physical characteristics; land use requirements during the construction and operational phases; main characteristics of the production processes; nature and quantities of material involved; type and quantity of expected residues and emissions (water, air and soil pollution, noise, vibration, light, heat and radiation); outline of main alternatives considered by the licensee (effect on the environment and justification for the chosen alternative); and a description of the environmental impact (on humans, flora and fauna, soil, water, air, climate and landscape, material assets and cultural heritage). It also requires details of the likely effects of the proposed project on the environment (including direct, indirect, secondary, cumulative, short, medium and long term, permanent, temporary, positive and negative effects); a description of the measures used to prevent, reduce and offset adverse effects; and a non-technical summary of the EIS [51].

5.4.1.3. Sustainability

According to the Economic and Social Council of the United Nations, sustainable development can be defined as “meets the needs of the present without compromising the needs of future generations” [52]. Sustainable development is a long term interactive process that embodies environmental, economic and institutional factors and that needs to be developed over time [53]. Following various international environmental initiatives and agreements there is increasing emphasis on the need to demonstrate the application of sustainability principles in all projects.

Principles 4 and 5 of Ref. [54] incorporate ‘sustainable development’ into the field of radioactive waste management. In terms of decommissioning this does not necessarily infer a strategy of immediate dismantling, but rather encourages the production of a comprehensive framework that establishes needs, develops policies and strategies and considers a wide range of related issues.

Good decommissioning practice, including the selection of a decommissioning strategy, is dependant on consideration of all relevant factors. In cases where a specific constraint or overriding factor such as a lack of decommissioning funds prevails, attainment of a good decommissioning practice or sustainable development may not be possible.

The sustainable development approach could help to ensure that good decommissioning practice is identified early in the life cycle of a nuclear facility. Sustainable development during decommissioning is a key factor in the overall life cycle of a nuclear facility.

Examples of important issues that impact on the choice of the decommissioning strategy are summarized below.

5.4.2. Release/clearance criteria

The accuracy and comprehensiveness of radiological measurements is very important when dealing with radiological site release, material clearance criteria and endpoints. For material containing radionuclides of natural origin it is essential to agree reference background levels for the various areas and buildings on the site. The background activity is an important factor when considering whether material (e.g. building rubble), the building or the site complies with the clearance criteria.

Accurate definition of release/clearance criteria is an essential prerequisite to successful planning and implementation of a decommissioning project and may considerably influence the selection of a decommissioning strategy. Until recently, the case by case approach prevailed in many countries. In such cases it is important to achieve a comprehensive agreement between the operator and the regulatory body, also including such details as measurement and averaging strategies. A practical example of the application of these criteria is the decommissioning of the JASON reactor, where the radiological clearance and release criteria for materials and the site were agreed between the operator and the regulatory bodies very early on in the planning stage of the decommissioning project [25].

A number of Member States have introduced clearance levels for various clearance options into their national legislation (in particular some Member States of the European Union), some only very recently. Current clearance levels (for the same material and the same purpose) vary significantly between Member States. However, for crucial radionuclides such as ^{60}Co, ^{137}Cs or ^{90}Sr the range of variation is relatively small. Nevertheless, this variation may result in situations where material that has been cleared in one country and is moved across the border to another country might not be clearable in the recipient country. Therefore, achieving international harmonization of clearance levels would be a sensible aim. For the purposes of international harmonization, clearance criteria have been developed over the past 10 years in international bodies such as the IAEA [24, 55, 56] and the European Commission (EC) [57–59].

5.4.3. Final survey

A decommissioning plan should include provisions for implementing a final radiological survey. This is crucial because it demonstrates that a significant milestone in the decommissioning project has been contractually completed, ensures that the regulatory bodies are satisfied and that they will issue the appropriate certificates of revocation and release. Equally important, it assists the process of achieving public confidence that the site is now satisfactory for unrestricted or other use. With the growing number of completed decommissioning projects, more attention has been given in recent years to this final step of the decommissioning process.

The final radiological survey report forms a key part of the basis for the application to release the facility or site from regulatory control [12, 60, 61]. It is important that the final survey be independent of previous surveys and that it be undertaken by adequately trained and qualified personnel. In many countries it is now undertaken by a completely independent organization, with a proven track record and having the respect and confidence of the general public. The statistical basis for the final survey is well established and the case by case approach prevailing in former times is obsolete. Examples of final survey methods are reported in Refs [62, 63].

5.4.4. Fuel management

The removal of spent fuel is an important step in the decommissioning of research reactors. Benefits of early defuelling include decreased radiological hazards, timely implementation of dismantling, downgrading of the operational licence, shutdown of some systems (e.g. surveillance), and reduced safeguards requirements. In addition, as long as fuel remains in the fuel storage pools, continuous manning of the unit with shift workers may be required, albeit with a reduced number. If consideration is given to adopting shorter refuelling cycles towards the end of the plant’s life the period required for cooling the fuel in the fuel storage pool is reduced. Thus the pool can be emptied earlier than would otherwise be the case. Costs could thus be reduced accordingly.

As long as all infrastructure and provisions are in place, final defuelling can be done in the same way as during plant operation. However, if removal of fuel is delayed for a very long time, loss of qualified staff and necessary equipment could create a problem. Also, the costs of surveillance and maintenance may increase dramatically.

In some research and prototype reactors defuelling is not a routine operation and requires special planning during the operation to decommissioning transition period. Even in projects where a transport container is available, some adaptation may be needed, e.g. to couple the container to the reactor [64]. Typical handling issues include:

(a) Reactors where refuelling is a one-off operation;
(b) No fuel storage pond is available;
(c) Lifting equipment may not be capable of carrying fuel transport containers;
(d) Space for loading fuel elements into transport containers may not be available.

Timely removal of reactor fuel is an important prerequisite of any decommissioning strategy. Recent international developments have highlighted this. Many research reactors were provided with fuel from another country. Reactor operators planned to return the spent fuel to the supplier when necessary, but in many cases this has now become impractical or difficult for a variety of reasons. As a result, spent fuel has been accumulating in at-reactor storage facilities for some time with an indefinite future storage period, complicating practical completion of decommissioning projects.

In the USA, the University of Illinois chose in 1999 to put its TRIGA reactor into a safe storage mode for at least a decade because they were unable to dispatch its spent fuel. The estimated cost of keeping the reactor in safe storage was US $23 000 per year, not including the salaries of the engineers responsible for periodic surveillance and monitoring. Even with a computerized monitoring system to allow remote monitoring of the entire reactor facility it was estimated that at least two individuals would spend 25% of their time on monitoring and surveillance. That brought the estimated cost of the project to nearly US $50 000 per year [65].

As another example the Egyptian ETTR 1 reactor, which uses Russian EK-10 fuel, has recently built a new spent fuel storage/fuel encapsulation facility to protect the fuel from corrosion prior to the Russian Federation making a decision on when it will take back the fuel. Repatriation of spent fuel of Russian origin will hopefully solve this major issue soon [2, 45, 66].

The USA has extended to 2016 its programme to take back US origin research reactor fuel (the deadline was recently extended by 10 years due to delays in developing new high density low enriched uranium (LEU) fuel to replace the HEU fuels currently in use around the world [67]). The US spent fuel repatriation policy has been in place for a few years and has contributed to solving this major issue for many research reactors worldwide [45, 66]. For reactors that operate with non-US or non-Russian origin (e.g. indigenous) fuel, however, disposition of used fuel is very problematic. Other technical aspects related to the removal of spent fuel from research reactors have been documented by the IAEA in Ref. [4].

In addition to the removal of nuclear fuel it is highly desirable to eliminate the potential for criticality during the transition period. If the spent fuel and other nuclear materials cannot be moved outside the nuclear installation, decommissioning cannot be fully completed. One example of the avoidance of this problem was the removal of spent fuel from the JASON reactor in late 1998. Special procedures were required to remove the spent fuel from the reactor hall without jeopardizing building integrity (Fig. 4).

In order to comply with the acceptance criteria for the safe transport of nuclear fuel, the precise unirradiated and irradiated characteristics of each fuel assembly have to be verified and be in full compliance with all safety rules at

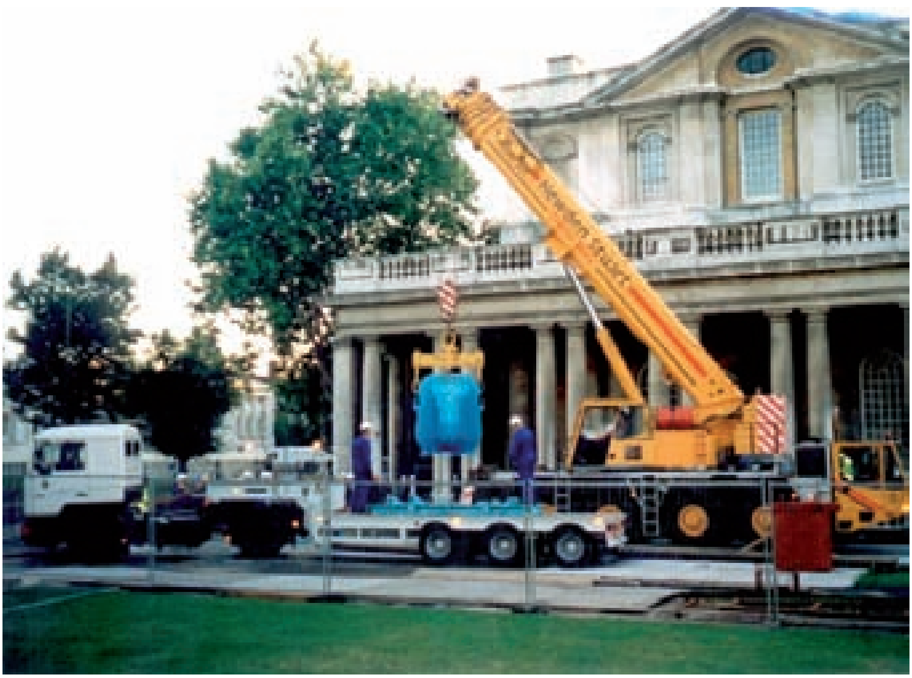


FIG. 4. Spent fuel removal from the JASON reactor, UK.

every step of transport, reception, unloading, storage and treatment of the spent fuel in the reprocessing plants, if any. COGEMA's experience [68] has shown that the first verification stages are based on documents, long before the fuel is shipped. General criteria for the acceptance of sound spent fuel were developed long ago and are well consolidated. They relate to geometry and mechanical integrity after chopping, non-leaking fuel and, for damaged and leaking fuel, to supplementary criteria having to be met.

5.4.5. Planning for decommissioning

Ideally, planning for decommissioning should start at the design stage [12, 30, 69]. This was not the case for early generations of nuclear facilities, which means that current research reactor decommissioning projects may not be able to benefit from design features that make decommissioning easier. However, the IAEA recommends that if an initial decommissioning plan was not prepared, it should be prepared without undue delay [12, 30]. Currently, the IAEA is assisting a few Member States (e.g. China, Romania, Serbia and Montenegro) in the drafting of decommissioning plans for research reactors [70]. It is noteworthy that some Member States such as Egypt, India and Pakistan [71] are now utilizing their refurbishment/upgrading projects to gain experience and establish a database for eventual decommissioning of their research reactors.

Experience from a wide range of decommissioning projects that have been implemented over the last years indicates that the basic principles of decommissioning can be applied, to the appropriate extent, to any nuclear plant, whether it is large or small, complex or simple. In evaluating concepts and choices it is a question of the extent to which a particular principle would apply in a particular case. Detailed decommissioning planning applies individually for each decommissioning project.

5.4.5.1. Structured approach

A particular decommissioning plan will normally be developed in a sequential manner that recognizes that all decommissioning projects consist of sets of generic tasks, namely:

(a) Preparatory work (supporting decommissioning);
(b) Final shutdown;
(c) Removal of radioactive sources (including liquids) sometimes called post-operational cleanout (Fig. 5);
(d) Radiological characterization;

FIG. 5. With a number of experiments having been conducted in them over their lifetimes, many research reactors appear untidy at final shutdown. Post-operational cleanout is a necessity in such cases to simplify subsequent decommissioning.

(e) Decontamination and dismantling;
(f) Demolition of structures and buildings;
(g) Surveillance and maintenance (throughout the duration of the project);
(h) Waste management (existing and during decommissioning);
(i) Site clearance and release.

5.4.5.2. Contents of a decommissioning plan

It is now widely recognized that any viable decommissioning project can be outlined in a decommissioning plan (what is to be done and how it is to be done), supported by a safety assessment (demonstrating safe methods and regulatory compliance).

Reference [12] sets out a contents list for a typical decommissioning plan. However, unless the project is very small the decommissioning plan is likely to consist of a series of documents, each produced to cover a particular purpose or a particular phase of the project. The important issue is that the planning documentation meet the spirit and intent of the IAEA guidance. Thus, in practice, a cross-referenced family of documents will typically be produced such that, when taken together, they do meet the IAEA guidance. Reference [72] describes in detail the contents of safety related documents in the context of decommissioning.

A key feature of the supporting safety assessment is that within the selected decommissioning strategy and associated decommissioning plan there is a demonstrated connection between the plant condition at shutdown, the proposed decommissioning tasks, the associated risks in performing these tasks and the resultant safety management arrangements.

5.4.5.3. Integrated approach

The availability of specialized nuclear facilities (such as waste treatment plants, interim storage facilities or repositories) can have a major impact on the viability of a proposed decommissioning project and on the realistic strategies. Therefore, decommissioning at any nuclear site is best organized in the context of an integrated site plan. As part of the overall site plan it is also necessary to determine the current condition of systems, buildings, facilities and equipment that are planned to remain in use. This will almost certainly involve a significant programme of surveys and investigations.

A recent good (and large scale) example of an integrated approach is represented by the life cycle baselines and near term work plans that have been prepared as integrated plans for each of the 20 nuclear sites in the UK (including a number of research reactors). These plans, which were produced for the recently formed UK Nuclear Decommissioning Authority (NDA) [73], have been structured on a common basis that allows all of them to be rolled up into one overall integrated NDA plan. Another example of an integrated approach is the decommissioning plan developed in Canada for AECL's Whiteshell Laboratories, documented in the Whiteshell Laboratories Decommissioning Plan [74].

5.4.5.4. Harmonization of approaches

Historically, decommissioning was regulated using procedures developed for construction and operating purposes, which has often resulted in ambiguities and delays in planning and implementation of the decommissioning programme. In recent years, however, regulations have been developed to specifically deal with the decommissioning activities.

Much progress has been made in the development and publication of a wide range of guidance dealing with various aspects of decommissioning, including approaches to harmonize licensing procedures. Reference [75] gives a German example. In order to provide assistance to those who are dealing with the decommissioning of nuclear facilities, a 'decommissioning guideline' was published in 1996 which compiled all regulations relevant for licensing and supervising the decommissioning of nuclear facilities. As the 'Länder' (Federal States) in Germany are responsible for licensing and supervising nuclear facilities/activities, this guideline helps to harmonize the application of the legal and regulatory framework and the overall licensing procedure among the Federal States. A great number of amendments have been made to the legal and regulatory provisions in Germany in recent years, so the decommissioning guideline is under review and will be updated.

5.4.5.5. Work breakdown structure

Although, in general, project management techniques have been widely used for planning and managing decommissioning, considerable effort has been made in recent years to ensure that best practice techniques have been adopted in the planning and implementation of decommissioning projects.

A particularly useful aspect is the increasing adoption of the work breakdown structure (WBS) as a means of defining the work elements and the relationships between them.

A WBS organizes the project into manageable activities. The activities are devised starting from the overall objective and a WBS is created, as in the following example:

(a) Project objective (e.g. decommissioning of research reactor X);
(b) Subsections (e.g. dismantling of system XY);
(c) Individual tasks (e.g. removal of pipe XY99P of system XY);
(d) Subtasks (e.g. cut part of pipe XY99P between valves XY55V and XY56V).

One advantage of this approach is that the individual activities (expressed in the form shown above) can also be shown on the corresponding schedule — which provides a time-based scheme of all the activities. In this way, the project plan is consistent and clear.

Such a chart or schedule organizes the various project activities (as specified in the WBS) into a logical activity flow, taking into account inter-dependences, key dates and milestones. It can be a simple bar chart, or a more complex chart (supported by dependency criteria and data), such as a Gantt or PERT (critical path) chart and including resource planning/reporting tools. This overall approach greatly assists the optimization of cost estimates, time, resources, project progress and the achievement of target dates. It also allows study of ‘what if?’ scenarios, identifies potential problems and focuses attention on the key tasks.

References [76, 77] provide guidance on the UKAEA PRICE system of parametric cost estimating for reactor and site decommissioning projects. This system requires that the task or project first be described in terms of a hierarchical or work breakdown structure. Reference [31] also recommends the WBS system to enable detailed decommissioning costs to be estimated.

5.4.6. Regulatory interfaces/licensing

Historically, review and assessment of decommissioning projects has implied several changes in regulatory and licensing aspects. These have been basically due to a major move from a case by case approach for ‘first of a kind’ projects to consolidated legislation, regulations and procedures. These changes took place gradually, in parallel with growing experience gained by regulatory bodies, operators and policy makers.

Initially, nuclear legislation in most Member States was based on design, construction and operation of nuclear facilities. Decommissioning was generally ignored and considered a long term issue. When the first decommissioning projects (including a number of research reactors) were submitted for the attention of regulatory bodies, they had to resort to the application of laws and regulations that were not conceived for decommissioning. This situation often resulted in a convoluted approach, ambiguous interpretation and possibly unjustified case by case variations. With time most Member States included decommissioning in their legislation and regulations. Licensing and regulatory procedures are now well consolidated in most Member States.

In parallel with the above developments, regulatory requirements and safety review procedures have become more standardized and available to nuclear operators. For example, the contents of a final decommissioning plan tended to be standard and applicable to all types of nuclear facilities, albeit at a different quantitative degree. It became clear that the technical specifications applicable to a decommissioning plan were not to be a simple reduction of those in force during operation, but were required to be radically different in their nature.

A significant example of regulations evolving over the years is clearance levels. Initially, in most Member States, clearance was based on practices in use during a facility’s operation. Then the case by case approach prevailed. Eventually, clearance levels were established in a number of Member States.

The current challenge is to attain international harmonization of clearance levels and it can be assumed that this objective is being achieved [24]. Several Member States are already using international recommendations as the basis for national regulations in this field.

Another major change in regulatory/licensing interfaces has been in the timing of decommissioning plans. The view prevailing in many Member States in the past decade or two was that a decommissioning plan was only required after permanent shutdown. It was generally unspecified how soon after shutdown the decommissioning plan had to be drafted. This resulted in a number of complications due to loss of experienced staff, deterioration of records, demotivation of remaining workers, etc. Eventually it became clear that a detailed decommissioning plan was essential prior to and not later than permanent shutdown, and this position is now generally accepted. IAEA Safety Standards [12, 30] now specify that preliminary decommissioning plans ‘shall’ be drafted at the design stage.

With time, the regulatory process included consideration of environmental impacts from the decommissioning of a nuclear reactor. This has led to legal requirements for an environmental impact statement, generally not limited to the radiological impacts but also addressing impacts such as socio-economic, transportation or land use impacts. Two US examples are given in Refs [78, 79].

5.4.7. Management of plant status and change

The activities associated with the planning/management of change during a decommissioning project can be divided into either technical or administrative activities [3, 4, 12]. These are discussed in the following sections.

5.4.7.1. Technical activities

Technical planning/management activities are normally taken to include a review of the operating rules, maintenance and emergency and health monitoring arrangements to reflect changes in plant status. It is now increasingly recognized that the transition from operation to decommissioning needs special attention, particularly at research reactors, where a team of researchers can find it hard to convert to demolition tasks [25]. In this transition phase the job specifications, qualifications and training of key staff are identified, including definition of interfaces among the facility personnel, contractors and regulatory staff. A recent development has been the increased emphasis on the operating organization’s responsibility, including ensuring proper management of contractors at all times [9].

Once the decommissioning team and support staff have been identified and appointed, the work packages are specified, together with the preparation of special work procedures, work allocation and review arrangements. The data collection, records, reports and system for updating existing documentation are normally reviewed and suitable arrangements are made for taking/collecting relevant project photographs and videos.

Emphasis on the need for accurate records is a relatively recent development [80], as growing experience with the decommissioning of older reactors shows how the lack of as-built drawings or material specifications can be very detrimental to successful decommissioning.

The decommissioning project would normally be divided into stages, and project reports on each stage or package would be produced as appropriate. Special decommissioning related equipment would then be selected and acquired. The overall safety management arrangements are normally reviewed and amended as required.

5.4.7.2. Administrative activities

Administrative planning/management activities usually include provision and approval of the project budget; recording and monitoring of financial expenditure; control of costs and schedules; allocation and control of contracts; communications with the regulatory bodies, personnel services and staff [9].

5.4.8. Implementation aspects

It is increasingly recognized that nuclear decommissioning is a generally mature industry and that practical solutions to most of the major implementation problems have been devised. The following sections highlight experiences of general interest.

5.4.8.1. Project resources and communications

Some key lessons learned and practical points that have proved to be valuable in managing the human resource and communications aspects of recent decommissioning projects include the early identification of a project team, resources and training before planning work is commenced; the inclusion of ex-facility operations staff in the project/decommissioning team (or at least ensuring that facility operations staff knowledge is available to the decommissioning team); and the implementation of activities preparatory to decommissioning by the operations staff.

5.4.8.2. General relationship with regulatory bodies

More than one regulatory body may be involved in decommissioning. For example, in the UK, the NII covers nuclear safety and the Environment Agency covers environmental discharges. In some Federal States in Germany, licensing and supervision of decommissioning are done by different regulatory bodies (ministries).

It is important to understand the role(s) of the regulatory bodies in each specific case and to establish interface arrangements. This can be difficult in countries where decommissioning is a new activity. In some instances, primacy may be agreed between the regulatory bodies — i.e. an agreement on which regulatory body is to take the lead. Historically, interface provisions were hard to set in place at the time when decommissioning projects were first of a kind, but they are well settled now and directly covered by law in many countries.

