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Decommissioning of Research Reactors and Other Small Facilities by Making Optimal Use of Available Resources

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International Atomic Energy Agency

DECOMMISSIONING OF RESEARCH REACTORS AND OTHER SMALL FACILITIES BY MAKING OPTIMAL USE OF AVAILABLE RESOURCES

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FOREWORD

The IAEA's programme in support of decommissioning seeks to provide Member States with comprehensive guidance on the planning and execution of safe and effective decommissioning of facilities in which radioactive material has been handled. A considerable literature has been produced on the technological aspects of planning and implementation. In recent years this has been supplemented with information on the organization and management of decommissioning. This report extends the latter area by considering the issues faced in the decommissioning of research reactors and other small facilities, which is often undertaken in situations where the available resources are limited.

There are large numbers of research reactors and many more small facilities utilizing radioactive material, some of which are coming to the end of their operating lives and will require decommissioning. These facilities were built in many States, and the extent of local nuclear experience varies widely. Although the radioactive source terms within research reactors and other small facilities are expected to be less in radioactive inventory than in larger facilities, small facilities may still pose significant radiological and other risks, due to ageing and other issues.

This report focuses on the matters that must be addressed to safely and efficiently decommission research reactors and other small facilities. Particular consideration is given to the resources required to achieve this and to managing in situations where these are in short supply. These resources are shown to be varied in nature, going beyond simply numbers of people or amounts of available funding. Experience gained in the wider decommissioning industry is recognized as needing to be applied in a fit for purpose and cost effective manner, avoiding unnecessary complexity. Making the best use of existing staff is discussed, along with their possible limitations. The advantages and disadvantages of external support are explored, and international support, for example from the IAEA, is noted as a means to build local capability in decommissioning issues and in being an informed purchaser of goods and services in the international marketplace. An overall requirement to have sufficient resources to safely undertake any work, before it is commenced, is also stressed.

The IAEA officers responsible for this report were M. Laraia and P.J. McIntyre of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

CONTENTS

SUMMARY

Worldwide there are large numbers of research reactors and many more small facilities utilizing radioactive material, some of which are coming to the end of their operating lives and will require decommissioning. These facilities were built in many States, and the extent of local nuclear experience varies widely. Although the radioactive source terms within research reactors and other small facilities are expected to be less in radioactive inventory than in larger facilities, they may still pose significant radiological and other risks, due to ageing and other issues.

This report focuses on the matters that must be addressed to safely and efficiently decommission research reactors and other small facilities. Its specific objectives are to:

(a) Provide practical and specific guidance to assist Member States in the planning and implementation of the decommissioning of smaller facilities in which radioactive material has been used;
(b) Guide the development of a decommissioning strategy that makes optimal use of available resources;
(c) Encourage a timely, well planned approach to decommissioning, preventing avoidable delays and hence alleviating the buildup of problems that would require increased expenditure and specialist knowledge as the condition of the facility deteriorates;
(d) Evaluate experience already gained from decommissioning in industrialized Member States and refocus it towards a pragmatic, fit for purpose approach meeting the needs of States and institutions with limited local resources for small decommissioning projects.

The decommissioning of research reactors and other small facilities is readily achievable. It requires adequate planning, the use of commonly available technologies and methods and the effective management of project delivery. It may be made more difficult due to limitations in the availability of necessary resources, which are varied in nature and go beyond simply numbers of people or amounts of funding.

There are advantages in retraining existing staff so that their new skills, coupled with their knowledge of the facility and its history, can be applied to decommissioning. However, the project delivery context of decommissioning requires different skills and behaviours to those commonly found in operation. Thus it is essential that a project structure be established, led by a competent project manager, to guide all staff in the new task to hand.

A project on a hazardous site requires work to be performed in a safe manner within established procedures and other controls, which should be proportionate to the hazards, number of people and size of the project. The size and complexity of the project should be minimized. Safety management, quality assurance (QA) and other control systems and processes should be designed to be adequate for the task, not simply brought across from a large scale decommissioning project such as for a nuclear power plant. This will naturally lead to a more optimized use of limited staff and other resources. Whatever the resource position, there remains an overall requirement to have sufficient resources in place to safely undertake any work, before it is commenced.

1. INTRODUCTION

Much of the work of the IAEA in the decommissioning field has concentrated on aspects of the decommissioning of larger nuclear facilities such as nuclear power plants and fuel cycle facilities. However, there are also large numbers of research reactors and many more small facilities utilizing radioactive material, some of which are coming to the end of their operating lives and will require decommissioning. These facilities were built in many States, and the extent of local nuclear experience varies widely.