One of the most challenging and substantial tasks is the preparation of the decommissioning plan, including safety assessment and its subsequent approval by the regulatory bodies. Within the context of the overall decommissioning plan, including safety assessment, experience has shown that having a single point of contact with the regulatory bodies and obtaining agreements on site clearance criteria and the methods for achieving these criteria are vitally important. These include determining natural background radiation levels, agreeing actual background radiation levels and the format of the final radiological survey, and the organization (ideally an independent one) that will carry out this survey. Clearance criteria, end point and the final radiological survey are considered in more detail in later sections.

Experience has shown that a productive and effective relationship with regulatory bodies can be achieved (a) through agreements over regulatory action plans that allow decommissioning work to continue while specified actions are completed to an agreed schedule, and (b) the use of document review processes that ensure that the regulatory review is proportionate to the potential magnitude of the hazard. It can be beneficial to agree a set of regulatory process categories together with associated review procedures. For example, a high category safety assessment would be subject to full external review, whereas the lowest category would only require local review and approval.

According to the IAEA, the end point of decommissioning occurs when the site is released from regulatory control.

5.4.8.3. *Use of contractors*

Contractors have been used in some research reactor decommissioning projects. The decommissioning market now typically covers a wide range of activities including the contracting out of project management services, cost estimates, robotic techniques, decontamination activities, dismantling and demolition. The decision about which work items are given to contractors or whether to contract the entire decommissioning project depends on the details of the research reactor in question, the market of possible contractors in the specific country, the personnel employment strategy and other considerations.

Provision of incentives to both contractors and staff can be beneficial when these are related to key objectives such as waste minimization, cost savings and exposure reduction. A potential issue with extensive use of contractors is that the operating organization — which remains legally responsible — might lose control of the project. Currently there is evidence to suggest that cooperation between the operating organization (with its site and regulatory experience and vested interest in discharging the liability) and contractors with clear prior experience of organizing and discharging decommissioning projects is the most effective combination [81]. Further information on this point is given in Ref. [9].

5.4.8.4. *Approach to radiological and conventional safety*

The general regulatory approach is that the licensee (operating organization) is liable for any harm to persons or property arising from ionizing radiation on the licensed site. Also, persons involved in nuclear decommissioning operations are expected to be suitably experienced and qualified for the work that they undertake [82].

The licensee is also responsible for ensuring that radiation doses from its operations are as low as reasonably achievable for its employees, contractors and the general public [82]. This is generally a legal requirement and is typically achieved by setting corporate dose restriction levels that are more restrictive than regulatory limits and setting dose restraint objectives for plant and activity managers and requiring mandatory dose minimization.

Much experience has been gained in recent years in the area of optimizing radiation exposure of decommissioning workers, in accordance with the ALARA principle. ALARA based designs and work instructions are aimed at producing cost effective solutions, taking into account all economic and social factors to reduce worker exposure. An example of how to meet the ALARA requirement during decommissioning is the VISIPLAN software tool developed in the context of the BR-3 decommissioning programme [83] (Fig. 6).

Another example of the benefit of using simulation to enhance decommissioning operations occurred during the decommissioning of the Advanced Reactivity Measurement facility reactor at the INEEL, USA. In this case it was initially believed that because of high radiation fields it would be necessary to use underwater cutting techniques to disassemble the core support structure, an expensive and time consuming process. After modelling the structure and applying the Decontamination, Decommissioning, and Remediation Optimal Planning System (DDROPS) software, it was determined that the structure could be removed in one piece and cut into smaller pieces using conventional cutting technologies [84]. A similar approach has been adopted at the BR-3 reactor, Belgium (Fig. 7). Radiation protection aspects of an ongoing reactor decommissioning project (ASTRA, Austria) are described in detail in Ref. [85].

During the decommissioning of the JASON research reactor a relatively small total collective worker dose of 1.688 man mSv was accrued by all licensee and contractor personnel, with most of this dose occurring during reactor dismantling (1.029 man mSv). The total collective dose was about 20% of the initial planning target, as the early planning estimates were pessimistically

FIG. 6. Typical Visimodeller screen shot. Geometrical elements from complex environments are selected by a simple click of the mouse.

FIG. 7. The ALARA principle put into practice: on-site cutting into large pieces of the BR-3 reactor using a semi-automatic tool.

based on surveys and calculations made immediately following the last reactor shutdown. In addition to global planning assumptions, dose estimates for individual jobs were calculated during the ALARP (the UK equivalent of ALARA) review/dose reduction measures that took place for each nuclear procedure or method statement carried out [19]. Another case where the predicted and actual dose uptakes differed considerably was the ICI Triga project, also in the UK. More details on that project are given in Ref. [64].

It is increasingly recognized that the radiological aspects of decommissioning, although very important, are among the routine activities that take place within the overall environment of health and safety in the workplace. Therefore, general health and safety principles are essential when planning and implementing a decommissioning project (covering radiological and non-radiological aspects). It is generally recognized today that non-radiological safety aspects may be as important in decommissioning as the radiological ones. A recent report by the OECD/NEA highlights both radiological (criticality, loss of containment, external irradiation, and ingestion and inhalation of radionuclides) and non-radiological (fire, explosion, toxic and hazardous materials, electrical, and physical) hazards [86].

5.4.8.5. Testing of decommissioning techniques in real scale projects

Over the past 10 years or so, several decommissioning projects have been used to test and optimize a number of decommissioning techniques. This information has proved to be invaluable for the decommissioning community at large in not 're-inventing the wheel'.

For example, the BR-3 (SCK/CEN, Mol, Belgium) and JEN-1 (CIEMAT, Madrid, Spain) decommissioning projects were conducted under the auspices of the EC [87, 88] and included a large portion of R&D activities [89, 90]. Figures 8 and 9 depict significant decommissioning activities at BR-3 and JEN-1, respectively. Reference [91] reports on the overall achievements of the R&D decommissioning programmes of the EC. In the USA, several research reactors (EBWR, CP-5, JANUS) were subjected to extensive R&D programmes during their decommissioning. Many innovative decommissioning technologies were also tested and demonstrated as part of a large USDOE programme [92, 93]. A relevant task during the ANL EBWR decommissioning project is shown in Fig. 10. Testing activities at ANL's CP-5 reactor are shown in Fig. 11. The IAEA also collected much data and operator experience, including R&D efforts, on decommissioning technologies [8, 71]. With the successful completion of the above-mentioned R&D and testing activities, most experts now consider that decommissioning is a mature industry, or at least that it offers technology capable of tackling almost all decommissioning issues.

5.5. DECOMMISSIONING AND WASTE MANAGEMENT TECHNIQUES

This section covers both equipment and technologies related to decommissioning, waste management and planning techniques. It discusses progress and lessons learned in the following areas: important strategic/preparatory considerations; decontamination and dismantling techniques either applicable to all types of research reactor or specific to particular types of research reactor; and decommissioning waste management. In addition, this section deals with related findings by the IAEA. Wherever practical, material from previous publications is used [4, 8, 94, 95].

FIG. 8. BR-3 decommissioning project, SCK/CEN, Mol, Belgium: lifting the BR-3 reactor pressure vessel (RPV) (26 t).

5.5.1. Important strategic/preparatory considerations

An important component of a decommissioning project is the availability of the various infrastructure/facilities in a country or at a site that will be needed to support the decommissioning of a particular facility.

It may also be necessary to consider the challenges and options presented by the fact that the nuclear infrastructure in some countries was historically shared (e.g. in the former Soviet Union or the former Yugoslavia). Subsequent independence has created a need to deal with the problems created by this previous centralization. In some cases it may be found that new plants and

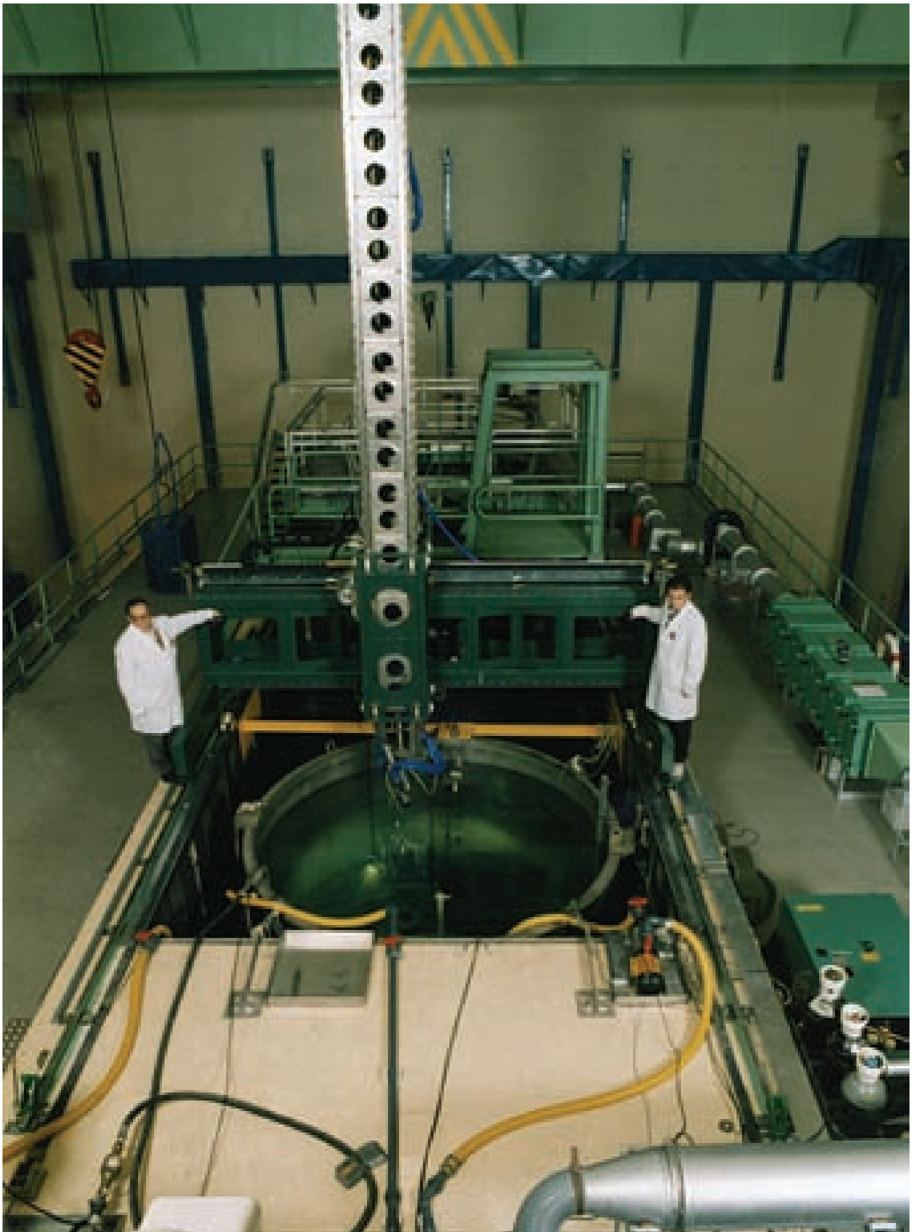


FIG. 9. JEN-1 decommissioning project, CIEMAT, Madrid, Spain: underwater cutting machine.

FIG. 10. Split ring cutting machine in place and ready to begin removal of the reactor vessel cavity liner at EBWR, ANL, USA (source: Argonne National Laboratory, USA, contract no. W-31-109 ENG 38).

facilities are required in order to support the proposed decommissioning project. One such case is the IRT reactor decommissioning project at Salaspils, Latvia. No waste conditioning was anticipated during operation, and a cementation plant was erected in 2002–2003 in preparation for decommissioning, with the assistance of the IAEA (Fig. 12).

5.5.1.1. Waste minimization

Studies of decommissioning projects have shown that one of the largest elements of cost is the treatment, handling and disposal of radioactive waste, and these costs are generally proportional to waste volume, noting also that the cost may vary dramatically with changing waste categories. According to recent IAEA estimates [96], waste management costs can be up to 50% of the total decommissioning expenditures. In addition, this situation can be complicated by the shortage of processing, storage and disposal capacities. Thus there has been a strong incentive to reduce the volume of wastes arising from decommissioning activities. Waste minimization can be enhanced in a variety of

FIG. 11. Robotics orientation session for operation of the Red Zone Robotics ‘Rosie’ unit (source: Argonne National Laboratory, USA, contract no. W-31-109 ENG-38).

ways, many of which have been documented in Ref. [95]. Additional measures include the waste minimization strategies adopted for the BR-3 reactor decommissioning project [97, 98].

The availability of clearly defined and officially approved clearance criteria and industrial capacities for pretreatment/decontamination of materials from decommissioning could have a positive impact on waste minimization by recycling and reuse. This provides licensees with the opportunity to choose between expensive disposal and the potential to recover costs through the sale of recycled materials.

During decommissioning, non-radioactive hazardous materials may be encountered or generated. These materials may include asbestos, mercury, beryllium, aggressive solvents, spent oils, etc. Quantitative assessments of hazardous, non-radioactive waste arising during decommissioning of research reactors are generally unavailable or extremely variable. To quote a few available examples, the central part of the BR-2 reactor vessel, Belgium, contains the beryllium matrix, which is used to position all fuel elements, control rods, beryllium plugs and experiments. Each moderator contains 79 beryllium channels. The waste that originated from the first moderator

FIG. 12. The IRT reactor, Selaspils, Latvia: waste cementation plant (detail).

(which has a lifetime of about 15 years) contained 535 kg of beryllium [99]. Asbestos data are also extremely variable. At the BR-3 reactor, Belgium, a major asbestos removal campaign resulted in a quantity of 6567 kg removed (more quantities were removed in subsequent campaigns) [100]. At EBWR, approximately 72.9 m^3 of asbestos was removed from the facility during decommissioning. Of this amount, only approximately 1 m^3, weighing 292 kg, was also radioactively contaminated [62]. Reference [62] also gives the amounts of contaminated and activated lead resulting from EBWR decommissioning. Problems encountered with the management of special materials, including beryllium, and solutions found in the course of refurbishment/decommissioning of SCK/CEN installations at Mol, Belgium, including the BR-2 and BR-3 reactors, are described in Ref. [99]. Consideration is currently being given in many decommissioning projects to the selection and implementation of processes that minimize the generation of such wastes.

5.5.1.2. Safe enclosure approaches

Many Member States have nuclear research facilities but no nuclear waste infrastructure (i.e. no capability to treat and dispose of radioactive wastes). Hence there are incentives in those States to place their shut down nuclear facilities into a period of safe enclosure (or period of care and maintenance) while the contained radioactivity decays and/or until appropriate arrangements can be made for disposal.

The IAEA has recognized this constraint and has published guidance [48, 101] on dealing with periods of safe enclosure, which involves ensuring that the stored facility remains in a passively safe state, requiring only minimal human intervention in order to maintain safety. An example of deferred dismantling is illustrated by the Estonian training reactors VM-A and VM-4 (see Section 5.1).

Safe enclosure approaches are not generally applied in cases where the research reactor site includes alpha contaminated facilities. There is a strong advantage in decommissioning such alpha facilities early because plutonium facilities suffer ingrowth of americium and alpha particle damage to materials in contact with the plutonium and deterioration with time as seals and gloves degrade.

One important element of deferred dismantling is the long term integrity of systems, structures and components. At first sight it may seem that there will be limited data and records with which to commence a long term integrity study for a reactor. Experience shows that advantage can be taken of data and records produced during normal operations. In particular, there will usually be information associated with operational safety (e.g. the condition of essential

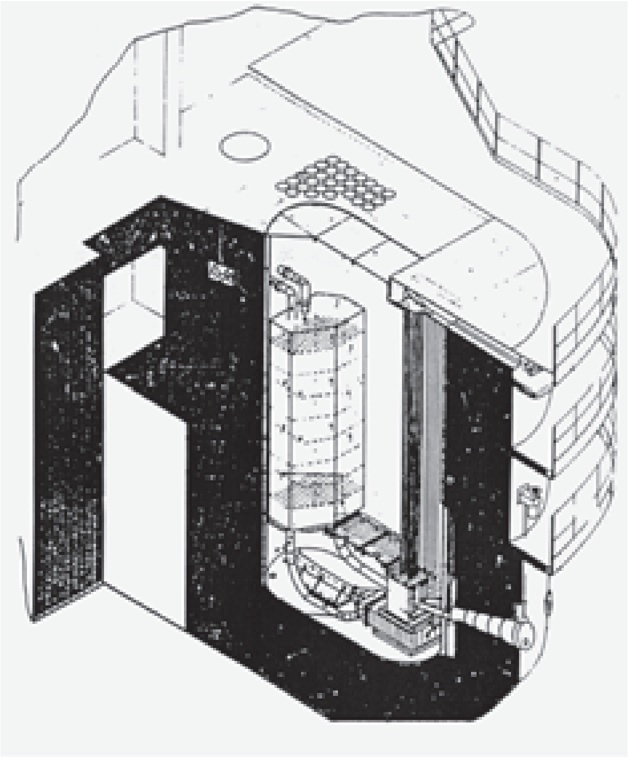


FIG. 13. Sketch of the nuclear reactor tank, IRT-M, Georgia.

reactor circuits and systems), planned maintenance, breakdown maintenance and routine inspections.

A realistic appraisal of the current condition is an essential starting point for estimating the potential lifetime and for estimating any new work that may be required. Obtaining such a realistic appraisal is not easy. Adequate time and resources need to be set aside within the overall decommissioning programme to allow assessment of the current condition.

It will be apparent from the above that considerable work and expense may be necessary to establish long term integrity data and decisions for a reactor installation. Therefore, when defining and evaluating alternative decommissioning strategies it is important to assess facility and equipment requirements before embarking on detailed analysis and investigations. Any resultant work can then be focused on the needs of the selected decommissioning strategy and plan.

FIG. 14. Sketch of the tank of the IRT-M nuclear reactor after concreting.

Many nuclear facilities are constructed from concrete and hence a good understanding of the ageing management of concrete structures is an important aspect of long term integrity studies [102, 103].

5.5.1.3. Entombment approaches

Entombment (in situ disposal), where the reactor is wholly or partly disposed of at its existing location, was a viable decommissioning strategy in the early years of the nuclear era. It was practised satisfactorily in a few countries. However, environmental concerns on the proliferation of actual disposal facilities in sites not necessarily optimized for that purpose led in practice to a moratorium of several years on this strategy.

However, entombment can also be attractive if the research reactor is situated far from the populated localities in an area and where the geological and hydrological characteristics are potentially suitable for construction of a near surface repository. Such conditions exist, for example, in the far north of the Russian Federation near Norilsk [104].

Another application of entombment would be the adaptation of some existing on-site facilities for on-site disposal. For example, it is intended that the operational and decommissioning low level radioactive waste from the RG-1M reactor at the Norilsk mining and metallurgical complex in the Russian Federation will be disposed of on-site in the existing radwaste storage facility, which will then be converted into a near surface repository [10, 104]. Another example of entombment is the IRT reactor in Georgia (Figs 13, 14), although this strategy is not foreseen by the Georgian operator to be a permanent solution. In general, entombment may be a viable decommissioning strategy for countries needing to decommission a single facility and not having the resources to develop or obtain the infrastructure needed for dismantling and waste disposal.

5.5.2. Decommissioning techniques

In the early days of decommissioning of nuclear facilities, considerable effort was expended to design and develop specialized devices to accomplish specific tasks in radioactive environments. As experience has been gained in a wide variety of decommissioning projects, it has been found that many tasks can be accomplished by adapting commercially available equipment. As a result, less R&D is currently pursued for decommissioning equipment. It should also be mentioned that large R&D programmes on decommissioning, such as those conducted by the EU and the USDOE, came to an end in the mid to late 1990s.

Experience has shown that mature conventional methods and commercially available technologies can be conveniently used wherever possible. This approach helps to reduce costs, optimizes worker efficiency, keeps decommissioning simple and improves equipment reliability. Currently available or adapted techniques often provide the quickest, safest, most reliable and cost effective solutions for decommissioning projects. Therefore, the best approach is to keep techniques and tools as simple as possible, use tried and tested equipment and, where necessary, also test the equipment on a mock-up of the proposed operation. Then, if possible, first gain experience on tasks associated with lower radiological hazard before moving on to more challenging activities. Figure 15 shows the mock-up facility used to test the grouting of the IRT reactor in Georgia. Figure 16 shows the wire cutting test facility at BR-3, Belgium.

FIG. 15. Mock-up facility to test the IRT-M reactor grouting, Georgia.

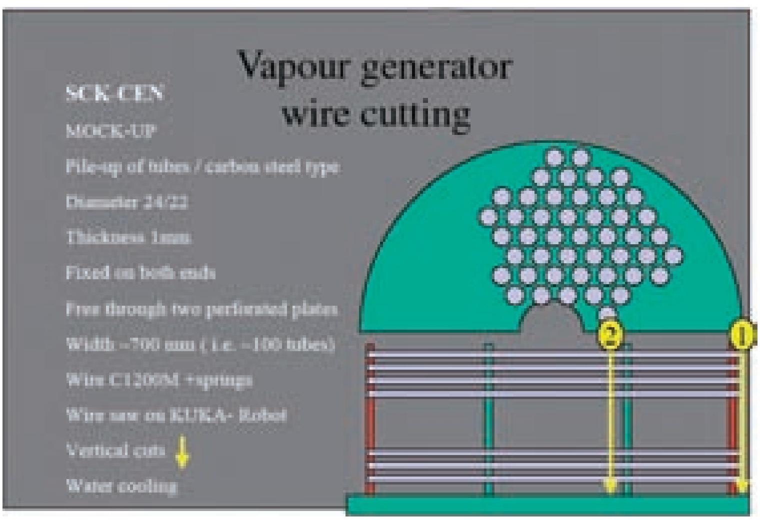


FIG. 16. Wire cutting test facility at the BR-3 reactor, Belgium.

In general, a detailed review of an earlier IAEA publication on decommissioning of research reactors [4] indicates that the technical aspects addressed in Section 6 of that report remain as valid today as when the report was written. Progress and changes in approaches or requirements to these areas have been documented under appropriate subheadings throughout this section. Since the publication of Ref. [4] a number of other publications have been issued by the IAEA on this topic. For example, a general overview of developments through the 1990s with respect to decommissioning techniques for all kinds of nuclear installations can be found in Ref. [8]. An overview of decommissioning techniques relating specifically to research reactors is contained in Ref. [71].

The following section provides a brief overview of decommissioning techniques. It is, however, not the intention of this publication to cover specific decommissioning techniques in great detail.

5.5.2.1. Segmenting/cutting techniques

The development of segmenting or cutting techniques (thermal, mechanical, others) has progressed considerably over the past 15 years. A considerable number of techniques used in conventional industrial segmenting/dismantling have been adapted and made ready for application in nuclear decommissioning projects. Segmenting and cutting techniques for application underwater have also been developed to maturity. Important examples are the R&D projects performed by the Lehrstuhl für Werkstofftechnologie at the universities of Hannover and Dortmund in Germany. Ultimately, a number of national and EU research projects have led to the development of a family of underwater segmenting techniques, which have found application in a number of research reactor decommissioning projects [105–107]. Other techniques have been specifically developed for research reactors. There is, for example, a special R&D activity in Germany for development of techniques designed for research reactors, taking into account constricted space, lack of certain waste treatment techniques (relevant for secondary waste generation), etc. [108]. A selection of cutting activities carried out at the HDR decommissioning project is shown in Figs 17–19. Suitable segmenting techniques for graphite reactor components have also been developed to some stage of maturity, for example water abrasive cutting techniques [109]. These techniques are especially needed for a large number of research reactors.

In summary, segmenting or cutting techniques for decommissioning have advanced to such a state that only minor development of certain techniques is required to fit the individual needs of certain research reactor decommissioning

FIG. 17. Thermal dismantling at the HDR project, Germany.

FIG. 18. Pipe sawing at the HDR project, Germany.

FIG. 19. Orbital sawing at the HDR project, Germany.

projects. However, a number of tools have been improved. Several decommissioning techniques have been tested and optimized at the BR-3 project (e.g. the reciprocating saw shown in Fig. 20). In the UK, several dismantling techniques were tested and demonstrated in the decommissioning of the LIDO reactor [110].

A selection of innovative US technologies can be found in Ref. [92]. Figure 21 shows the BROKK excavator during decommissioning of the EBWR, USA. Advances in robotics have been conspicuous over the last years and have been applied, among others, to cutting and segmenting tools. Robotic developments are documented under the USDOE's large scale demonstration projects, e.g. Refs [111–113]. Figure 22 shows a robotic manipulator at the JEN-1 reactor decommissioning project, Spain.

5.5.2.2. Decontamination techniques

Like segmenting techniques, decontamination techniques have also been developed to a very advanced state. Chemical and mechanical techniques can now cope with practically all decontamination issues. However, a general tendency towards the use of mechanical techniques can be observed, especially

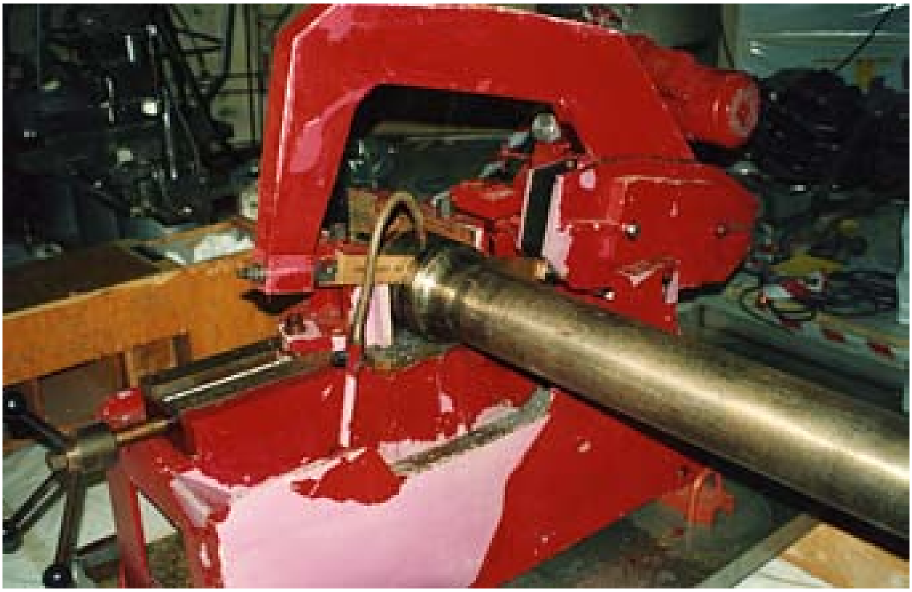


FIG. 20. Reciprocating saw cutting reactor head standpipes at the BR-3 decommissioning project, Belgium.

for large scale decontamination in decommissioning projects. The reason is that the secondary waste generated by mechanical decontamination techniques is considerably easier to treat, especially at research reactors where liquid waste treatment plants may not be readily available. This may also influence the possibility for decontamination of cooling circuits of research reactors prior to dismantling (the equivalent to a full system decontamination in nuclear power plants with light water reactors, which is often performed before decommissioning begins to reduce radiation levels).

In 1998, the IAEA provided an update on decontamination techniques [114]. This publication was intended as a tool to assist those involved in the selection and implementation of decontamination techniques for particular installations. In summary, it has been found that decontamination techniques need only slight adaptation to fit most decommissioning projects. A comprehensive description of decontamination techniques and experience gained in the course of the BR-3 decommissioning project is given in Ref. [115]. Figure 23 shows a device used for decontamination of concrete surfaces at the CP-5 facility, USA [116].

FIG. 21. BROKK excavator being lowered to the lower level at EBWR in preparation for the start of bioshield concrete removal (source: Argonne National Laboratory, USA, contract no. W-31-109 ENG 38).

5.5.2.3. Radiological characterization techniques

The success of a decommissioning project depends to a large extent on adequately establishing the radiological inventory, covering radiation sources, contamination and activation products such as ^{60}Co. This process is called radiological characterization. Its main objective is to determine the scope of the decommissioning project. There have been cases where inadequate characterization of parts of the site (e.g. building foundations, sewage or groundwater) has led to significant extra costs and delays. The case of the Cintichem reactor, USA, is highlighted in Ref. [80].

Radiological characterization is executed in three phases, namely an initial desk survey followed by the physical survey and interpretation of data. The initial desk survey is an information gathering and planning exercise covering facility and site layout details, uses of the site before current reactor operations and the current operational plant records. This desk survey provides information in order to adequately plan the physical radiological survey.

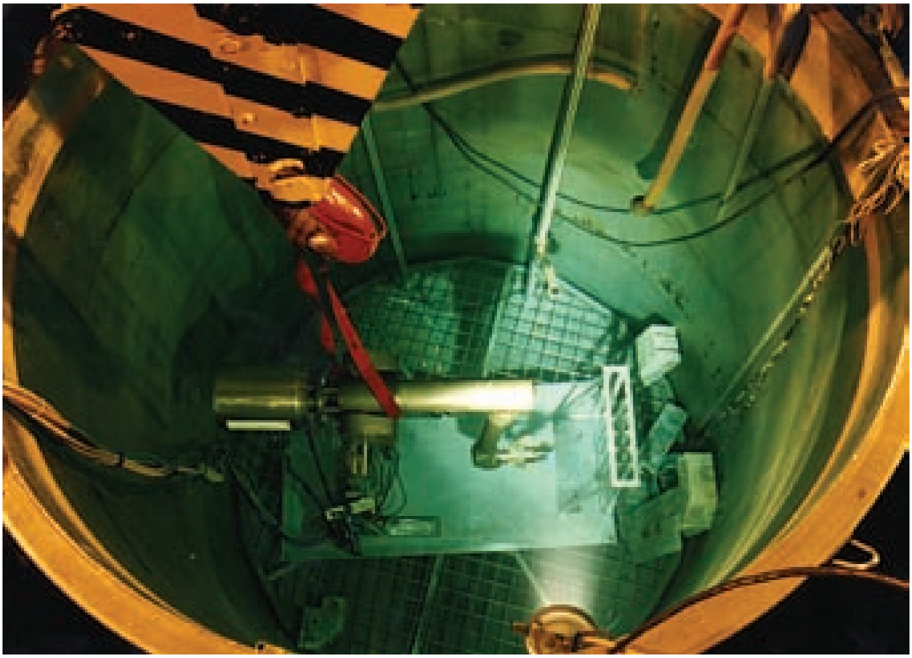


FIG. 22. JEN-1 decommissioning project, Spain: robotic manipulator.

The physical survey covers all potential contaminated and activated structures, components and surrounding areas in order to quantify the actual radiological inventory. The physical survey may cover reactor/site/store internal and external dose rates and contamination levels, activated components, drains, ventilation systems, core sampling, background radiation levels, types of radionuclides, etc.

A prerequisite to successful characterization is the identification of all geometrical and layout details. A facility database is commonly prepared during operation to plan for decommissioning. 3-D models and interactive software are now available, which allow the optimal planning of decontamination and dismantling activities. Figures 24 and 25 (from the TRIGA decommissioning project, Republic of Korea) illustrate the use of IGRIP software, a tool to graphically simulate decommissioning activities [117]. Another software package, Visimodeller, was developed in the course of the BR-3 decommissioning project in Belgium and is based on radiological characterization and simulation of decommissioning activities (Fig. 6).

FIG. 23. ROTO PEEN sealer/VACPAC being used for decontamination of concrete surfaces at the CP-5 facility, USA.

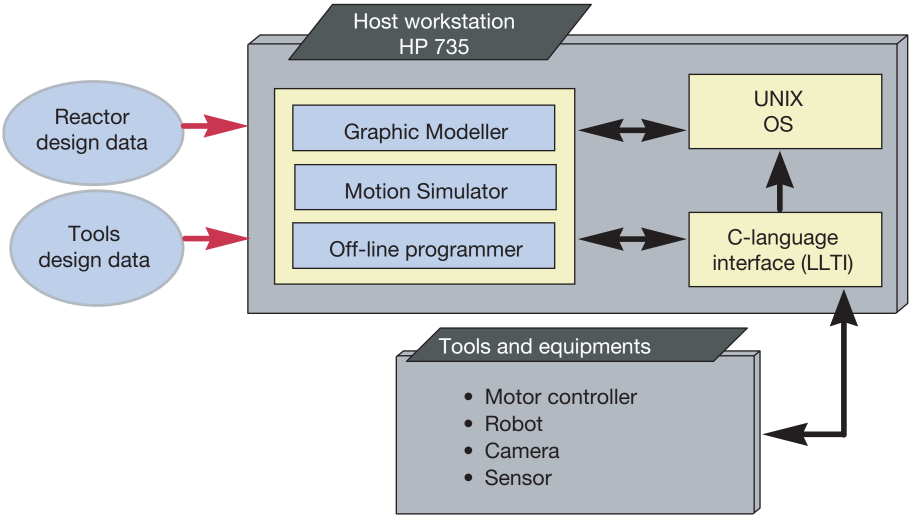


FIG. 24. TRIGA reactors, Republic of Korea: configuration of the IGRP graphic simulation system.

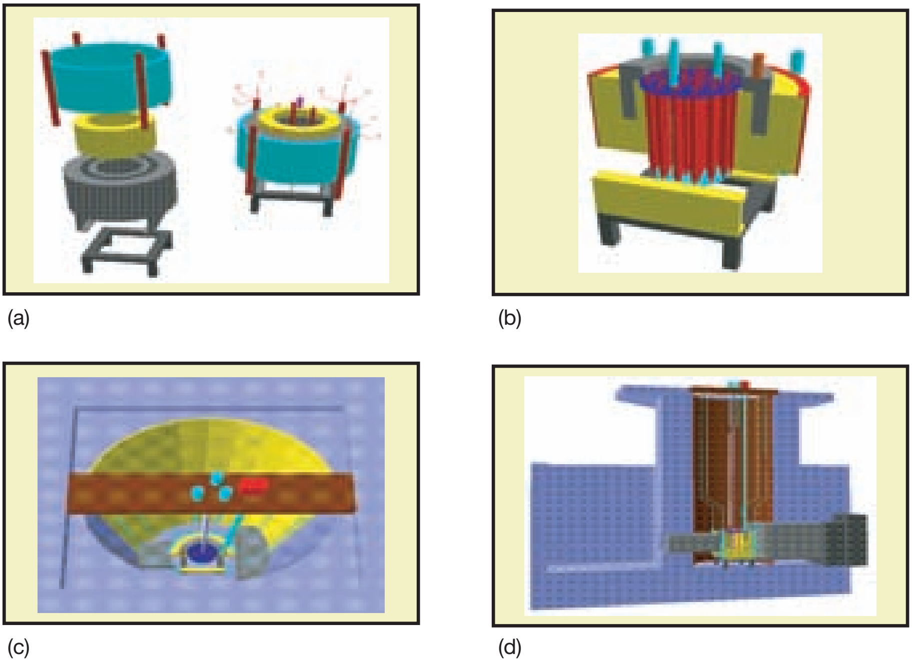


FIG. 25. Model of the TRIGA research reactor, Republic of Korea (a) core and reflector, (b) fuel element, (c) centre channel, (d) reactor internals.

In recent years the need to ensure thorough and accurate record keeping in view of future decommissioning has become clearer to a number of countries. For existing reactors, a situation of poor or inaccurate radiological data may require that missing data have to be reconstructed prior to implementing active decommissioning. Reference [80] reports on experience and issues in record keeping from several research reactors.

Radiological characterization provides important information for the identification of contaminated/activated areas, delineation of radiologically controlled zones, estimation of types, quantities and class of radioactive waste and support of planning and cost estimates. One significant change that has taken place over the last decade is the emphasis on earlier and more detailed radiological characterization. In recent years there has been an increased regulatory driven requirement to include more detailed characterization data in decommissioning plans issued for approval. These data then form part of the basis for assessment of project strategy and for the decontamination/ dismantling approaches taken for individual project components.

Experience has shown that investigations (such as core sampling) and surveys are always necessary, as things may not be exactly as anticipated. Also, radiological samples can show large variations in trace element concentrations. Hence it is important to ensure that the radiological characterization provides adequate statistically significant coverage. Comprehensive reviews of radiological characterization methods are available in Refs [94, 118, 119]. It is particularly important to determine the most relevant isotopes, taking into account the type, history and age of the facility, to survey all areas where spills or other radiological accidents are known to have occurred and to assume that the radioactivity is higher than the exemption level for inaccessible surfaces.

Other considerations arising from experience include determination of the degree of penetration of contamination into the concrete or soil, which is especially important around construction joints or under floors or roads that have been resurfaced. In some cases it may be necessary to take core samples or to sink boreholes to confirm compliance at depth and on the surface. It is also important that sufficient and up to date information on the radionuclide composition be available, because previous radionuclide transport/adsorption processes may well have changed the original composition and position with time. This is particularly critical for penetration into subsoil or concrete foundations [80].

Another significant change over the years concerned the radioisotopes under investigation. The traditional release or clearance criteria have normally been expressed in terms of alpha, beta and gamma surface or mass specific activity, or in terms of dose rates, derived from fundamental risk and dose levels. Radionuclides of interest were typically ^{60}Co, ^{137}Cs or alpha emitters.

Currently, the concentrations of a larger number of radionuclides need to be measured, and this requires extensive laboratory analysis for some hard to detect radionuclides. Radionuclides that have been difficult to detect have usually been correlated to other key radionuclides which are easy to measure, so called 'fingerprinting' (e.g. ^{63}Ni is correlated to ^{60}Co or transuranics to ^{137}Cs).

The development of in situ gamma spectrometers over the last decade has transformed this technique, which was once confined to laboratories, into a standard technique particularly suitable for building surface and soil measurements. A number of devices with NaI or Ge detectors are available, some of which have been specifically designed for clearance measurements of buildings and sites, using a collimator (thus restricting the area to be measured in order to allow quantitative measurements in Bq/cm^2). These types of detector require extensive calibration techniques, which have been well developed over the last decade. Examples of applications are given in Refs [120, 121]. An important development over the last few years relates to increasing reproducibility and automation of the results.

The in situ object counting system (ISOCS) is a portable spectroscopy system designed to provide information on the type and amount of radioactive material. The associated software automatically determines the relationship between the radioactive source geometry, the measured count rate and the amount of radioactive material. The ISOCS was demonstrated at the CP-5 decommissioning project and at INEEL [122, 123]. Similar experience in Europe is summarized in Ref. [124]. Another system also used at CP-5 was the Mobile Automated Characterization System (MACS) for large open floor areas (Fig. 26) [125]. Another application is described in Ref. [126]. Over recent years, detection and measurement of alpha emitters has become increasingly important during reactor decommissioning. Reference [127] reports on further developments in this area.

Progress in characterization techniques also includes devices that are capable of accessing difficult to reach areas, e.g. for sampling purposes. For example, a variety of products are now available for pipe characterization [36, 92] (Fig. 27), concrete core drilling (Fig. 28) or underwater characterization [128]. While a large variety of detectors have been developed, the innovative application of these devices has resulted in sophisticated measurement techniques used for material clearance. Section 5.4.2 provides relevant descriptions [94, 117, 118, 123].

FIG. 26. The MACS being used at CP-5 for radiological characterization (source: Argonne National Laboratory, USA, contract no. W-31 109 ENG 38).

Various types of area/material characterization devices are currently available:

(a) Gamma locators/gamma cameras superimpose different coloured spots reflecting gamma dose rate intensity onto a normal picture of the environment [129–134].
(b) Release measurement facilities (RMFs) consist of a number of detectors (usually large scintillation counters) surrounding the material to be measured on four or six sides (4π geometry). The total gamma emissions are counted, which allows back-calculation of the nuclide specific activity contents via nuclide vectors (‘fingerprints’). RMFs are usually designed for material quantities of several kilograms, up to 1000 kg. They have typical measurement times of around one minute or less and normally have a high degree of automation, allowing a fast throughput of material for clearance evaluation. One example out of many is given in Ref. [135].
(c) The cobalt coincidence measurement (CCM) method is feasible in areas where the main contamination originates from ^{60}Co and where there is a high radiation background. Pairs of detectors surrounding the material to be measured detect the two photons emitted at each decay of a ^{60}Co

FIG. 27. Pipe crawler characterization technology being 'checked out' prior to demonstration at the CP-5 facility (source: Argonne National Laboratory, USA, contract no. W-31-109-ENG-38).

atom. If the two photons are registered within a certain time window, the decay is attributed to the material, otherwise they are discounted as background. This technique has proved to be applicable to clearance measurement in a variety of nuclear installations [136].

(d) By way of a recent example of a land quality characterization exercise, during the decommissioning of the JASON research reactor site characterization was carried out for both the reactor hall facility and adjacent buildings and land. The land characterization survey was split into two phases. Phase 1 was the desk survey and phase 2 was an intrusive site survey [137].

The phase 1 assessment of all land and buildings on the site covered:

(1) Site reconnaissance (records of past and present activities, underground drainage, storage tanks, PCBs, made ground, adjacent activities, blighted vegetation and surface drains);
(2) Area reconnaissance (records of adjacent land use, off-site activities and public rights of way);

FIG. 28. Concrete core drilling device, ASTRA reactor, Austria.

(3) Historical records (past and present area maps and town plans, locations of dumps, stores, workshops, laboratories, boilers and transport areas);
(4) Review of geology and hydrogeology (groundwater, surface water, local rivers, aquifers, surface pollution, drinking water and borehole data).

The phase 2 intrusive surveys covered the site drains; adjacent building radiological survey; sludge sampling; soil borings and surface swab sampling. The actual intrusive surveys consisted of a closed circuit television survey of the drains in the areas that could have received fluids from the reactor or other hazardous chemical and radiological workshops, laboratories or sources; radiological survey of all drainage systems and adjacent buildings; excavation and sampling of soil and sludge located at areas of the drainage system suspected of having leaked or having collected silt or sludge; sampling of all laboratory surfaces and subsequent full analysis at National Measurement Accreditation Service (NAMAS) laboratories [19].

A further example of a detailed programme for pre-decommissioning radiological characterization at Risø, Denmark, is given in Refs [119, 138].

5.5.3. Decommissioning waste management

5.5.3.1. Waste treatment, conditioning and packaging

Many of the waste treatment techniques (such as evaporation, supercompaction and incineration) and waste conditioning techniques (such as bituminization and cementation) that are still in use today have been available for a number of years. However, in some countries commercial companies are offering more and more state of the art facilities and services covering waste treatment and conditioning.

One reason for this trend is the increase in the types and quantities of wastes resulting from the substantial growth in decommissioning activities worldwide. For research reactor decommissioning projects it will often be found that it is not economically worthwhile to buy the equipment needed to treat and condition such wastes, hence the trend towards commercialization of such services and equipment.

One of the driving forces for application of waste treatment techniques with a high potential for volume reduction has been the fact that interim storage space as well as repository space (where available) has become increasingly expensive. Volume reduction therefore has a considerable cost reduction potential [95]. As an example of a disposal facility for decommissioning waste, Fig. 29 shows a view of the Baldone disposal facility, Latvia, currently in use for the Salaspils reactor's decommissioning waste.

A dominant trend in recent years is the recognition that all wastes (both operational and decommissioning) must be properly processed and conditioned prior to storage and/or disposal. This was unfortunately not the case in a number of old research reactors where radioactive wastes were commonly dumped in underground vaults with no proper conditioning. The interim waste storage facility at the Salaspils reactor, Latvia, is one such example. Eventually wastes were retrieved from the pits in a remote controlled manner. Figure 30 shows one detail of the process, the video system assisting the retrieval operations inside the interim storage building. A similar situation existed at the Paldiski site, Estonia. The solid waste storage is illustrated in Fig. 31. At Paldiski these miscellaneous wastes were eventually removed and conditioned.

As a result of such initiatives, current methods and technologies for radioactive waste management are more comprehensive than they were 15 years ago. In addition, methods for waste treatment and conditioning for disposal have become more harmonized, including more standardized

FIG. 29. The Baldone disposal facility, Latvia.

FIG. 30. Remote controlled system for cutting radioactive parts extracted from the first interim waste storage pit, Salaspils reactor, Latvia.

FIG. 31. Solid waste storage at Paldiski, Estonia.

packaging. Figure 12 shows a detail of the cementation plant at Salaspils, Latvia. A waste cementation facility was not in place during the operation of that reactor and had to be installed — with the IAEA's assistance — in preparation for decommissioning. Figure 32 shows various types of waste containers used at the Salaspils decommissioning project.

Waste characterization in preparation for storage or disposal has received increasing attention in the past few years. At the Joint Research Centre (JRC) Ispra a waste characterization system has recently been installed which allows characterization of 200 L barrels both by gamma scanning and by active neutron interrogation [139].

5.5.3.2. Wastes requiring special handling

Research reactors, by definition, are experimental facilities intended for investigation of new processes or new materials, or behaviour of existing materials in specific conditions, etc. Therefore, radioactive wastes generated during such operations may have unusual radionuclide and chemical compositions when compared with those from nuclear power plants. As an example, Table II in Ref. [71] lists unusual contents of liquid wastes from

FIG. 32. Waste containers at the IRT decommissioning project, Salaspils, Latvia.

research reactors. Such wastes may require special and rather complicated technologies for treatment and conditioning. Compliance with waste acceptance criteria may require special consideration.

Fission product contaminated graphite is a further example of unusual waste. Fission products influence the physical and chemical properties, and the inherent stability of graphite during storage. Examples of graphite problems and solutions are given in Refs [38, 140, 141]. Similarly, as stated above, beryllium requires special handling [99].

5.6. INFORMATION EXCHANGE

The sharing of information and experiences among decommissioning projects on an international level may be very beneficial in achieving efficiency and safety. Operating organizations and regulatory bodies are encouraged to adopt best practices that stem from past experience. Various means are available today for efficient information exchange, ranging from working groups and training courses to databases and web pages. Important aspects are outlined below.

5.6.1. Information dissemination

It is now recognized that there is a need for continued development and use of improved documented techniques by which best practices, know-how, experiences and lessons learned are made available to a wider audience. There has been increased emphasis on improving the dissemination of all information relevant to decommissioning, particularly regarding the improved availability of information and published documents on the Internet over the past decade.

A major step towards having relevant information available at any time has been achieved by making a large number of IAEA publications available on the Internet [142]. Other international organizations such as the EC and the OECD/NEA (as well as important national organizations like the competent ministries and other authorities in Member States) have put documents and general information concerning decommissioning of nuclear installations on the Internet. It should also be mentioned that a number of decommissioning projects have designed informative web sites which show details of the decommissioning process.

An example of the effective promotion and dissemination of decommissioning related information is the bibliography of relevant web sites [143]. Relevant findings extracted from IAEA publications are quoted in the following to provide examples of how information is disseminated by the IAEA to the world's community.

Section 6 of Ref. [8] deals with methods and technologies for decommissioning, under the headings of radiological and non-radiological characterization; decontamination; disassembly; waste management; robotics and remote operation; miscellaneous techniques and operations; and software tools.

Section 7 of Ref. [8] summarizes the lessons learned. These lessons learned include, among many others, that estimated activation and contamination levels are often far from the actual values and sampling is necessary to assess real values; on-site decontamination is to be preferred if it is consistent with optimization of operator dose, costs and waste management; plasma arc and all other thermal cutting systems tend to spread contamination and require means to contain it; underwater cutting is an efficient technique that limits operator exposure; regardless of the above, all the advantages and drawbacks of the different methods (cutting speed, overall speed, secondary waste generation, dose uptake, cost, etc.) should be balanced

Other valuable lessons learned cover the sorting and segregation of waste streams, which should be done as soon as possible, preferably at the point of waste generation. To keep things simple the use of robotics should only be considered after a thorough analysis of other options. Few projects require telemanipulators or sophisticated tools. To be useful for decommissioning applications, manipulators need a sufficient payload capacity and must be robust. Umbilical and cable management is always a problem and improvements are needed.

Much of the work presented in Ref. [94] is relevant to research reactors. Reference [94] covers objectives, health and safety considerations, the characterization process, the radionuclide inventory, methods and techniques for characterization, and quality assurance requirements. Experiences from various Member States are presented in a series of annexes. The main objective is to identify both the importance of and the major factors relevant to a complete radiological characterization in order to support the decommissioning planning effort, together with the methodology for performing such a characterization of a shut down nuclear reactor. Radiological characterization involves a survey of existing data, calculations, in situ measurements and/or sampling and analysis. Successful radiological characterization provides a reliable database of information on the quantities and types of radionuclides, their distribution and their physical and chemical states. This information is then used to consider appropriate decontamination processes, dismantling procedures, radiological protection measures, waste classifications/estimates and cost estimates. Comparison and optimization of these factors will lead to the selection of a decommissioning strategy.

5.6.2. National and international working groups

The information exchange in national and international working groups provides a good opportunity to share information, experience and knowledge among decommissioning project managers. In recent years, several working groups have been established in an effort to exchange decommissioning related information. The EC's Thematic Network on Decommissioning of Nuclear Installations [144] and the OECD/NEA's Co-Operative Programme on Decommissioning [145] are useful in this regard. The newly established IAEA Technical Group on Decommissioning has similar objectives [146]. The Working Group on Decommissioning of Research Reactors (Arbeitsgruppe Stillegung Forschungsreaktoren) was founded in 1995 and includes members from decommissioning projects in Austria, Denmark, Germany and Switzerland [147]. For a similar initiative see Ref. [148]. The major objective of such working groups is to exchange information on topics such as planning, licensing procedures, availability of special techniques and experience gained with it, suitable contractors and their skills, and costs of certain work packages.

Working groups also consider a wide variety of related aspects, with the aim of achieving efficiency by benefiting from experience already gained in other projects. These groups also may serve to save costs for the removal of the spent fuel by combining the necessary shipments to the country of origin.

The decommissioning programme of the Commonwealth of Independent States (CIS) is huge and gives useful indications of the issues countries face in decommissioning their old research reactors. A CIS review by the EC [149] identified the following main issues resulting from a study of power and research reactors in CIS countries (in particular see the section on Considerations for Research Reactor Decommissioning). Reactor graphite has to be treated or disposed of since it can be susceptible to long term deterioration. Fuel from research reactors varies in configuration and type and requires a number of reprocessing techniques. Techniques are required to remove or fix mobile radioactive contamination in cases where significant periods of deferred dismantling are proposed.

Many CIS research reactors are very old and were operated when the restrictions of military secrecy and high workload limited the ability to pay due attention to decommissioning planning and documentation. The neutron flux in the more powerful research reactors exceeds that of power reactors and therefore produces a higher level of activation in components located near the core. The design features, materials used and duration of operation differ greatly from one research reactor to another, thereby complicating any attempt to develop common decommissioning requirements.

Research reactors typically contain a number of different experimental devices, some of which can be difficult and complicated to dismantle (e.g. horizontal experimental channels, test loops and experimental fuel assemblies which were sometimes tested beyond design limits and therefore in potentially uncertain conditions). Beryllium can also be a problem in the decommissioning of some CIS research reactors in terms of conventional toxicity and also radiation hazard following irradiation. A further example of beryllium handling issues is that from the Belgian research centre [99].

5.6.3. Provision of practical assistance and training of decommissioning personnel

In recent years the IAEA has increased its efforts to provide regional and inter-regional training covering all aspects of decommissioning of research reactors [70, 150]. In addition to such training courses, the IAEA has sent expert missions to selected decommissioning projects, assisting the beneficiaries in various aspects of the projects (characterization, waste management, dismantling techniques, etc.) [70, 150, 151].

In addition to this, the number of training courses at the international level has increased. An example is a series of courses provided by the European Commission on decommissioning of nuclear installations, providing personnel of decommissioning projects as well as authorities and expert organizations with the relevant basic knowledge [152]. The training of nuclear personnel has already become a commercial activity in some countries [153]. Other training courses on decommissioning are periodically held in the USA by Argonne National Laboratory for both US and international clienteles [154].

5.6.4. Organization of conferences and seminars

Workshops and seminars are particularly useful in facilitating the transfer of lessons learned. They also provide direct exchange of know-how, including technical topics and organizational aspects. There have been many such workshops and seminars in recent years. They have often focused on practical approaches to a wide range of technical topics, including planning and management aspects for decommissioning projects.

The number of national and international conferences and symposia dealing with research reactors has increased over the last decade. Decommissioning issues are invariably a major focus of these meetings.

Although major conferences on the decommissioning of nuclear power plants continue to be of value, a number of international conferences have been dedicated exclusively to research reactors, for example IAEA conferences [155]. One example on the national scale is the series of conferences in Germany called Shutdown Symposium Hannover, which is organized by the German Federal Ministry of Education, Science Research and Technology and where a considerable part of the topics deal with decommissioning of research reactors and research installations. One example of the Hannover conferences is given in Ref. [156]. Another German example is the biennial series of Kontec symposia. The 2003 proceedings are quoted in Ref. [157].

5.6.5. Databases

An important part of information exchange in the field of decommissioning of research reactors is information gathering and information management in databases, which are accessible to ongoing and future decommissioning projects. Such documentation is tailored to research reactors. It has been observed that existing databases pertaining to the decommissioning of nuclear power plants and large scale nuclear installations are not always useful in meeting the needs of research reactors. It should be mentioned, however, that not all databases are available to the general public, but only to selected users. The EC's decommissioning-oriented databases are presented in Ref. [158].

The IAEA's Research Reactor Database (RRDB) provides a variety of information on construction and operation of research reactors worldwide, including limited information on their decommissioning status [159]. Efforts are ongoing to expand and update the decommissioning related part of the RRDB. The CD-ROM attached to this report is a one-off exercise to gather and disseminate this information to IAEA Member States.

An example of a database which was developed for the information management of a particular decommissioning project is the Database for Decontamination and Decommissioning of Research Reactors (DADOR). This database was developed by the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany) for the decommissioning of the FMRB research reactor in Brauschweig and is described in Ref. [160]. Because the DADOR database was tailored to a specific project it is not easily accessible to ongoing or future decommissioning projects, and it is not available to the general public.

5.7. COSTS AND FUNDING

The costs of dealing with research reactor nuclear liabilities include radioactive waste, spent fuel and decommissioning of the facilities and remaining nuclear structures. These liabilities have been accumulating over many years of reactor operation. The legacy of liabilities is large and unavoidable. It is important that there be a fundamental strategy in place to deal with nuclear liabilities, based on sensible development and cost effectiveness. In this context the main issues are to ensure that estimates and funding arrangements are adequate.

Even in a case where the liability estimates are complete and adequate, the funding arrangements may still be inadequate and require reassessment. Where the liability estimates are incomplete and/or inadequate, the existing funding arrangements will certainly be inadequate.

5.7.1. Decommissioning cost estimates

With growing experience in the decommissioning of nuclear facilities, significant progress has also been achieved in the accuracy of decommissioning cost estimates. In order not to 're-invent the wheel' and utilize others' experience it is important to define cost factors in detail and prevent the comparison of inconsistent items. Member States have recognized the need for a standard list of decommissioning items and costs, thereby providing a consistent baseline for comparing liability management options and decommissioning plans.

In 1999, a joint EC-IAEA-OECD/NEA task group [31] proposed a standard list of items for costing purposes in the decommissioning of nuclear installations. Although this is an interim technical document, it is proving to be a practical way forward, but requires further discussion and development. The wish of the task group is that the list be broadly distributed, discussed, used and regularly updated in the future. The objective is to eliminate cost evaluation discrepancies and to allow a better information exchange in this area in the future.

As one example, this document has been used for cost estimates at the DR-3 decommissioning project in Denmark [32]. Another example of the successful application of the above guidance is described in Ref. [96].

It is clear that cost items and their relevance vary among nuclear power plants, research reactors and nuclear fuel cycle installations. When applying these cost items to a specific research reactor decommissioning project, it should therefore be recognized that they may need adaptation to the specific requirements of that project.

Comprehensive parametric cost estimating models are now used by some organizations, and are supported by extensive decommissioning databases. One such example is the PRICE system developed by the UKAEA [77].

5.7.2. Provision of decommissioning funds

Member States fund decommissioning projects in a variety of ways. Budgeting for decommissioning often varies considerably between State owned facilities (to which most research installations belong) and privately owned facilities. Depending on the country and its financial arrangements, either a decommissioning fund already established during the lifetime of the facility or a funding commitment secured for the future may be applicable.

If funds are created during the lifetime of facilities, it is important to ensure that the money will be available when decommissioning is about to start. Work has been done on this issue in some Member States and there are good examples of instances where ‘segregated funds’ have been created. Such funds are secured to ensure that the money is only available for the specific purpose of financing the decommissioning of the plant in question. To quote one example from the Czech Republic, the Radioactive Waste Repository Authority (RAWRA) is responsible for ensuring, by means of an audit, that relevant licence holders honour their obligations to create financial reserves for the future decommissioning of their plants. All licence holders in possession of a certificate verifying their decommissioning cost estimates, and whose proposed strategy for and method of decommissioning has been approved, are subject to such an audit. This also includes research reactors [161].

In the past, it was not uncommon for a research reactor to face permanent shutdown without a financial plan for decommissioning. Any approach to decommissioning that defers dismantling for a considerable number of years may be associated with the risk of increased undefined costs in the future. In cases where no funds have been set aside the operating organization is faced with few alternatives to deferral.

In general, it can be stated that there has been an increased awareness of this issue over the last few years and progress has been made in ensuring that dedicated funding for decommissioning projects is available. A key aspect of this progress has been the trend towards more comprehensive and accurate estimates of decommissioning liabilities [162].

6. PENDING ISSUES

The objective of this section is to identify and summarize remaining and pending issues in the field of nuclear decommissioning, taking into account experience gained and problems encountered over the last 10–15 years. In general, the topics considered are common to all decommissioning tasks in the nuclear industry. Hence any new project to decommission a research reactor is expected to take these considerations into account. In addition, this section highlights instances where a topic requires particular emphasis when dealing with a research reactor.

Decommissioning has to be achieved in an evolving regulatory and political climate, so there will always be pressure for further improvements in approaches and methods. Issues arise from areas where there is a known solution but more action is required, or where a complete solution has not yet been found, or where an existing topic has become more critical (see Section 6.1).

Almost 200 research reactors operating today are already 30 years old and will become likely candidates for decommissioning in the near term (see Annex I). Many of these reactors are located in Member States where appropriate decommissioning experience may not be readily available.

Decommissioning activities are expected to increase in the short term as more nuclear installations are taken out of service, but may decrease greatly during the following years [5]. The actual number of decommissioning projects is difficult to predict, as it depends not only on operational age but also on other factors such as legislation, competition, finance, waste management, stakeholders' interactions and/or expertise. The process of deciding between continued operation, major refurbishment or decommissioning, while taking into account business, financial, technical, regulatory and other aspects, and the uncertainties attached to each of these factors, is often a difficult one. For a specific example, see Ref. [163].

The decommissioning process with all its challenges (prolonged planning, strategic decision making, safe enclosure, unavailability of waste disposal sites, etc.) can sometimes last for several decades. Uncertainties are extremely great over such a time period.

For research reactors, the average operational lifetime prior to shutdown increased from 5 years in the 1960s to about 30 years around the year 2000. It is not unreasonable to expect that, in the future, the mean operating lifetime will reach or even exceed 40 years. In the case of a 40 year lifetime, the decommissioning needs will culminate within the next 10 to 20 years (see Table 1 and Annex I). However, extensive refurbishment and life extension programmes could significantly postpone this anticipated peak. In cases where reactors have undergone major upgrades, for example the Budapest research reactor [164], the life extension may be almost equivalent to the lifetime of a new reactor. As another example, Egypt collaborated with the IAEA through a technical assistance project and produced a modernization plan for control and instrumentation, radiation protection, process control and safety systems of the ETTR-1 reactor (see Section II–1.6 of Annex II).

Spent fuel and radioactive waste management have been major issues for many research reactor operators in that often only limited local or national handling and storage facilities are available. Although the removal and management of spent fuel may be carried out under the operational safety assessment as part of the shutdown, fuel removal remains the primary prerequisite to implementing a decommissioning project and waste management will continue to be the dominant feature of decommissioning strategies. It is convenient to consider pending issues in the field of nuclear decommissioning first in terms of planning and management and then in terms of the implementation of these plans.

6.1. REASONS FOR DECOMMISSIONING

Of the various reasons for decommissioning outlined in Section 5.2, the most common now are the end of the lifetime of the reactor, the completion of research and experimental programmes, and economic considerations. For example, the permanent shutdown of the R2 research reactor and the smaller R2-0 has been announced recently by the Studsvik Board of Governors, Sweden. The decision is due to lack of profitability as well as a stronger strategic group focus on nuclear industry services. Studsvik has also launched a strategic partnership with the reactor at Halden, Norway, securing the continuity of all client business involving examination, testing and analysis of fuel material [165]. Nearly half of the research reactors operated worldwide have been closed, while others have undergone upgrades and modifications resulting in life extensions and use for new purposes (see Sections 5.2 and 6.1).

6.2. FACTORS AFFECTING NATIONAL POLICY AND STRATEGY

6.2.1. Regulatory framework

As noted in Section 5.3.1, there is a tendency among Member States to develop decommissioning oriented legislation and/or regulations, often based on IAEA guidance. One point of special importance is clearance criteria. It is noteworthy that the need to adopt internationally harmonized clearance criteria for materials and waste has been widely recognized over the past few years. This has led to newly issued international clearance levels [24], even though differing national limits persist. Further work is required to harmonize measurement methodologies and criteria, e.g. on averaging criteria.

A regulatory challenge is that the process of regulation needs to reflect the constantly changing physical situation of the plant and the related hazards during decommissioning. Another current challenge is to promote the drafting of preliminary decommissioning plans early in a reactor’s life cycle, as recommended by the IAEA. This practice is not common yet but is quickly spreading to the international community of research reactors [23].

6.2.1.1. Strategic approach

There is an emerging trend towards nationally optimized solutions to the management of civil nuclear liabilities. Two national examples are summarized below, but the underlying considerations are applicable in principle to any country that has to deal with the decommissioning of nuclear facilities and the remediation of nuclear sites.

The early years of the British nuclear industry created substantial historic liabilities (sometimes called 'the legacy') in the form of wastes that needed to be treated and plants that needed to be decommissioned. The Government recognized that the industry operates within a rigorous, robust and transparent regulatory framework that insists on stringent safety, health, environmental and security standards. It was also recognized that progress has been made in recent years in dealing with the legacy.

Taking these factors into account, the UK Government has set up a new public body — the NDA — responsible for the Government's interest in the discharge of public sector civil nuclear liabilities. The NDA is seen as providing the driving force and incentives to get on with the job of systematically and progressively reducing the hazard posed by legacy facilities and wastes. It has a specific remit to develop a clear and focused overall long term UK strategy for decommissioning and cleanup.

The NDA has four guiding principles:

(1) Focus on getting the job done to high safety, security and environmental standards;
(2) Best value for money consistent with those standards;
(3) Openness, transparency and ensuring public confidence;
(4) Development of competitive markets for cleanup contracts, to drive innovation and ensure the best possible use of available skills.

The NDA commenced its formal activities in April 2005. It works in partnership with site licensees, as well as the safety, security and environmental regulatory bodies to achieve the most effective and safe means of discharging the liabilities [73].

As another example, in Denmark a new State company, Danish Decommissioning, has been made responsible for the decommissioning of all the nuclear facilities at Risø, i.e. the three research reactors DR-1, DR-2 and DR-3, the hot cell facility, the fuel manufacturing facility and the waste treatment plant. Danish Decommissioning has taken over these facilities, which will, when they are finally released, either be returned to Risø or dismantled. Danish Decommissioning operates independently of Risø and its budget is provided by the Ministry of Science, Technology and Development [166, 167].

6.2.1.2. Modern standards for safety assessments

In general, regulatory bodies in any industry wish to see safety assessments that relate the proposed decommissioning activity to the application of modern standards (e.g. designing a new ventilation system to current best practice). The significance and impact of modern standards on nuclear decommissioning can be controversial, for example in cases where such standards were not required during plant operation and also in cases where a particular activity or campaign will have a limited duration, after which the plant in question will be decommissioned.

There is a need for owners/operating organizations and regulatory bodies to undertake continuous and effective dialogue to ensure that appropriate and proportionate measures are taken when applying modern standards to nuclear decommissioning. This in turn will help to ensure that appropriate work programmes and costing are factored into the optioneering process. It also assists in meeting the general objective of achieving cost effective decommissioning.

Decommissioning safety assessments are increasingly based on modern standards. For example, a significant development that occurred recently is the so-called ‘graded approach’ based on the radiological hazard that a facility poses to the environment, the public and workers. Research reactors are used for specific and varying purposes such as research, training, radioisotope production, neutron radiography and material tests. These call for different design features and operational regimes. Design and operating characteristics may vary significantly, since experimental devices may bear upon the performance of reactors. In addition, the need for greater flexibility in their use requires a different approach to achieving and managing safety [168]. A similar approach could also be applicable to decommissioning. For example, the regulatory inspections have to be flexible as the plant configuration is continuously changing. One decommissioning project using the graded approach is described in Ref. [169]. For activity concentrations exceeding standard clearance levels a graded approach is suggested by the IAEA in Ref. [24]. The USNRC graded approach to enforce institutional controls to post-decommissioning restricted site use is described in Ref. [170]. Use of the graded approach for USDOE decommissioning work is discussed in Section 2.3 of Ref. [171].

In general, for the decommissioning of research reactors few requirements related to decommissioning, if any, may actually be waived. But the efforts associated with fulfilling them, for example in the preparation of the necessary plans and procedures, with their respective evaluation and review, may vary greatly in line with these difficulties. It should be noted that the application of grading to the safety requirements should be based only on considerations of safety, maturity and complexity as outlined above. Grading of the requirements is not intended as a tool for cost optimization. Selection of the least expensive strategy once it has been decided to shut the reactor down permanently is not the purpose of grading.

Two safety related areas which have been gaining importance in recent years are the retention of knowledge and safety culture [86]. In decommissioning it is desirable to retain, for as long as possible, some of the key staff from the operating phase of the facility. Their knowledge and experience may be essential to ensure that the safety of certain activities is not compromised by inadequate knowledge of the facility and its operating history. With regard to safety culture it is possible that the staff may perceive the nuclear facility as being much less hazardous during decommissioning than it was during operation. Although true to a certain extent, this may result in complacency and relaxation of the customary vigilance necessary to ensure continuing safety. As with the issue of knowledge retention, it is important to retain staff already imbued with the operational safety culture so that this can be passed on to new staff.

A particular example may arise in Member States abandoning the nuclear option after current facilities are shut down. Further work in this area is likely to address the issue of how to maintain the capability of those bodies responsible for carrying out decommissioning operations and for their regulation. This means, inter alia, ensuring that sufficient appropriately qualified staff are available including, as far as possible, those with knowledge and experience of the relevant operational facility, and that staff changes and development are properly managed over the necessary timescales. It also requires recognition of the management challenges associated with the use of short term contractors or temporary staff [172].

6.2.2. Resource aspects

Optimization of human, technical and financial resources remains a challenge [81]. In some countries decommissioning is still a first of a kind exercise and transfer of technology and know-how from more experienced countries is not necessarily a straightforward process [71]. Lack of financial resources in developing countries remains a serious issue to the timely, effective and safe decommissioning of research reactors. Even technical assistance to provide expertise and know-how has limitations and takes time to be ‘digested’.

There is a growing interest in decommissioning plans being set in the context of an overall (integrated) plan for the nuclear site in question. It is therefore desirable to consider the possible future programme for the overall site rather than the individual facility to be decommissioned as a starting point for the identification of realistic decommissioning strategies and provisions of financial resources.

It can be said with confidence that nuclear decommissioning is now a generally mature industry using established techniques through an internationally competitive market. However, a fully developed 'package solution' will only be available in the longer term. Currently, it is still necessary to ensure that adequate emphasis is given to 'keeping it simple' through the adaptation of proven equipment. It must also be recognized that some R&D will be needed in special cases.

6.2.3. Facility reutilization

In some cases the reactor site (land and infrastructure) can be a profitable asset. This solution is fully applicable to a number of research reactors, particularly in countries which do not have sufficient funds for full decommissioning, and may partly offset decommissioning costs. This topic is currently being addressed by the IAEA [34]. Many possibilities for reuse of the reactor after decommissioning can be taken into account, such as:

(a) Construction of the spent fuel dry storage in the reactor block shaft;
(b) Utilization of the hot cells for encapsulation of fuel elements for further storage;
(c) Utilization of the hot cells for material testing;
(d) Utilization of the reactor hall for construction of a stand for gamma ray sterilization (see the Venezuelan case quoted in Ref. [34]);
(e) Nuclear museums (see the exhaustive list of these in Ref. [34]).

The decommissioning of Winfrith facilities in the UK is expected to result in a number of buildings and large amounts of land being returned to non-nuclear applications [35]. In the context of strategic studies, the usefulness of taking into account any information that may exist on possible future strategies or plans for use of the land or buildings associated with the facility that is to be decommissioned is being recognized. Keeping a specified post-decommissioning reuse of the facility and its site in mind from an early stage is expected to streamline the decommissioning process, offset costs and provide all the parties involved with social and commercial opportunities [173].

6.2.4. Waste management

It is becoming increasingly accepted that if a research reactor is to be dismantled there should at least be a suitable interim storage facility available for radioactive waste, if not a repository. Research reactor operating organizations typically reserve an appropriate amount of space in (planned or existing) centralized interim storage facilities or repositories for their anticipated decommissioning wastes. Noting that the smooth and timely transfer of decommissioning waste is normally beneficial for the schedule of the entire decommissioning project, sufficient waste processing capacity needs to be provided so that the decommissioning waste can be put into the correct form for storage.

Reference [174] reports on two research reactor decommissioning projects where the availability of or, alternatively, the lack of waste processing and storage facilities were important factors in the selection of a decommissioning strategy. Immediate dismantling was possible only in the case where waste facilities were readily available.

Depending on the situation in a particular country there may also be the possibility of cooperation between research reactor operating organizations, which are often State owned, and power utilities, which may be privately owned, with respect to the sharing of interim storage facilities. The construction of interim storage facilities dedicated to the radioactive waste from research reactors may often not be a financially viable option.

6.2.5. Stakeholder acceptance

The use of 'stakeholder dialogue' is becoming more important as a means of convincing the public that decommissioning is safe and routine. Political and government groups are generally interested in ensuring that adequate mechanisms exist to communicate with all the parties involved. It is also important to demonstrate two way communication and the existence of a concerted effort to seek and address broad public input.

Part of this issue is the need to deal with the fact that transport of radioactive materials is to some degree inevitable in any decommissioning project. It is also important to take into account the potentially negative impact of any socio-economic issues in relation to reactor closure and to the building of repositories for radioactive waste.

6.2.5.1. Social impact

Open and comprehensive communication with all involved is a key element in dealing with the social impact of the closure of nuclear facilities.

Also, it is recognized that reliable and open information is helpful to all. It may also help to motivate and retain those staff needed for the decommissioning work.

The social impact of the closure and decommissioning of nuclear facilities depends to a great degree on the size of the facilities. For small nuclear sites such as individual research reactor installations the effect is limited and there may not be much room for business development initiatives. For large nuclear establishments, including, inter alia, research reactors, e.g. the Dounreay site in the UK, it is helpful to set up local enterprise agencies and support regional development initiatives [34]. In a recent development, the Decommissioning and Environmental Remediation Centre (DERC) has been established in Caithness, Scotland, providing links with major universities in the UK and abroad and programmes for a wide range of specialties undertaken by undergraduates, PhD and Masters students. It is expected that DERC will become an international centre of excellence in nuclear decommissioning [175]. DERC and many similar initiatives are intended to counteract the job losses and the local economic decline associated with the gradual completion of a major decommissioning project.

6.2.5.2. Stakeholder consultation and public relations

Comprehensive consultation with all stakeholders is rapidly becoming the current best practice. The authoritative approach can in fact lead to the termination of a project. More generally, and even though much has been done in the field of public relations, there is still a serious lack of public acceptance of nuclear activities.

In the case of decommissioning the problem should be simple and easily dealt with because the message is fundamentally attractive — that is, environmental remediation. However, the challenge is to demonstrate that the proposed decommissioning method is safe, is the best practicable environmental option and is the best value for money.

Currently, there is much more emphasis than in the past on the use of liaison groups and stakeholder dialogue processes. These interactions with interested parties are now considered to be essential features of any well planned nuclear decommissioning project. In other words, the approach of the proponent selecting and deciding on the project direction and then striving to convince stakeholders of the validity of the selected approach is no longer viable.

6.2.6. Safeguards

The risks posed by research reactors in relation to weapons proliferation during the decommissioning process needs to be seen in the broader context of public health and environmental issues — covering spent nuclear fuel and other radioactive wastes. Therefore consideration is usually given to fissile material and radionuclides that could be used in weapons [44, 176].

The use of HEU has always been controversial, as the material can be used in nuclear weapons. The USA, as a supplier of HEU fuel, prohibited export of this type of fuel except on an interim basis prior to conversion to LEU (low enriched uranium). The high flux reactor (HFR) at Petten, Netherlands, is one example of a research reactor that has been converted to LEU fuel [177].

The operating organization responsible for decommissioning is also entrusted with the follow-up on safeguards and physical security. Some of the lightly irradiated HEU fuel elements from research reactors which have been cooled for many years, could be easily handled because they are not sufficiently radioactive to be self-protecting against theft. Fresh HEU fuel can also be misused. It should be noted that other materials that can be found in research reactors, e.g. heavy water, raise proliferation concerns. Currently, operating organizations of nuclear facilities are typically required to implement more security arrangements [178]. The current trend towards repatriation of US and Russian origin fuel is expected to reduce security concerns [2]. In addition to safeguards materials, radioactive waste generated during the decommissioning of research reactors is a possible source for the manufacture of radiological dispersion devices (in which radioactive materials are dispersed by conventional explosives).

6.2.7. Expertise

There is a growing shortage of overall nuclear skills (including those needed for decommissioning) and an associated need to put more effort into training programmes.

6.2.7.1. Nuclear skills

Decommissioning presents significant engineering challenges. Associated generic skills include project management, planning, engineering design, safety assessment and risk management. There is widespread recognition of the ageing of the industry (not a high enough proportion of younger people). Recruitment is needed over the next decade to replace retirees, the potential shortage being in all areas — practitioners, educators, trainers and regulatory bodies [179]. To help in this situation, some countries retain retired experts on a part-time basis.

Recognizing the problem of ageing in the nuclear industry [180, 181] and the necessity to undertake active efforts in strategic planning of education and personnel, in 2002 the Russian Federation's Minatom created a working group for comprehensive analysis of the situation and development of a special programme (green vector).

The IAEA has recently initiated a programme to deal with the retention of skills and knowledge (nuclear knowledge management) [182].

The OECD voiced this concern in their report on Nuclear Education and Training: A Cause for Concern? [183], which contained the recommendation that: "Governments should engage in strategic planning of education and manpower, integrated with human resource planning, to encourage young students into the industry". However, young people are only likely to choose such a career if there are reasonable prospects for future employment.

Research reactors may sometimes offer a particular challenge if the available skills set has to be rebalanced to match the requirements of the proposed decommissioning activities. For example, a team of researchers may find it difficult to adjust to the realities of industrial demolition.

European Union programmes in this field are described in Refs [184–186]. At the university teaching level, the European Nuclear Education Network (ENEN) has been created. The ENEN resulted from the cooperative action of ENEN partners (universities and research institutes) from 16 countries under the EURATOM 5th framework programme [187].

In the UK the NII report on Education and Research in British Universities [188] identified a situation of ageing academics, ageing facilities and no undergraduate courses with significant nuclear content. It was recognized that more needed to be done. A national UK forum (February 2001) resulted in the creation of the Nuclear Skills Group (NSG), which was then established in the DTI [189].

The skills needed by industry over the next 10–15 years were considered by the NSG — this timescale being necessary to address root causes and training lead times. The needs assessment will be used to inform those engaged in planning (in industry, academia, education, professional institutions and Government) of potential shortages of skills and the recruitment, education and training needed to avert those shortages.

Human resource planning was a key priority. The report estimates that in the UK the nuclear and radiological sector will require 50 000 engineering and health recruits over the next 15 years, resulting from age profiles plus expected growth in demand for health and nuclear cleanup skills. Of these recruits, 15 500 (i.e. about 1000 per year) will need to be engineering and physical sciences graduates.

Some initiatives have already been taken in the UK to address the need for more nuclear recruits — notably the creation of the Nuclear Technology Education Consortium (NTEC). The NTEC represents over 90% of nuclear teaching expertise in the UK and aims to meet the UK's projected post-graduate nuclear skills requirements in decommissioning, reactor technology, fusion and nuclear medicine [190].

6.2.7.2. Corporate memory

The move towards a competitive market, combined with the ageing of the nuclear industry, is leading to increasing regulatory concerns about corporate memory — that is, the ability of an organization to retain all the knowledge needed to undertake decommissioning. This is particularly relevant to decommissioning projects that include a lengthy deferral period, and also to nuclear facilities in countries that have abandoned their national nuclear programmes. Immediate dismantling mitigates this problem. Comprehensive records of work carried out during decommissioning could also reduce the danger of old mistakes being repeated, of lessons learned being lost and of inappropriate decommissioning plans being chosen. Regulatory bodies are increasingly requiring that operating organizations/owners provide convincing plans (including comprehensive record keeping, training and recruitment) by which the continuity of corporate memory can be achieved. Recent experience also suggests that regulatory bodies have the same problem of retaining corporate memory within their organizations.

6.3. MANAGEMENT AND PLANNING

6.3.1. Selection of the decommissioning strategy

References [12, 30] provide guidance on particular aspects to be considered when a decommissioning strategy is being selected. These aspects are being used increasingly in decommissioning plans and include among others:

(a) Radionuclide inventory and distribution;
(b) Physical and technical condition of systems;
(c) Hazard evaluation (radiological and conventional);
(d) Safety requirements;
(e) Storage/disposal options for fuel and wastes;

(f) Possible reuse of buildings, equipment or land;
(g) Possible need for new tools and equipment necessary for dismantling;
(h) Cost estimate and funding;
(i) Social, political and environmental impacts;
(j) Availability of qualified and experienced personnel;
(k) Radiological protection;
(l) Site release criteria;
(m) Documentation and record keeping.

Clearly, many aspects have to be addressed, the challenge being to achieve this in a logical and structured way [4, 15]. This approach is particularly important in demonstrating that the selected option represents the best way forward, taking into account all the factors considered.

In the past, a decommissioning strategy was usually selected on the basis of overwhelming factors such as the need to reuse the site or the availability of funds. More recently there has been a tendency to adapt scientific analytical methodology for the optimization of the decommissioning strategy. In general there is a growing feeling that the quality and content of strategy studies require improvement — especially in the treatment of environmental aspects and in the rigour of the process by which a preferred strategy is selected. There is a need to encourage greater use of formally structured optioneering methods, such as multi-attribute utility analysis [69, 191, 192], and to ensure that all realistically possible scenarios are taken into account. In addition, most national regulatory bodies now demand an assessment of possible strategies and a justification of the selected strategy.

Public and regulatory expectations are tending towards immediate decommissioning. However, it is recognized that many factors need to be taken into account and that deferral of later decommissioning activities may be justified in specific cases. The challenge therefore is to recognize that deferral strategies need more robust supporting arguments than has been the case in earlier years. Ongoing/emerging issues in decommissioning strategy selection are detailed in the following sections.

6.3.2. Release/clearance criteria

The achievement of a specified and agreed end point is crucial to the completion of a decommissioning project. In this context there is increased emphasis on the importance of specifying and achieving agreed radiological clearance levels for materials, buildings and sites. Some countries have enacted specific legislation. For example, in Germany quantitative requirements for the release of materials, buildings and sites from nuclear regulatory control were introduced into the Radiation Protection Ordinance in 2001 [193, 194].

The recent achievement of internationally harmonized radiological clearance levels for materials/wastes is expected to be of the greatest importance to all decommissioning projects [24, 55, 57, 58]. Guidance on cleanup and release of sites is given by the IAEA in Ref. [195].

Regardless of these achievements, disputes and confusion over interpretation of clearance criteria (e.g. averaging of measurements, statistical methods) continue to create substantial difficulties and misunderstandings in decommissioning projects. It is essential to establish agreed methods and quantified criteria as early as possible in the planning of such a project. In cases of ambiguous interpretation of regulatory requirements, effective and timely communication between all the parties involved is particularly important. In the UK, for example, the safety and environmental regulatory bodies have developed and agreed memoranda of understanding, setting out how they will work together to resolve any regulatory issues that may arise.

6.3.3. Final survey

The final radiological survey is a vital part of the clearance process, but it can lead to a very expensive and time consuming programme of surveys and analysis unless a proportionate approach is agreed. In one recent research reactor decommissioning project (JASON) such a proportionate approach was achieved by obtaining regulatory agreement in advance on a range of survey scales and on methods appropriate to each of these scales. Reference [196] addresses the planning phase of the JASON project, Ref. [197] its implementation phase. (A ‘scale of survey’ is conducted, as appropriate, to the anticipated level of radiation or contamination and the requirement to demonstrate that the area can be released for unrestricted use.)

The agreed survey scales were:

- ONE: Areas and buildings where it is unlikely that radioactive materials have been used;
- TWO: External areas (e.g. grass and tarmac);
- THREE: Buildings where the previous presence of radioactive materials is unlikely, but cannot be excluded;
- FOUR: Laboratory, storage and other areas where unsealed radioactive materials are likely to have been used or stored;
- FIVE: Areas where unsealed radioactive materials have definitely been used and areas where neutron activation may have taken place.

The agreed survey methods for the five scales were:

- ONE: Gamma dose rate measurements in rooms, visual inspection, overall gamma sweep as required;
- TWO: Air dose rate measurement, overall sweep with a gamma monitor on a coarse grid;
- THREE: Gamma dose rate measurements in rooms, gamma sweep of floors, lower walls and other surfaces;
- FOUR: As scale 3 plus contamination surveys on a fine grid, material samples, swab samples;
- FIVE: As scale 4 plus core samples and analysis for activation products.

6.3.4. Fuel management

6.3.4.1. Removal of spent fuel

Developments worldwide have resulted in a situation where removal of spent fuel to off-site facilities may become a serious problem. For example, some research reactors were provided with fuel by a supplier from another country. Reactor operating organizations had planned to return the spent fuel to the supplier, which, however, in many cases has now become impracticable. As this situation was unforeseen, only a few of these reactor operating organizations have their own off-site spent fuel storage facilities. In other cases, plans for a national fuel disposal facility have been seriously delayed. There are ongoing activities and plans to repatriate US and Russian origin fuel. However, the spent fuel removal strategy may remain uncertain for other types of fuel.

It is now recognized that it is important for decommissioning planning to specifically consider what is to be done with the spent fuel — which may involve constructing a local, national or regional spent fuel storage facility if no other alternative exists. Currently, some Member States consider that the use of a spent fuel storage installation external to the reactor and which uses dry instead of wet storage technology (e.g. casks, modules and vaults) is a successful method for storing spent fuel after sufficient time has elapsed for decay heat reduction. Some national examples of this trend are described below.

The LEU uranium–zirconium–hydride fuel of the TRIGA reactor in Finland may either be sent back to the USA before 2009 under the USDOE fuel return programme or, as an alternative, if the reactor is operated beyond 2009 it may be stored in the Finnish spent fuel repository presently under construction. In this case the TRIGA fuel will be stored together with the spent fuel elements from Finnish nuclear power plants [198]. In Germany, the spent fuel elements of the research reactor in Rossendorf (RFR) is being transported to a central storage facility in Ahaus in 18 CASTOR type cases. This operation faces massive public opposition [199].

6.3.4.2. Transport of spent fuel

The large variety of different designs for research reactor fuel is still creating problems with transport of the spent fuel. Other shipment problems are caused by the variety of shipment casks, the different transport regulations in various countries, cask licensing aspects and public opposition [199]. Some countries do not allow fuel shipment across their borders, which also complicates overall planning. Adaptation of a transport cask to accommodate a new fuel form is always a significant engineering and licensing effort, normally requiring several years of advance planning.

6.3.4.3. Transport of fresh fuel

In the context of repatriating fresh HEU, the IAEA has recently supported operations in Bulgaria, the Czech Republic, Latvia, the Lybian Arab Jamahiriya, Romania, Serbia and Montenegro, and Uzbekistan. In all these cases the fuel was intended for use at research reactors and was returned to the Russian Federation. One case history is given in Ref. [200].

6.3.5. Decommissioning planning

6.3.5.1. The owner/operating organization as the 'intelligent customer'

There is a growing awareness of the need for site operating organizations to demonstrate that they continue to be intelligent customers for the work to be performed at their sites [9]. That is, the site owner/operating organization is expected to demonstrate full and effective understanding and overall control of all matters associated with the site at all times, even if much of the work is being done by other organizations. Responsibility cannot be delegated to a third party. The operating organization is responsible for ensuring that any subcontracted decommissioning work is acceptable in terms of site requirements, particularly in relation to safety arrangements and to the risks associated with the subcontracted work.

6.3.5.2. The competitive market

Receiving value for money is an important aspect of any project. The nuclear industry is showing a growing interest in the value for money potential of measures such as privatization, contractorization (including joint ventures, partnering arrangements and alliances) and the leasing of parts of sites for re-use. In addition to the growing use of strategy studies, best value for money is increasingly being sought through contracting in the international competitive market. Application of these processes to decommissioning projects is not easy, and procurement specialists are usually needed.

One difficulty is that, by its very nature, the full extent of the radiological inventory and associated decommissioning problems may not be known until the practical work has started. The application of adversarial fixed price contracts may therefore not be appropriate. If the client is able to specify parts of the dismantling work precisely, then fixed price contracts may be appropriate. Other approaches involving incentives, risk sharing alliances and partnerships are being considered and implemented.

6.3.5.3. Organizational and contractual aspects

The operating organization (licensee) is responsible for all decommissioning activities on the site and hence manages all contractors involved in the work. A strategy selected by BNFL, UK [81], is to minimize the number of contracts by placing them for each of the major disciplines only, such as plant and waste characterization, decontamination, dismantling/size reduction, packaging and demolition. Where specialist services are required to support these major contractors, such as tools and rigging, remote handling techniques, shielding, they would be the responsibility of the major contractors to buy in directly. This approach facilitates better work specifications and control, in comparison with the placement of many small parcels of work which inevitably would result in increased interfaces (organizational/contractual) and require extra resources to manage.

6.3.6. Regulatory interfaces/licensing

When seeking to identify a preferred decommissioning strategy, it is essential to recognize that there is now a greater expectation (especially from the public) that best practicable environmental options are chosen rather than least cost. It is therefore important to ensure that the decommissioning planning team has access to expertise in the field of EIA techniques [201].

The EIA has been a legal requirement in the European Union since 1997, specifically including the decommissioning of research reactors above 1 kW(th) power. Socio-economic, resource, visual and traffic impacts, etc., are considered [202]. One example of an EIA for a research reactor is given in Ref. [203]. It should be noted that, in addition to radiological aspects, this EIA includes public and workers' interest, conventional waste, etc. A recent example of a US environmental report for a research reactor decommissioning project is given in Ref. [204].

An example of a recent detailed environmental assessment for a nuclear site including several research reactors is documented in Ref. [16]. The report details the approach followed to analyse the environmental effects of the entire decommissioning project to a final end state. Where several options are available for achieving the end state, a comparison of environmental effects of each is considered in selecting the preferred option.

The objective of the assessment was to identify residual effects (after mitigation) as a basis for a determination meeting the Canadian Environmental Assessment Act requirement of whether or not the project has any significant adverse effects on the environment. The baseline condition was selected as a point in time at which substantial portions of the facility had already been placed in an operational shutdown state.

The analysis addresses the effects of decommissioning activities on the environment throughout the decommissioning project. It recognizes that a successfully completed project will generate substantial positive benefits, specifically that:

(a) Decommissioning will lead to improvements to the environment as the overall risk posed by the facilities is progressively reduced;
(b) The achievement of operational shutdown will dramatically reduce any current discharges;
(c) Radioactive decay will reduce radioactivity on-site;
(d) There will be no new sources of contamination;
(e) As the decommissioning of each facility is completed, the land on which it is located will be restored to a more natural condition, that is, the land will be seeded with natural grasses and left to develop naturally.

6.3.7. Management of plant status and change

There is a continuing need to ensure a smooth change (transition) from operation to decommissioning [25]. A key aspect of this process is early planning (several years before shutdown) for decommissioning during operation, including provision of all technical, managerial and funding resources. In this way, gaps between operation and decommissioning can be reduced to a minimum.

One important challenge is to remotivate former operators in terms of the new demands and expectations of decommissioning. It is also necessary to ensure continuity of knowledge and key safety responsibilities. There may sometimes be a particular challenge in the case of research reactors where the available skills set may have to be rebalanced to match the requirements of a decommissioning project.

From the experience gained so far, (e.g. Refs [37, 64]), the transition phase would be an ideal time for fuel removal and for conducting radiological characterization surveys. Such activities facilitate detailed planning and cost estimation for subsequent decommissioning.

6.3.8. Implementation aspects

The challenge here is to identify and effectively use the techniques that are best suited to a particular decommissioning project. In the context of pending issues there are a few points to be made. These are summarized in the following sections.

6.3.8.1. Project resources and communications

It is important to have a good communications system between all parties involved in the project, involving regular briefings, interface discussions and feedback. The provision of regular workshop sessions offers a practical and motivating way of identifying and assessing options and hazards (including avoiding potential surprises).

6.3.8.2. General relations with regulatory bodies

One point needing further clarification in many countries is the determination of how to/who will approve the final radiological survey and revoke the necessary nuclear and environmental discharge authorizations. The range of documentation required to delicense the site needs to be determined, together with a demonstration that the site will be available for future unrestricted or restricted use. The format of the post-decommissioning report needs to be agreed on, together with the method of releasing the site from regulatory control, if applicable. Recent guidance on these matters has been provided by the IAEA [12].

6.3.8.3. Culture change for existing staff

The option of using contractors for the decommissioning of research reactors does not exist in many countries. Decommissioning therefore must rely on the use of operational and research staff to plan and implement the work. This may introduce issues arising from the culture change involved in the transition from operation to decommissioning [25]. This issue is ultimately linked to the development of national or international decommissioning services, and to the resources available to reactor operating organizations.

6.3.8.4. Approaches to radiological and conventional safety

There is a growing emphasis on all the work being planned and implemented in accordance with the ALARA principle. Much experience has been gained in recent years in the area of minimizing radiation doses to decommissioning workers in accordance with this principle.

It is important to note that all reasonable steps to minimize doses are taken through the implementation of appropriate control measures, including engineering measures such as extra shielding. It is increasingly recognized that dose reduction management procedures and associated work instructions are required in addition to reasonable engineering measures. This approach is based firmly on experience, which has shown that people make mistakes regardless of the comprehensiveness and clarity of management instructions — hence the emphasis on achieving an engineering solution wherever this is practicable. Good solutions provide benefits for worker health, while at the same time achieving value for money project costs. More effort is now being applied to showing how to achieve worker dose/project cost optimization. This is a challenge for future decommissioning projects.

Safe and effective decommissioning requires an understanding and capability in technical risk management, involving such skills as safety and risk analysis/assessment, applied to normal and accident scenarios.

If used correctly, risk analysis and assessment will help to identify hazards associated with decommissioning, remove and mitigate identified hazards, identify safety critical items and conditions, form the basis for operational radiation protection regimes, and show compliance with safety criteria as required for the safety assessment.

Non-radiological aspects of decommissioning are at least as important as radiological ones. This may pose a significant challenge to the nuclear operating organization, which may or may not be fully familiar with (conventional) safety requirements.

6.3.8.5. Testing of decommissioning techniques in real scale projects

There is a general feeling that the need for extensive R&D decommissioning programmes has greatly decreased, particularly for research reactors, on account of the general maturity of the nuclear industry. There seems to be a shift from developing completely new techniques to efforts at cost reduction and optimization of existing techniques. Nevertheless, it remains necessary to maintain some R&D on innovative technologies, e.g. to reduce the generation of secondary waste. Future developments are likely to focus on robotics and 3-D computer simulation tools to further improve worker safety [205].

6.4. DECOMMISSIONING AND WASTE MANAGEMENT TECHNIQUES

6.4.1. Important strategic/preparatory considerations

Ongoing developments in infrastructure and decommissioning strategies are outlined below.

6.4.1.1. Waste minimization

There is a growing international trend to maximize recycling of material. An example comes from the Russian Federation, where appropriate regulatory requirements have been inserted into the latest versions of the national standards [206–213]. These standards indicate that any solid raw materials and products with specific activities of less than 0.3 $kBq \cdot kg^{-1}$ are approved for unrestricted use in economic activities. For selected β radionuclides the federal regulatory authority can establish even higher levels of specific activities (para. 3.11.3 of Ref. [206]). They also detail permissible specific activities of the main long lived radionuclides for unrestricted use of metals (Annex 10 of Ref. [207]). These regulations, together with the availability of advanced technologies and industrial facilities for decontamination of metals by remelting, provide an opportunity for the large scale utilization of suspect radioactive scrap metals. This approach can also lead to significant volume reduction of radioactive waste.

6.4.1.2. Safe enclosure approach

It is anticipated that the long term integrity of the structure, supporting systems and associated buildings of a research reactor will have to be taken into account when future decisions on the operational lifetime and decommissioning strategies for a research reactor are made. Estimates of present condition, maintenance needs and possible future remedial works are needed to make realistic comparisons between candidate decommissioning strategies.

Clearly, such estimates are particularly needed when strategies involving deferral of dismantling for a number of years are being considered. Usually it is found that some remedial work is necessary as part of the safety assessment for a deferral strategy. For example, extensive building renovation was needed for the two Estonian reactors mentioned in Section 5.1, on account of their expected long term stay in safe enclosure. In Canada, a comprehensive study on the long term management of the Chalk River Laboratories site (including several research reactors) is a good example of both an integrated site decommissioning programme and a building condition assessment programme [214]. As mentioned previously, immediate dismantling is the preferred decommissioning strategy in most cases.

6.4.1.3. Entombment approaches

It has been recognized in recent years that in some cases entombment may be the only practical approach available due, for example, to the lack of suitable waste management arrangements. In the future, due to such issues as the siting of waste repositories and the potential for monetary savings, it is possible that more emphasis will be given to entombment.

6.4.2. Decommissioning techniques

Suitable dismantling and decontamination techniques exist for virtually all aspects of research reactor decommissioning. From the large number of decommissioning projects in progress or already completed, the conclusion can be drawn that conventional, robust methods and commercially available technologies can be used almost everywhere. Especially for smaller research reactors with a low activity inventory and correspondingly low dose rates, the adaptation of techniques from conventional industrial applications provides good solutions in most cases. Where possible, tools and equipment already available from the reactor operation might usefully serve new decommissioning applications. As one example, the ASTRA reactor at Seibersdorf, Austria, is currently being dismantled and the concrete bioshield is being diamond cut into segments weighing just under 10 t because of the capacity limits of the overhead crane [215].

Although decommissioning is a mature industry, innovative or substantially modified techniques will sometimes be needed in the future. For example, during the dry dismantling of the RPV closure head of Germany's multipurpose research reactor (MZFR), the upper and lower spacers, the weight ring of the upper spacer and the single segments of the RPV itself, a band saw had to be applied. However, the very complex boundary conditions of this RPV dismantling required considerable alteration of standard equipment [216]. The band saw and a dismantling table had to be specially designed and installed in the limited space available in the reactor housing of the MZFR. A large scale commissioning, test and trial programme for the equipment (covering band speed, tension and feed, depending on the properties of the material) and for the associated training of the operating personnel was applied. A commercially available band saw was modified and optimized according to the specific requirements of the MZFR. The activity potential of the components within the RPV necessitated a remote control dismantling process. Therefore the band saw has been modified for remote controlled operation and equipped with additional audio and video systems for supervision of the system from the central control room. Further control devices for band tension, system pressures and filling levels have been installed.

Another example is the decommissioning of the Russian TVR reactor at the Institute of Theoretical and Experimental Physics, where one of the most radiation intensive operations was the removal of horizontal channels. As the dose rate in the area of these channels was 250 μSv/h, a special remotely controlled machine equipped with a crown milling cutter was developed, manufactured and successfully used in dismantling operations [10].

6.4.2.1. Segmenting/cutting techniques

Experience indicates that for the immediate future there is no general purpose segmenting/cutting method that can be recommended for all segmenting tasks. Thermal techniques, though generally small and easy to apply, usually require substantial effort for air filtering and contamination control, which makes them unsuitable for a number of segmenting tasks in contaminated areas of research reactors. On the other hand, mechanical tools such as saws produce aerosols, which are very easy to control but cannot be used in confined spaces. Slightly different considerations apply if segmenting can be done underwater. Many thermal and mechanical cutting techniques have been developed for application in underwater nuclear decommissioning. In this case, thermal cutting techniques require substantial water cleaning systems.

Reference [8] illustrates a large number of dismantling techniques and provides examples of applications and related issues, many of them for research reactor decommissioning projects. References [217–222] provide further examples of ongoing technological developments in Germany. Hundreds of similar developments from other countries can be found in the specialist literature. In summary, segmenting or cutting techniques for decommissioning have advanced to such a state that only minor development of certain techniques is usually required to suit the individual needs of research reactor decommissioning projects. However, a number of tools may still need case by case adaptations, as outlined above.

6.4.2.2. Decontamination techniques

There is no universal decontamination technique because the performance of any given solution will depend on a number of plant specific parameters and requirements. Although decontamination techniques are generally available off the shelf, special consideration has to be given when planning their use in research reactors. Depending on the size of the research reactor, the costs and time required for installing and operating suitable decontamination techniques vary. Aspects to consider include the costs for management of secondary waste from decontamination and costs that can be saved by downgrading the material suitable for decontamination from a higher to a lower category of radioactive waste (or even to conventional waste after clearance). Such an analysis also takes into account the fact that some material will require significant preparation before decontamination can be applied (e.g. pipes need to be segmented to make inner surfaces accessible). Such an effort will only be worthwhile if the amount of material that can be salvaged in this way is sufficiently large. The break-even point will depend, of course, on country specific conditions. A plant specific analysis is therefore necessary.

Decontamination techniques still leave some room for improvement. As of today, the physical-chemical process of contamination is not fully understood and most of the decontamination processes are still partly based on trial and error. Chemical techniques, which are easier to use than mechanical techniques in small applications, still produce a certain amount of secondary waste. Reduction of this secondary waste can be achieved by improved regeneration of the decontamination chemicals. There is also scope for the waste treatment plants at research reactors/centres to be adapted to take these secondary wastes. In addition, experience indicates that more work may be required on radioactively contaminated concrete, addressing characterization methods, low dose methods and improved volume reduction for secondary wastes resulting from concrete decontamination.

6.4.2.3. Radiological characterization techniques

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 core drills used for sampling concrete and graphite (Fig. 28). Some additional developments have been undertaken on material containment systems and on techniques for minimizing secondary waste production. While established techniques for sampling contaminated and activated surfaces and materials are available, new techniques are emerging for specific applications.

Examples of some recent characterization techniques which have the potential for further development are described in Ref. [8] and can be summarized as follows:

(a) Systems for superimposing β radiation readings and spectrographic information onto visual images of an object.
(b) Methods for simulation of decommissioning activities by plotting these against positional data. Positional data can be provided for indoor situations by modified surveyors or outdoors by means of global positioning systems. Data are displayed in the form of a CAD image of the survey area or a geographical map (Figs 24, 25).
(c) Methods for inserting radiation probes into pipes (Fig. 26). A comprehensive discussion of Pipe Explorer and similar probes is given in Ref. [36].
(d) Methods for automated collection of a large number of surface contamination readings (Fig. 27).
(e) Extensive use of in situ gamma spectrometers [223].
(f) Increased experience and instrumental sensitivity in detecting very low contamination levels, e.g. close to clearance levels [224].
(g) Broader identification of radionuclides, including those that are difficult to measure, by the use of radiochemical separation and fingerprinting techniques.

A major application of such techniques is in the area of clearance measurements, which are typically performed using RMFs as discussed in Section 5. RMFs provide very reliable, cost effective and fast measurements. Although the use of such devices has become common practice at nuclear power plants and large nuclear installations, they are not often considered for use at smaller research reactors. The reason is that the overhead costs of renting, installing and calibrating an RMF for a few hundred tonnes of waste from a smaller research reactor site are comparatively high. However, a general purpose RMF capable of measuring at least 200 L drums, which requires a very short time for set-up, is expected to be commercially available in the near future and might therefore be valuable for research reactor decommissioning.

Characterization techniques are also important for establishing nuclide vectors for the radioactive waste from a research reactor, allowing the amount of such nuclides, which are hard to measure, to be calculated from easy to measure key nuclides. While these nuclide vectors (often also called fingerprints) are well established for nuclear power plants, especially during the operational phase, this is not often true for research reactors due to their variable or experimental operation. Better methods for correlating the difficult to measure nuclides to the key nuclides would therefore be welcome in order to avoid considerable overestimation of the actual nuclide content in radioactive waste.

Experience indicates that if the radiological inventory of the plant is begun early enough, a sufficient quantity of easily measurable, short lived radionuclides will still be available for the necessary measurements. After a longer period of time (for example after safe enclosure) the characterization of the radioactive inventory by measurements becomes more difficult because relevant easily measurable radionuclides may have decayed. In turn, the characterization of difficult to detect, long lived radionuclides by fingerprinting becomes more problematic.

A market has evolved over the past decade. This not only includes manufacturing companies that are highly innovative and offer a wide variety of measurement devices, but also extends to contractors offering a total release measurement service. This may be useful in the future for those decommissioning projects that have a small waste inventory and where the specific purchase of a state of the art characterization device may not be economically feasible.

In summary, technical areas still presenting characterization issues include the following:

(1) Characterization and measurement of hard to detect radionuclides (e.g. α or weak β emitters), mostly when these measurements have to be carried out in situ;
(2) Characterization of components/parts in areas of limited accessibility due to layout and/or high radiation/contamination fields;
(3) Remote controlled measurements or sampling are often the best solution, but not always easy and inexpensive to implement [225].

6.4.3. Decommissioning waste management

When planning and implementing a decommissioning project it is helpful to recognize that regulation and policy will inevitably evolve. Increasing attention is currently being given to waste management issues. Any long term planning should therefore take into account trends in this area, so that the chosen strategy is flexible enough to be adaptable to policy changes.

6.4.3.1. Recycling

More attention is being given to life cycle risk associated with an action, including the decontamination and dismantling of nuclear facilities, for example examination of the potential benefits of implementing the recycling and reuse of materials versus disposal as radioactive waste. Associated with this approach is the need for broadly accepted release criteria, regulations for recycled and reused materials that are scientifically sound, and a common approach to EIAs for decommissioning activities.

A typical recycling method in decommissioning is melting of metallic parts. As one recent example, slightly activated metal parts (pipes, plates) from the ASTRA Seibersdorf reactor have been collected and will be melted for compaction or reuse at the Siempelkamp establishment, Germany [226]. Another example, from the BR-3 reactor decommissioning project, Belgium, concerns the recycling of metallic materials by melting in dedicated facilities outside Belgium. This included either the fabrication of shield blocks or unrestricted release of some batches [227]. Another example of recycling is the melting facility used during the dismantling of the JEN-1 reactor, Spain, as illustrated in Fig. 33. In France, metallic parts from the Siloe and Pegase research reactors were sent for melting [228].

6.4.3.2. Reductions in discharges

In general there is continued and increasing regulation that creates pressure to further reduce radioactive discharges — especially to the marine environment (e.g. the London and the OSPAR conventions) [229–231].

6.4.3.3. Radioactive waste policy

Matters to be considered in the future include emerging policies on long term storage and final disposal. One important policy point increasingly being

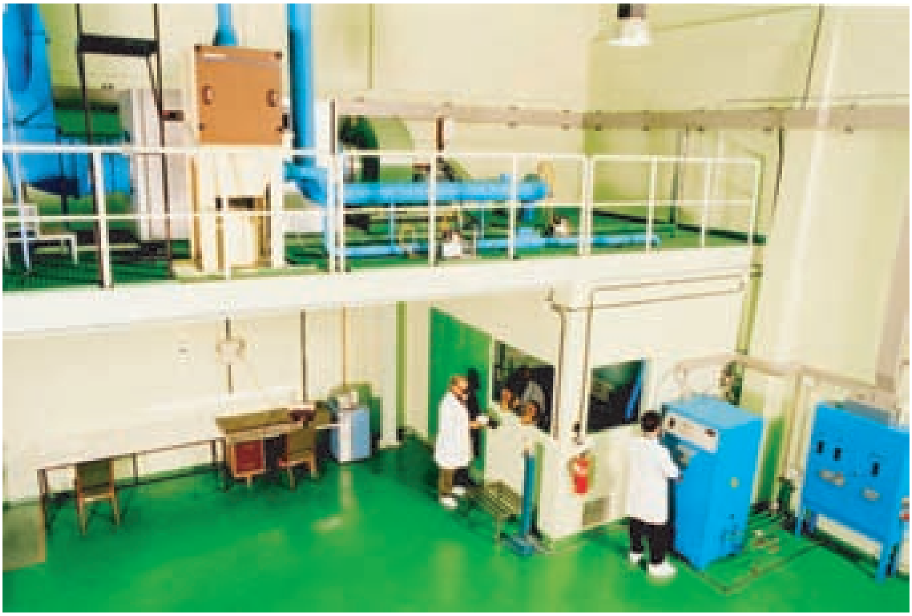


FIG. 33. CIEMAT melting facility, Spain.

acknowledged by Member States is that the absence of a final waste repository is not considered an obstacle to early dismantling, particularly for smaller research reactors [232]. The rationale for this is the continuing difficulty many Member States are having to site and construct a national waste repository. The assumption is that interim storage facilities would be available and adequate to store decommissioning waste.

6.4.3.4. Waste minimization

Taking into account the progress made and the problems encountered over the past 10–15 years, additional efforts to enhance waste minimization are required in the following areas:

(a) Development and use of industrial quality instrumentation for sorting non-radioactive and radioactive materials generated during decommissioning. A challenge here is that such instrumentation needs to be capable of ensuring compliance with increasingly restrictive clearance criteria without unduly compromising decommissioning costs.

(b) Standardization of measurement and calibration methods to facilitate uniformity in the evaluation of decontamination and dismantling techniques.
(c) Increased use of decontamination techniques that are suitable for industrialization, are cost effective, and that produce minimal amounts of secondary waste.
(d) Specific problems have also been identified with the decommissioning of research reactors. For example, how to best dispose of irradiated and contaminated graphite from graphite moderated reactors, thermal columns and reflectors; and how to manage beryllium, thermo-insulating materials (e.g. asbestos), cables, etc. Some practical experience is being gained in these areas. However, it could be timely to review existing solutions and innovative approaches, taking into account state of the art technologies and prevailing trends in waste management, including disposal aspects.

6.4.3.5. Remaining problems with wastes requiring special handling

Although many aspects of waste treatment and conditioning are now routine, some difficulties still remain. Some materials used in the early age of the nuclear industry, such as asbestos, present strong toxic hazards often combined with radiological hazards. Commonly, it is only feasible for certified companies to remove asbestos. These do not always have the necessary skills and competence to work in a radioactive environment. As another example, beryllium, which is widely used in research reactors (even as a component of fuel), creates problems in decommissioning waste management in terms of conventional toxicity and also radiation hazard following irradiation. In addition, beryllium structures that have been subjected to high accumulated neutron flux can exhibit radiation induced swelling and associated cracking, thereby leading to uncertain structural integrity and physical conditions. This requires a non-traditional approach to the technologies of beryllium waste handling, conditioning and disposal.

Such issues are being addressed in the ongoing IAEA programme on disposal aspects of decommissioning waste. This programme commenced in 2002 and it is anticipated that its findings will contribute to the effective management of unusual wastes arising from the decommissioning of research reactors. Reference [38] and Section II–3.3 of Annex II present various technologies for the decommissioning of radioactive graphite.

Management of sodium and sodium alloys is a serious issue in fast reactors. One example of sodium management is given in Ref. [233]. A comprehensive overview of sodium cooled reactor decommissioning projects is given in Ref. [234], with a focus on sodium removal. Reference [235] offers a review of methods to deal with a range of unusual decommissioning wastes.

6.4.3.6. Contaminated land

Increasing attention is being given to the possibility that the land upon which a nuclear facility is located may be contaminated. A case such as Cintichem [80] is not expected to happen again. It is becoming a normal regulatory assumption that land associated with a nuclear facility needs comprehensive radiological characterization. Resolution of contaminated land issues involves a careful review of the operational history of the facility, together with calculations, experimental studies (e.g. groundwater migration, leakage pathways), sampling and analysis. Characterization and remediation of contaminated land is an area in which significant technological developments are under way [236–238]. In the context of decommissioning, the presence of underground structures, systems or components can often be associated with soil contamination [36]. Eventually, land remediation may become a significant process in itself, but this is outside the scope of this report.

6.5. INFORMATION EXCHANGE

6.5.1. Information dissemination

People involved in decommissioning projects often have an operational background. In some cases this can mean that their experience is more related to following checklists and written instructions than having to write detailed reports (such as those described in Ref. [12]) on the various steps of the work they perform. This means that so far few detailed reports exist on how the decommissioning of specific reactors was done. It is expected that, owing to the growing attention to decommissioning and the transparency required by today's social standards, more and more information on completed decommissioning projects will be available.

While an ample amount of literature on the general approach to research reactor decommissioning exists, some countries would welcome publications on particular tasks, which can help participants in reactor decommissioning projects in solving their specific problems.

In addition to the reports mentioned above, the ongoing organization of workshops and training for people actually carrying out reactor decommissioning is also expected to help the exchange of experience and promote the dissemination of information. The IAEA (particularly through its

Technical Co-operation Programme) and other international organizations are dedicated to promoting these activities.

6.5.2. National and international working groups

International networking in the field of nuclear decommissioning has been established and is continuing to develop. However, there is an emerging tendency that in the future information exchange may become more difficult, due to factors such as the liberalization of the electricity market, subsequent competition between suppliers for decommissioning services, and the growing number of patents applying to decommissioning. This potential restriction of information could be a worthwhile topic for consideration by future working groups.

6.5.3. Provision of practical assistance and training of decommissioning personnel

The IAEA continues to provide practical assistance to ongoing and future decommissioning projects in Member States in order to ensure that decommissioning is planned and carried out safely, in good time and as cost effectively as possible. It is generally desirable to increase the capabilities so that the beneficiary (a project or a Member State) can perform decommissioning without external assistance to the extent practicable. In order to achieve this, the beneficiary needs to obtain an adequate understanding of the most effective methods and procedures and also needs to acquire the necessary skills and experiences of appropriate practices. Among other things the IAEA sponsors a number of decommissioning oriented training courses and workshops at the national, regional and interregional level.

Existing training centres where decommissioning personnel are introduced to the working environment of decommissioning perform well, since they attract personnel skilled in practical work. Such centres are very helpful for the bulk of the hands-on work of dismantling contaminated systems or components, and some enterprises have already seen the chances of making a profit by offering training services. One such example of a nuclear centre active in research reactor decommissioning is SCK-CEN in Mol, Belgium [239].

As a general trend, it should be noted that training is increasingly being sought on specific decommissioning issues or components of the decommissioning process (e.g. record keeping, radiological characterization or public information), since the basics of decommissioning are now generally known. But a number of dismantling activities are in most cases specific to the individual reactor and its physical and radiological state. Experience has shown that training may require practising certain dismantling sequences, e.g. remotely controlled fragmentation work at 1:1 mock-ups, which in turn are individually constructed. There is little scope for generalizing those training activities in training centres. Therefore ad-hoc assistance is typically provided to reactor operators by national or international organizations where requested.

6.5.4. Organization of conferences and seminars

Many seminars and conferences for the decommissioning of research reactors are being offered. Although this looks like a saturated market, ongoing research in areas such as innovative reactors, desalination reactors or partitioning and transmutation facilities will certainly produce new directions for decommissioning R&D. The IAEA is seen in the role of following up on new tendencies.

6.5.5. Databases

Efforts are continuing to ensure that existing international databases remain up to date and appropriate as support for the planning and implementation of decommissioning projects. One recent development has been the publication by the OECD/NEA and other international organizations of a recommended standard list of definitions of decommissioning cost items [31].

Other decommissioning oriented databases are provided by the USDOE, e.g. Refs [240, 241]. A recent trend is the use of large scale refurbishment activities to collect data for future decommissioning. One such case is the Cirus reactor, as described in Ref. [242]. The IAEA specifically requires [168] that "Documentation of the reactor hall shall be kept up to date and information on experience with the handling of contaminated or irradiated structures, systems or components in the maintenance or modification of the reactor shall be recorded to facilitate the planning of decommissioning".

6.6. COSTS AND FUNDING

It is becoming increasingly important to ensure that greater cost effectiveness is achieved in the management of nuclear liabilities, including research reactors. One way to achieve this is to identify less capital intensive, simpler technological options. It should be possible to save money within a given framework of objectives by exploring the deficiencies of the current strategies [243, 244]. The future trend is to achieve a better understanding of decommissioning cost estimates and, based on those, to fine tune funding mechanisms.

6.6.1. Decommissioning cost estimates

It is being increasingly recognized that cost estimates are essential to secure an appropriate level of funding for a programme. Therefore the IAEA recommends [12] that the decommissioning cost study be done early in the life cycle of a facility, and that the first draft be drawn up during construction. According to Ref. [12] this plan should be updated regularly and finalized prior to implementation of the decommissioning strategy. Unfortunately these recommendations are not yet fully implemented in a number of countries, but a positive trend is emerging.

The EC-IAEA-OECD/NEA study described in Ref. [31] has proposed a standardized accounting method to hopefully achieve consistency among decommissioning projects. However, difficulties in the circulation of results generated through the use of this model have arisen because of commercially sensitive information. There is a trend towards using comprehensive parametric cost estimating models supported by extensive databases, but research reactors are so varied that each case is best approached taking into account the site specific factors. New approaches are expected to contribute to the accuracy of future cost estimates by using benchmarking based on the cumulative experience. Robust estimates, quantified within defined levels of certainty, can be achieved through the use of techniques such as quantity surveys, multi-point estimating, experience from previous decommissioning projects and risk analysis [245].

6.6.2. Provision of decommissioning funds

There is an increased awareness of this issue and progress is being made towards securing the availability of funds. In an ideal scenario these funds would be made available as soon as possible after final shutdown, in order to facilitate a smooth and timely transition to decommissioning.

However, the funding situation for some research reactors remains uncertain in that no funds have been set aside and there is no way of financing decommissioning. Such situations are likely to result in a deferred dismantling strategy.

Additionally, where funds have been dedicated to decommissioning, costs are often severely underestimated. There is a common trend to only compare the available funds with the actual funding needed at the beginning of the decommissioning process. Ideally, where a fund has been created it should be revised periodically during operation, taking into account the operational history and modifications to the facility, as well as technological improvements and changes to the social, political and economic environment. Cost estimates should take into account all immediate and discounted costs throughout the lifetime of the decommissioning project. A general trend in this field is the obligation of the owners to periodically report the status of the fund to the safety authorities and to share more and more information with the stakeholders.

7. CONCLUSIONS AND RECOMMENDATIONS

This report develops on earlier IAEA technical reports dealing with the decommissioning of research reactors and provides an update on technological progress and experience gained, taking into account the progressive ageing of research reactors, many of which have already reached the stage of permanent shutdown and may be fully decommissioned in the near future. It provides an up to date review of decommissioning experiences, and disseminates information and practical guidance based on experience and lessons learned in the planning and implementation of the decommissioning of research reactors. The main conclusions and recommendations of this report, which captures and distills the collective knowledge and experience of the authors from many IAEA Member States, should help to better focus future research reactor decommissioning activities in the areas of general management, planning, waste, fuel, technologies, communications, costs and funding, as delineated in the following sections.

7.1. GENERAL MANAGEMENT ISSUES

The main general management related conclusion of this report includes the strong recommendation that reactor operating organizations establish a decommissioning project team, composed of members of the facility's staff and outside experts, well before final shutdown. It is also important to provide retained facility staff with adequate retraining in new skills and attitudes and to ensure that corporate memory (plant and decommissioning knowledge) does not disappear. It is equally important to keep regulatory bodies informed well in advance and throughout the decommissioning project. Contracting issues deserve particular attention in that nuclear safety responsibility cannot be delegated or contracted to a third party and experience indicates that fixed price contracts are only suitable for well specified parts of the project. The use of appropriate stakeholder dialogue methods to inform and communicate with all interested parties should ideally start before decommissioning commences and should continue throughout the project.

7.2. PLANNING ISSUES

The main planning related conclusion of this report is that, while research reactor decommissioning is a well established process, a comprehensive decommissioning plan should be produced several years before final shutdown. The report also recommends that the initial radiological characterization of the facility and, if necessary, of the site be carried out well before final shutdown. Following final shutdown it is desirable to do as much pre-decommissioning work as is possible, to ensure a smooth and timely transition from reactor operation to decommissioning. This will add impetus to the project and tend to speed up the whole dismantling process. In addition, the early move towards more practical activities, such as spent fuel removal and site characterization, just after final shutdown will help to improve the motivation of staff. Ideally the many other physical activities necessary to completely decommission the reactor will be implemented on an ongoing basis immediately following shutdown, unless a deferred dismantling policy has been adopted.

7.3. WASTE AND FUEL ISSUES

The main waste and fuel related conclusion of this report is that early removal of the fuel from the facility will significantly reduce the radiological hazards and allow many ancillary systems to be shut down and safeguards requirements to be reduced. It is vitally important to ensure that all local and national requirements associated with radioactive waste management are known and, if necessary, clarified up front, as the actual decommissioning strategy will be heavily influenced by waste classification, storage, transport and end point issues and regulations.

7.4. TECHNOLOGY ISSUES

It has been shown that a very broad spectrum of technologies is available today to deal with almost all kinds of decontamination and dismantling operations. Experience in using these technologies in actual operations is also more widely available and could be used to avoid re-inventing the wheel in future decommissioning projects. However, even if technologies and expertise are available for most decommissioning activities, some technical issues still need to be solved and hence there can be requirements for R&D within dedicated projects and institutions. When a process or tool is being selected, due regard should be given to aspects including generation of secondary waste, ease of maintenance, reliability and ease of decontamination.

7.5. INFORMATION EXCHANGE

The main information exchange conclusion of this report is that experience from other research reactor decommissioning projects should be considered and, where appropriate, incorporated into the actual decommissioning plan, noting that some experiences from the decommissioning of power reactors may also be relevant. It is important that a comprehensive post-decommissioning report on all aspects of the work carried out, including the lessons learned, is produced for each research reactor decommissioning project so that others can benefit from these experiences.

7.6. COSTS AND FUNDING ISSUES

In common with other engineering projects of significant size, some decommissioning projects have suffered from escalating costs and programme overruns caused, in part, by insufficient thought having been given to developing robust cost estimates at their start. State of the art project management techniques are applicable to decommissioning projects. The use of these techniques can lead to improved cost estimates and programme planning. Robust estimates, quantified within defined levels of certainty, can be achieved through the use of techniques such as quantity surveys, multipoint estimating, experience from previous decommissioning projects and risk analysis.

It is also important to ensure that an early decommissioning cost study is carried out and that it is regularly revised during operation to ensure the adequacy of decommissioning funds. It is equally important to pay attention to the accuracy of the cost estimates by benchmarking with respect to other decommissioning projects and accumulated experience. Cost estimates should take into account all immediate and discounted costs through the lifetime of the decommissioning project.

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Annex I

DATABANK FOR DECOMMISSIONING OF RESEARCH REACTORS

A computerized research reactor databank was prepared and updated as part of this report. The information is presented on the attached CD-ROM in pdf format. The databank is based on the following sources:

(a) The IAEA databank on Nuclear Research Reactors in the World, published as Reference Data Series No. 3;
(b) Questionnaires returned by Member States;
(c) Published literature;
(d) Internet sources;
(e) Private communications with experts from Member States.

This databank was first used in the IAEA publication on Decommissioning Techniques for Research Reactors (Technical Reports Series No. 373) published in 1994 and has subsequently been updated. It reflects the reactor status and information as of May 2005. It contains a list of all known research reactors, provides information on planning and management of decommissioning projects for research reactors, and detailed data from those projects where available. No detailed information is available for some of the projects presented, and only their existence is known. It is hoped that the missing information will be obtained in the future.

The CD-ROM contains the following files:

— Research reactors — main list;
— Reported research reactor decommissioning projects — foreword;
— Reported research reactor decommissioning projects — shut down reactors;
— Reported research reactor decommissioning projects — operating reactors;
— Detailed data from research reactor decommissioning projects — foreword;
— Detailed data from research reactor decommissioning projects — table;
— Detailed data from research reactor decommissioning projects — figures;
— References.

By noting the reactor type, power, decommissioning status and other parameters it should be possible to focus on one or more projects that have experience and data possibly relevant to the reader's own project. However, caution is requested in extrapolating data since many other unquoted parameters may influence a decommissioning project.

Annex II

LESSONS LEARNED

The following examples of the lessons learned from research reactor decommissioning projects include an outline of the problems and requirements encountered, the solutions found and the lessons learned. The situations described are typical of the issues that can arise in the planning or implementation of decommissioning activities.

The information in this annex is organized under the general categories of events and issues. A summary of the operating experience in the decommissioning of research reactors in the United Kingdom is provided in Ref. [II–1].

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

II–1. MANAGEMENT AND PLANNING

II–1.1. Operational safety: BR-3, Belgium

Problem encountered

During decommissioning of the BR-3 reactor [II–2] an operator working in a controlled area was concerned about the potential contamination of his ladder. This ladder was made of aluminium to allow easy decontamination, but he thought the rubber pieces at the extremities of his ladder would give rise to problems of further contamination. The worker decided to protect those areas against potential contamination by covering them with plastic bags. When being used in the controlled area, the ladder slipped. The worker fell and broke one of his legs, resulting in a three month absence from work.

Lessons learned

In the optimization of the radiological aspect of decommissioning work, attention should also be given to non-radiological risks. The influence of one safety aspect on the other can be important and there may be a need for an extension of the ALARA approach to a broader extent than radiological protection.

II–1.2. Accuracy of drawings: JANUS, USA; JASON, UK

Problem encountered

During decommissioning of the JANUS reactor [II–3] the wiring of two energized circuits (which were supposedly de-energized) was cut while the reactor control panels were being dismantled. This led to two live wires being cut and subsequently capped with wire nuts. These wires had been installed in the early 1990s as part of installation of an emergency power system. The emergency circuits had been incorrectly routed through reactor control panels instead of through their own conduit. The problem was identified when it was noticed that the exit lights were off in the stairway while the emergency lights were on.

During decommissioning of the UK JASON reactor [II–4] it was recognized that the installation records and, in particular, the records of previous nuclear or radiation related operations in the facility prior to the installation of JASON, were not comprehensive. The less than comprehensive installation and previous building use records had the potential to delay the completion of the decommissioning, particularly regarding meeting the final site clearance criteria.

Lessons learned

These two and many other examples clearly show that the drawings of the facility as built and operational records do not always reflect the current conditions, and personnel need to be continuously reminded that, when conditions or events do not meet expectations, work must be stopped and management notified before work continues.

II–1.3. Surveillance and maintenance: BGRR, USA

Problem encountered

The Brookhaven graphite research reactor (BGRR) was a graphite moderated air cooled research reactor. It operated from 1950 to 1968 and the reactor's enriched uranium fuel was removed in 1972. Surveillance and maintenance had been conducted for areas with general access, but there had been limited surveillance and maintenance of the remainder of the facility because it was considered secure. In 1997, contaminated water was found in the reactor's air cooling ductwork system. After this discovery further investigation into the physical status of the BGRR complex was initiated, as was the potential for facility degradation to have caused an impact on the surrounding environment. A facility review of the BGRR identified a need to perform a more systematic closure of the complex.

Solution found

Near term stabilization (i.e. a benign plant status) is currently under way, and a deactivation and stabilization plan has been developed. BGRR is becoming a very sensitive issue regarding decommissioning activities as well as expectations about continuous progress in addressing environmental issues.

Lessons learned

Regular and active involvement of those responsible for both current stabilization and future decommissioning pays benefits both in developing a common understanding of conditions for facility transfer and in identifying opportunities for early decommissioning planning to ensure a 'seamless' transition from stabilization to decommissioning.

II–1.4. Intervention containment arrangement: Switzerland

Problem encountered

The PSI Hot Lab at the Paul Scherrer Institute (PSI) had to be refurbished for safety reasons. The operator claimed that operating the different sections of the laboratory would be possible during refurbishment. This meant that personnel and waste routing had to be separated.

Solution found

The corridors within the laboratory were divided into two halves by a thin wall (sealed against the spread of contamination). On one side of the wall the laboratory crew was able to walk to those sections that remained in operation, while workers and waste materials were transported on the other side. Laboratory personnel could enter the controlled area normally. Other workers entered the refurbishment area by means of 'intervention' containment devices such as air locks fitted to the window apertures of the sections under refurbishment.

Lessons learned

The operating costs of the Hot Lab during a total shutdown could be reduced significantly with a simple solution. Since some refurbishment activities are similar to dismantling activities, similar applications can be considered for decommissioning of research reactors.

II–1.5. New route for high activity waste: MELUSINE and SILOE reactors, France

Problem encountered

The MELUSINE research reactor had not been in use since 1993 and had some residual HLW in its pool. When the decommissioning programme restarted in 2000, the reactor's hot cell (the normal route for HLW) was not usable due to a lack of maintenance. The cost of its refurbishment was estimated at € 1 million, and the engineering planning would take two years.

The SILOE research reactor and its hot cell, located on the same site, had been shut down since 1997 and therefore were not allowed to receive any waste from the outside.

Solution found

The waste from the MELUSINE pool was transferred to the SILOE research reactor's pool. To do this the operator requested authorization from the safety authorities to transfer external waste into the SILOE pool and hot cell and then transferred HLW from MELUSINE to SILOE in order to use its hot cell for waste conditioning.

Lessons learned

The decommissioning plan of a facility should be developed in the context of an overall (integrated) programme for the nuclear site. The safety authorities should be informed as soon as possible and authorizations should be obtained for the integrated programme.

II–1.6. System modifications (as-built drawings): ETRR-1 research reactor, Egypt

Problem encountered

The Egyptian research reactor (ETRR-1) was commissioned in 1960. At the beginning of 1990 a modification plan for upgrading the instrumentation and control system was developed. The very experienced facility shift supervisor died during the installation of the new control system for the primary cooling pumps and the only copy of the original drawings of the dismantled system was lost.

Solution found

The reactor operating organization painstakingly traced and produced a series of as-built drawings of the existing components, cables, connections, etc., which subsequently needed to be thoroughly checked. While this caused a major delay to the modification programme, the new installation subsequently worked perfectly.

Lessons learned

Documentation and original drawings of all reactor systems are very important and valuable, and must be available before implementation of any decommissioning or modification activity. Copies of these drawings must be available in more than one place. Also, information exchange with suitably qualified and experienced persons is important to make the correct judgment about dismantled components or systems.

II–1.7. Safe enclosure and reuse: FRF1/FRF2, Germany

Problem encountered

The FRF1 reactor (TRIGA) was shut down in 1968, and in 1970 some components were partially dismantled. The reactor building, the biological shield and certain components were earmarked for reuse in a new facility at the same site and building. Commissioning and construction of FRF2 were complete but it was decided that the new reactor should not be put into operation. A solution had to be found for the final disposal of the residual components of FRF1.

Solution found

Since 1983 the residual components of FRF1 have been enclosed in the reactor block of FRF2 and parts of the reactor building have been used as a storage facility for additional radioactive waste from the University of Frankfurt.

Lessons learned

The amount of waste can be reduced when some components or the building of a shut down facility can be reused for a new facility. A shut down facility adapted to enclose residual components can also be used for storage of radioactive waste from other facilities or institutions.

II–2. INFORMATION EXCHANGE

II–2.1. Generic databases: Germany

Problem encountered

In Germany it was observed that various research reactor decommissioning projects had to cope with similar or identical issues such as the preparation of sets of documents for the licensing procedures, selection of suitable decommissioning techniques, negotiations with possible contractors, and selection of equipment for radiological surveys and clearance measurements.

Solution found

The operating organizations of a number of German, Swiss, Belgian and Austrian operating organizations of research reactors facing or undergoing decommissioning joined in the Working Group on Decommissioning of Research Reactors (Arbeitsgruppe Stillegung Forschungsreaktoren) in order to exchange information on the topics addressed above and others. Furthermore, a database dedicated to research reactor decommissioning experience, which collects and systematizes this information, has been developed and installed.

Lessons learned

The information exchange is of extreme importance for fast, cost effective and safe decommissioning projects. Research reactor decommissioning projects should therefore seek information exchange as early as possible. If necessary, this information exchange may be organized and structured by establishing work groups and databases, which can assimilate the information from decommissioning projects for the benefit of other projects.

II–2.2. Record keeping: DR-2, Denmark

(a) Problem encountered: Documentation of the work performed

During the DR-2 project, the project leader was present during all major operations and wrote entries in his project diary at the end of each day. This included a record of the movements of all components taken out of the reactor. Digital photographs were also taken of all major operations. The results of the measurements were recorded and kept by the health physicist responsible for the measurements, or in a few cases the project leader. Even though this arrangement worked quite well during the project it may be argued whether keeping two sets of records, e.g. one with the health physicist and one with the project leader, was actually the best approach.

Lessons learned

It is of the greatest importance for the management of the project that detailed records be kept of who did what work at which time and of where which components are placed. It is preferable that these records stay with the project leader or their deputy. The records of a given day are to be written immediately after the work has been carried out, and for the same reason the project manager or their deputy is responsible for attending all major project operations.

(b) Problem encountered: Component accounting systems

The number of components to be handled was significant, of the order of 200. They had to be moved around in the reactor building — sometimes even outside the building — to be more accurately measured in another building. If they could be cut, the active components were disposed of in waste drums which when filled were sent to the waste management plant. If they could not be cut they were stored in the storage facility. The non-active components were put into plastic bags and marked with an identification code.

A record of which components were placed where was kept in the logbook of the project leader. This record was brought up to date every time components were moved. This system seemed to work quite well but sometimes the identification of the smaller, active components gave rise to problems. For example, ‘small Al-tube’ is not a unique definition of a component.

Solution found

To reduce personnel doses and to avoid contamination, the identification code was only applied after a component had been found to be non-active or only slightly active. The active components were, if at all possible, cut into drums and therefore not identified by a special code, only given a more or less unique name.

Lessons learned

Identification of waste/material items requires that there be no ambiguities.

(c) Problem encountered: Archives

At DR-2, two archives, which were kept in separate locations, were established shortly after the final shutdown of the reactor. Unfortunately nobody was appointed to ensure that the archives were kept in a proper state and that new relevant information was included in the archives.

Solution found

A considerable effort had to be made at the start of the DR-2 project to bring the two archives up to the required level.

Lessons learned

It is important to ensure that archives containing all information relevant for the decommissioning are properly maintained until the facility has been finally decommissioned.

II–2.3. Data collection from HD1/HD2 projects: Germany

Problem encountered

The TRIGA HD1 in Heidelberg was partially dismantled, and a period of safe enclosure commenced in 1980; it is now intended to completely dismantle this reactor at some time in the future. The TRIGA HD2 at the same site was shut down in 1999 and immediate dismantling was also planned. HD1 will be the first research reactor to be dismantled after a long period of safe enclosure. A comparison of decommissioning data from different research reactor projects in Germany showed that generic assumptions could not be made, as the decommissioning conditions differ for each type of reactor

An important factor is the general infrastructure associated with the decommissioning project, for example the degree of storage and conditioning facilities at the site or nuclear centre. Nonetheless, the decommissioning and dismantling of the HD1 and HD2 reactors may provide suitable data that can be used to compare future decommissioning strategies covering either deferred or immediate dismantling.

Solution found

Partial dismantling with subsequent safe enclosure was chosen as the decommissioning strategy for FR2, FRN and HD1. For the recent FRH and HD2 decommissioning projects, immediate dismantling is planned.

Lessons learned

Decommissioning related data may be best obtained by comparison with similar decommissioning projects and reactor types. However, the adoption of differing decommissioning strategies for similar reactor types may mean that much of these data are not generic. For small TRIGA type research reactors decommissioning is relatively straightforward and the current trend in Germany is towards immediate dismantling.

II–3. TECHNIQUES

II–3.1. Dismantling of the activated zone of the bioshield: FMRB, Germany

Problem encountered

The research and measurement reactor (FMRB) of the Physikalisch-Technische Bundesanstalt in Braunschweig was a swimming pool type material test reactor. The activated zone of the pool walls is comparatively thin. It is therefore desirable to have a segmenting technique that allows for removal of the inner layer of activated material only. Due to the limited space available in research reactors and the very different materials used, the separation techniques which have so far proved effective in the dismantling of nuclear power plants can be used at research reactors only to a limited extent.

Solution found

This problem has been investigated in an R&D project carried out for the FMRB but is relevant to many research reactors. The project took into account dismantling in a limited space with minimized waste generation (because of limited infrastructure for waste management on the site) and covered the development, adaptation and qualification of advanced methods under consideration of cost minimization aspects.

The techniques under consideration are laser cutting techniques using Nd:YAG and CO_2 lasers (under atmospheric conditions and underwater, remote controlled and hand-held), the diode laser (thermoshock decontamination combined with dry ice cutting techniques), water abrasive suspension jet and stripping by means of dry ice laser cutting. The technique of dry ice and laser cutting was further developed. Ablation of the surface is caused by the thermal shock effect induced by the dry ice beam while the laser beam still enhances the thermal shock. The dry ice prevents the sublimation of the material (prevention of plasma formation) so that no problematic aerosols are generated, which is very important in research reactor decommissioning [II–5].

Lessons learned

Although a large number of techniques are now available (commercially or at least experimentally), it may sometimes be worthwhile to undertake special R&D developments leading to a technique that will best fit the purposes of a specific decommissioning project.

II–3.2. Mobile transport flask for moving fuel elements from the reactor to the fuel cask: TRIGA, Hannover, Germany

Problem encountered

The TRIGA reactor of the Hannover medical school is located within the building. During its operation it has never been refuelled, nor has fuel been removed from the reactor. The problem encountered was that it was not possible to bring any licensed fuel casks near the reactor so that the fuel could be directly transferred from the reactor to them. Furthermore, the route through the building to the nearest place where the fuel cask could be placed was complicated and did not belong to a controlled area. The fuel had to be moved between floors with a conventional elevator, which imposed weight limits on any transport device (especially on shielding).

Solution found

A mobile transport flask was developed to transport the fuel elements between the reactor and the fuel cask. This flask could accommodate five or six fuel elements and could be directly attached to the shutter device of the reactor. After being filled with fuel elements it was moved through the building on a transfer vehicle. The parts of the building though which the flask was moved were temporarily designated as controlled areas. After arrival in the temporary hall where the fuel cask had been placed, the flask was attached to a transfer unit mounted on top of the cask and the fuel elements were lowered from the flask into the cask. The device can be used for a number of reactors [II–6].

Lessons learned

Unloading of fuel elements from a reactor, even under unfavourable conditions in buildings, is possible if only a few fuel elements are transported at a time. It is advisable that the necessary equipment be designed in such a way that it can be used at more than one reactor.

II–3.3. Graphite conditioning: Diorit reactor, Switzerland

Problem encountered: Waste management for irradiated graphite

While planning the waste routing for the DIORIT research reactor, especially the processing of the graphite reflector blocks to final disposal conditions, any of the various treatment proposals published worldwide were deemed to be inappropriate to the established Swiss waste routing system.

Solution found

With a view to minimizing the waste volume, the Paul Scherrer Institute, in close cooperation with Nagra, developed a graphite treatment process which is now officially accepted by the licensing authority and successfully established. At the heart of the process is the milling of the graphite blocks down to a granulate under dry conditions (Fig. II–1) and use of this granulate as

FIG. II–1. Graphite management in Switzerland: hammer crusher.

filler material for the cementation of activated metal scrap by mixing it with cement, thus avoiding the use of sand (Fig. II–2).

Lessons learned

In a special collaborative effort, experts in waste immobilization, acceptance criteria for intermediate level waste disposal as well as from the licensing authority, jointly found a solution for disposing of graphite in Switzerland. While obviously a Swiss customized solution, both the methodology and the process developed could be of interest to other countries.

II–4. CHARACTERIZATION AND SURVEY

II–4.1. Estimation of the radionuclide inventory: UTR-300, UK

Problem encountered

For any well planned and implemented reactor decommissioning project it is necessary to obtain a reasonably accurate estimate of the inventory of

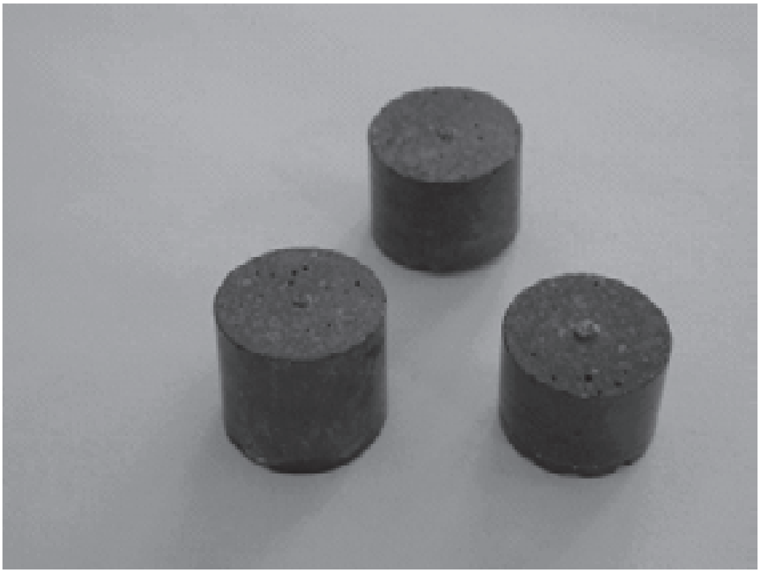

FIG. II–2. Graphite management in Switzerland: graphite concrete samples.

radionuclides remaining after removal of the fuel. In the early stages of decommissioning of the UTR-300 Argonaut reactor at the Scottish Universities Research and Reactor Centre it was particularly important to establish the categorization of material close to the LLW/ILW boundary (for reasons of cost) and the LLW/free release boundary (to avoid needless use of the national LLW disposal facility).

An adequate estimate of the radionuclide inventory had to be achieved knowing that the reactor was constructed from a variety of materials, notably aluminium alloy, mild steel, stainless steel, graphite, ordinary concrete and barites concrete. In addition, there were uncertainties as to the trace element contents of the various components and their distributions within these components.

Solution found

A model was formulated for the calculation of activities at shutdown using a set of assumptions that included a simple analytical form for the neutron flux distribution. Also, given that the period between shutdown and dismantling was more than five years, activation products with half-lives of less than one year were ignored. Only thermal neutron activation was considered important.

Calculations were performed and these were compared with results from samples. The sampling programme included graphite from the large thermal column and concrete cores obtained by diamond drilling.

Lessons learned

It was concluded that, given the above uncertainties, it appears that the predictions of a 'fairly crude' flux model backed by a judicious sampling and measurement strategy can produce satisfactory estimates of total activity. Such estimates are reliable enough to delineate the various waste boundaries and also to set suitably conservative limits to ensure that waste removal authorizations are not breached [II–7].

II–4.2. Unexpected presence of americium: EBWR, USA [II–8]

Problem encountered

There were two exposure incidents at the Argonne National Laboratory. One occurred in the experimental boiling water reactor (EBWR) fuel pool area and the other took place during a glove box job.

In the fuel pool incident the internal exposures were 300 mrem (3 mSv), while the administrative limit was set at 1500 mrem (15 mSv). Nevertheless, operations were suspended until the situation was assessed. The exposure during the glove box incident was 90 mrem (0.9 mSv). The contaminant was americium, which was not expected at this facility. In determining the cause of the exposure it was discovered that the contaminant, americium, was not expected to be on-site since it did not show up in the facility characterization. As a result, the proper precautions had not been taken.

Solution found

Because of the exposure, several precautions were taken for the remainder of the work. On the fuel pool, containment was set up to protect workers not actually working on the pool. An air supply was provided inside the containment area and the surface of the pool was sealed off. On the glove box an airlock entry was added. As in the EBWR area, a ventilation system was added, complete with HEPA filters and air purifying respirators.

Lessons learned

A few lessons were learned as a result of these exposures. By incorporating these lessons, this type of problem can be avoided at other sites. These lessons include:

(a) A thorough search of historical data about operations can greatly aid in more complete characterization;
(b) Based on past operations, monitoring for nuclides that were present while the facility was operating, even if they did not show up in the characterization process, is essential;
(c) Bioassay data are useful indicators for project managers and not to be held by the dosimetry staff as confidential medical data;
(d) For reconstruction of events and dose assessment, archiving air samples and employing good record keeping methods can be very valuable.

By using these lessons, exposures that may not have been foreseen can be avoided. This will save both time and money in the form of decreased work stoppages and time lost due to accidents.

II–4.3. Core samples: TRIGA Mk II, Vienna, Austria

Problem encountered

There was a lack of adequate up front detailed information on the activation levels anticipated on the inner concrete shielding of the TRIGA Mark II reactor, Vienna, Austria, for future decommissioning planning purposes.

Solution found

A cylindrical 30 cm long sample of the outer unirradiated part of the shielding was cut out and placed in a beam tube near the reactor core. This sample was subject to neutron irradiation for four weeks to simulate the same conditions as anticipated on the inner concrete shielding of the reactor. After the irradiation, the sample was removed from the beam tube and cut into 30 discs. The discs were allowed to decay for one week to eliminate short lived activation products. The gamma spectra of these concrete discs were measured to analyse the activity and the distribution of the activation products as a function of the distance from the reactor core. As expected, the long lived ^{133}Ba was identified, as barium is a major part of this type of concrete. Some trace elements, mainly europium, were also identified.

Lesson learned

It may sometimes be necessary to conduct up front in situ radiation experiments to determine potential activation and dose levels for reactor/ shielding components as part of the decommissioning waste and radiological characterization planning process.

II–5. STAKEHOLDER CONSIDERATIONS

II–5.1. Characterization of environmental media: Whiteshell Laboratory, Canada

Problem encountered

As part of a formal environmental assessment for the Whiteshell Laboratory decommissioning project [II–9], the proposed end state of contaminated sediments at the process water release point to the Winnipeg

River met with public and regulatory resistance. The key issue was the existence of adequate data to justify the proposed end state.

Solution found

A team of divers was contracted to carry out a detailed river bottom survey and sampling programme. The resulting data and subsequent analysis confirmed that the contamination of these sediments was well below any possible impact level for aquatic biota and that no mechanisms existed for an impact on humans. On the basis of the detailed information and results of the analysis, the final end state approach of in situ abandonment was accepted.

Lessons learned

A requirement for detailed environmental analysis, raised as a result of public and regulatory concern during the environmental assessment process, added real value to the project. The resulting study confirmed the acceptable end state for a significant project component as in situ abandonment. (While not directly a research reactor issue, this lesson learned has been included to provide an example of the importance of adequate environmental monitoring and assessment in any nuclear decommissioning project).

II–5.2. Inadequate supervision of contractors: Tower shielding facility, USA

Problem encountered

During the late autumn of 1997 and winter of 1998 a subcontractor was surveying surplus materials at the Tower shielding facility at ORNL. Since many of the metal items had been exposed to the neutron flux from the reactor, the predominant radioisotope present was ^{60}Co, a beta–gamma emitter. Alpha contamination was much less prevalent. Due to schedule constraints, a shortage of qualified personnel, an insufficient number of alpha monitors and the scarcity of historic alpha contamination, the subcontractor ceased to consistently conduct alpha surveys on all the items. However, the subcontracted radiological control technicians (RCTs) continued to fill in ‘no alpha detected’ on the green tags.

During June 1998 ORNL RCTs discovered ^{241}Am, an alpha emitter, on a piece of a box that had been tagged as having beta–gamma contamination only. The original box had previously been partitioned to remove the contaminated portion and the remaining portion had been surveyed for beta–gamma contamination only and green tagged for free release. The green tagged part of the box had recently been sold as clean scrap metal to a local foundry. Expecting that more undetected alpha contamination could be present on the other pieces of the box, the high ranking facilities deactivation project manager dispatched an RCT and the tower shielding facility manager to the foundry site to resurvey the other section of the box. The RCT's survey results determined that the other section of that box was free of alpha contamination, but found previously undetected alpha contamination on a similar box from the tower shielding facility. This contaminated box was decontaminated at the foundry site and later returned to ORNL.

Because of insufficient oversight of the subcontractor, the prime contractor was not aware of the lax surveying practices of the subcontractor until after contaminated material had been released off-site. Since schedule constraints and other pressures can often tempt subcontractors to cut corners by deviating from established procedures and practices, sufficient oversight must be provided to oversee subcontracted work to verify that radiation protection requirements and other contractual obligations are being met.

Solution found

Subcontract technical representatives are now in place to oversee all subcontracted work to verify that the subcontractors are meeting their contractual obligations and properly following procedures, standards and applicable regulatory requirements.

Lessons learned

Oversight of subcontracted work is essential to ensure that all contractual obligations, including radiation protection requirements and proper radiological procedures, are strictly enforced.

II–5.3. Regulation and safeguards: ANSTO, Australia

Problem encountered

In Australia a separate regulatory body is tasked with matters relating to safeguards and non-proliferation. The scope of this oversight is very broad and includes administrative controls and monitoring of a variety of associated nuclear material and equipment, in addition to fissile material. Also, while research reactors conduct routine but infrequent shutdowns of extended duration every few years, more opportunity could be taken to facilitate future decommissioning planning.

Solution found

To minimize potential safeguards and non-proliferation problems it is beneficial to consider the early removal of all such associated material and equipment during the decommissioning project so as to minimize future administrative burden and costs. Also, during the final extended shutdown of the research reactor prior to decommissioning, activities that might improve decommissioning planning, such as inspections, surveys and modifications, demand consideration.

Lessons learned

Undertaking decommissioning activities such as inspections, surveys, modifications and the removal of all redundant nuclear materials very early on in a decommissioning project will help improve decommissioning planning and reduce any safeguards/non-proliferation issues.

II–5.4. Organizational difficulties in the shipment of DR-3 fuel elements from Risø, Denmark, to the USA

Problem encountered

The Risø shipments of Danish research reactor DR-3 fuel (255 DIDO irradiated fuel elements) presented unique difficulties due to short timescales and the fact that this was a first time application of personnel, equipment and ships to this issue.

Solution found

The NAC's international efforts, technical performance and precision in project management supported the accomplishment of secure and safe spent fuel transport operations as originally scheduled by Risø. This required close cooperation between Risø National Laboratory, NAC, the US Department of Energy, Westinghouse Savannah River Company and competent authorities of several countries. The NAC International personnel worked with the Risø team over a twelve month period during the project. Successful completion of the work and the delivery of the second shipment ended successfully [II–10].

Lessons learned

In complex projects the cooperation of all stakeholders is essential.

OPERATIONAL EXPERIENCE OF DECOMMISSIONING RESEARCH REACTORS IN THE UK [II–1]

Project activities	Problems encountered and lessons learned	Comments
Planning		
Clear and concise understanding of the problem/deliverables	A clear and concise understanding of the overall decommissioning problem and definition of the exact deliverables is necessary before any development of a strategy is undertaken.	
Full understanding of all the parameters that could have an impact on decommissioning	From experience it is imperative to review all of the parameters which have the potential to affect the optimum decommissioning methodology. Time is a valuable investment in understanding all the issues which need to be factored into the overall solution.	Include peripheral and interface parameters, e.g. special waste acceptance criteria, local site restrictions, access
Development of an optimum decommissioning methodology	The initial stages of any project are key to its overall eventual success. It is important to ensure that adequate time is allocated for the development of the optimum strategy and subsequent detailed design.	Incorrect decisions at this critical stage of project development can have a very onerous effect on both safety and costs at a later date.
Tasks outside the direct control of the project team	Probably general project management but for tasks outside the direct control of the project team it is important to allow adequate time within any programme.	This issue is particularly relevant to the production of documentation and applications for regulatory approval.
Reactors were designed to be operated not decommissioned	Decommissioning presents completely different demands on a facility which may never have been envisaged during original design and construction.	Considerable preparatory work may be required before decommissioning can commence.

OPERATIONAL EXPERIENCE OF DECOMMISSIONING RESEARCH REACTORS IN THE UK [II–1] (cont.)

Project activities	Problems encountered and lessons learned	Comments
Hazard and operability risk assessment	Undertake extensive hazard and operability risk assessment both throughout the development and operational phases of any project.	For maximum benefit ensure that a broad cross-section of representatives attend risk workshops including previous operational reactor staff.
Management and implementation		
Development of safety documentation	It is important to develop all the safety documentation in parallel with the engineering solution, as they are inherently linked. Where possible 'what ifs' should be factored into both the design and documentation to provide flexibility.	
Availability and accuracy of information	Information can sometimes be very difficult to obtain, particularly if the facility has been shut down for some time. There is a need to physically confirm all information — it should not be assumed that drawings accurately reflect the current status of the plant.	
Designation of a dedicated decommissioning project management team	From experience to date it has proved invaluable to appoint a dedicated and integrated project team comprising individuals from both a decommissioning and an operational background. Where possible, ensure that continuity of the team is maintained from project conception, through design and implementation, to completion.	

OPERATIONAL EXPERIENCE OF DECOMMISSIONING RESEARCH REACTORS IN THE UK [II–1] (cont.)

Project activities	Problems encountered and lessons learned	Comments
Completion of tasks 'in house'	Where possible the project management team should coordinate all aspects of the project to gain a complete knowledge base of the project. Although specialist resources may be required to supplement project staff, certain key tasks (particularly drafting documentation) should be undertaken by the team wherever possible.	
Equipment commissioning and associated training	The benefits of comprehensive training and commissioning have been repeatedly proved. Where possible, utilize inactive mock-ups away from the reactor site to demonstrate and improve the operation of equipment. Once these have been installed on-site, further inactive trials should be conducted to confirm compatibility and/or functionability of equipment.	This not only allows the equipment to be exhaustively tested but also provides an ideal opportunity for personnel to familiarize themselves with the proposed tasks and to incorporate any identified improvements into the overall scheme.

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GLOSSARY

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

clearance level. A value established by a regulatory body and expressed in terms of activity concentration and/or total activity, at or below which a source of radiation may be released from regulatory control.

critical assembly. An assembly containing fissile material intended to sustain a controlled fission chain reaction at a low power level, used for investigating reactor core geometry and composition.

decommissioning. Administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility. This does not apply to a repository or to certain nuclear facilities used for mining and milling of radioactive materials, for which closure is used.

decommissioning phase. Well defined and discrete set of activities within the decommissioning process.

decommissioning plan. Documentation containing information on the proposed decommissioning activities for a facility. This would allow the regulatory body to make a proper evaluation to ensure that decommissioning of the facility can be performed in a safe manner.

decontamination. The complete or partial removal of contamination by a deliberate physical, chemical or biological process.

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

disposal, on-site. Disposal of the nuclear facility or portions thereof within the nuclear site boundary. It includes in situ disposal (entombment), where the nuclear facility is disposed of wholly or partly at its existing location; or on-site transfer and disposal, where the nuclear facility or portions thereof are moved to a repository at an adjacent location on the site.

enclosure, safe (during decommissioning). A condition of a nuclear facility during the decommissioning process in which only surveillance and maintenance of the facility take place.

graded approach. The process of ensuring that the level of analysis, documentation and actions used to comply with a requirement are commensurate with: (1) the relative importance to safety, safeguards and security; (2) the magnitude of any hazard involved; (3) the life cycle stage of a facility; (4) the programmatic mission of a facility; (5) the particular characteristics of a facility; (6) the relative importance of radiological and non-radiological hazards; (7) any other relevant factor.

HEU — (more than 20% enrichment).

licence. A legal document issued by the regulatory body granting authorization to perform specified activities related to a facility or activity. The holder of a current licence is termed a licensee.

operating organization. The organization (and its contractors) which undertakes the siting, design, construction, commissioning and/or operation of a nuclear facility.

regulatory body. An authority or a system of authorities designated by the government of a State as having legal authority for conducting the regulatory process, including issuing authorizations, and thereby for regulating the siting, design, construction, commissioning, operation, closure, decommissioning and, if required, subsequent institutional control of the nuclear facilities (e.g. near surface repositories) or specific aspects thereof.

risk analysis. An analysis of possible events and their probabilities of occurrence together with their potential consequences.

risk assessment. An assessment of the radiological risk associated with normal operation and potential accidents involving a source or practice. This will normally include consequence assessment and associated probabilities. For the purposes of this report, risk assessment also includes the decommissioning process.

use, restricted. The use of equipment, materials, buildings or the site, subject to restrictions imposed for reasons of radiation protection and safety.

use, unrestricted. The use of equipment, materials, buildings or the site without any radiologically based restrictions.

waste management, radioactive. All activities, administrative and operational, that are involved in the handling, pretreatment, treatment, conditioning, transport, storage and disposal of radioactive waste.

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Consultants Meetings

Vienna, Austria: 7–11 April 2003; 17–20 May 2005

Technical Committee Meeting

Vienna, Austria: 17–21 May 2004

The attached CD-ROM contains the following files:
(click to open)

Research reactors – Main List - Table;

Reported Research Reactor Decommissioning Projects – Foreword;

Reported Research Reactor Decommissioning Projects – Shutdown Reactors – Table;

Reported Research Reactor Decommissioning Projects – Operating Reactors – Table;

Detailed Data from Research Reactor Decommissioning Projects – Foreword;

Detailed Data from Research Reactor Decommissioning Projects – Table;

Detailed Data from Research Reactor Decommissioning Projects – Figures;

References.

This report reviews, from a historical perspective, decommissioning projects completed in recent years or under way, and assesses progress, as well as open and new issues. It is meant to facilitate timely, safe and efficient completion of decommissioning projects for research reactors by highlighting technologies, and planning or management methodologies, and suggesting ways to overcome expected issues. The report includes a CD-ROM providing details of several hundred research reactor decommissioning projects.

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA
ISBN 92–0–112605–0
ISSN 0074–1914