The construction and operation of relevant small facilities commenced in the 1940s. There are now over 250 research reactors still operating out of a total of over 800 built (see Ref. [1] and its update in Annex III of this report on the attached CD-ROM) and many other smaller radioactive material handling facilities worldwide [2, 3].

Although the radioactive source terms within research reactors and other small facilities are expected to be less in radioactive inventory than in larger facilities, they may still pose significant radiological and other risks, due to ageing and other issues. There may be a perception in some States and institutions that such facilities are of low priority and may be safely left in a relatively unsupervised state. However, this can result in their structural deterioration and an increased risk of release of radioactivity to the environment.

The management approach to the decommissioning of nuclear power plants and other large facilities is broadly applicable to smaller projects. However, care must be taken not to extrapolate from large to small facilities without due consideration of the relevance of the approach. Nevertheless, the following topics are generally of common importance:

(a) Decommissioning planning and prioritization;
(b) Security and fire protection;
(c) Historical site assessment;
(d) Contamination control, including during operations;
(e) Pre-shutdown and transition activities;
(f) Sampling, monitoring and characterization;
(g) Decontamination and demolition techniques;
(h) Engineering and use of technology;
(i) Waste conditioning and packaging;
(j) The use of contractors for decommissioning operations;
(k) Regulatory and stakeholder interactions.

The decommissioning of small facilities should not be underestimated. Under certain conditions, a small project may face a range of issues as challenging to the licensee or operator as the decommissioning of power reactors is to other licensees. Additionally, since the design intent was often to conduct research or to use radioactive material for medical or industrial applications, decommissioning was rarely a consideration in design or during operation.

While the IAEA has addressed the issue of research reactor and small facility decommissioning in the general sense [3–5], no publication has specifically covered the special problems likely to arise when such facilities need to be decommissioned by institutions or in States with limited local resources. Funding may be uncertain and the local nuclear infrastructure may be only partly developed or even absent. In such cases, specific approaches need to be developed and optimized for the local circumstances.

1.1. OBJECTIVES

The objectives of this report are to:

(a) Provide practical and specific guidance to assist Member States in the planning and implementation of the decommissioning of smaller facilities in which radioactive material has been used;
(b) Guide the development of a decommissioning strategy that makes optimal use of available resources;
(c) Encourage a timely, well planned approach to decommissioning, preventing avoidable delays and hence alleviating the buildup of problems that would require increased expenditure and specialist knowledge as the condition of the facility deteriorates;
(d) Evaluate experience already gained from decommissioning in industrialized Member States and refocus it towards a pragmatic, fit for purpose approach meeting the needs of States and institutions with limited local resources for small decommissioning projects.

The readership of this report is mainly intended to be licensees, operators and others directly involved in the implementation of decommissioning projects (contractors, technical support organizations, waste managers), as well as facility owners and those making decisions on funding (often governments or related institutions). In particular, this report should be of use to Member States with little experience in decommissioning or to universities, institutions and other smaller users of radioactive material in any Member State.

1.2. SCOPE AND STRUCTURE

This report focuses on the matters that must be addressed to decommission research reactors and other small facilities safely and efficiently. Particular consideration is given to the resources required to achieve this and on how to manage in situations in which these resources are in short supply.

Section 2 details the principal issues that arise when decommissioning small facilities in which resources may also be limited. The need for an early and structured approach to planning is described in Section 3, together with the resource related factors that will influence the selection of an appropriate decommissioning strategy. Establishing an appropriate approach to managing the decommissioning project is covered in Section 4. This includes coverage of the safety and organizational aspects that are relevant to cost control. Actions to be taken to facilitate matters at each stage of decommissioning are presented in Section 5. Closing remarks and conclusions are brought together in Section 6. International experience, including lessons learned, is presented in Annexes I–III on the attached CD-ROM.

2. DECOMMISSIONING OF SMALL FACILITIES WITH LIMITED RESOURCES

In recent years the extent of the so called nuclear legacy has become more fully apparent [6]. There is a very large number of facilities around the world that will require decommissioning. Decommissioning of redundant facilities can be a demanding undertaking, even for a State or organization with extensive human and other resources together with adequate funding. In many cases the facilities are small and may be one of a kind in the organization or State, and there may be limitations on the resources and experience available to their operators for decommissioning.

Additionally, there are a number of special aspects that apply to smaller facilities:

(a) A multiplicity of research reactor types, from small critical assemblies (zero energy) through to larger, multimegawatt material testing reactors.
(b) Proximity of many facilities to centres of population — partly as a result of urban sprawl since the facilities were built decades earlier.

(c) A broad spectrum of operational activities, from nuclear physics research through to isotope production, medical treatment and agricultural and/or industrial applications.
(d) The presence of shielded hot cells for the handling of a great variety of irradiated material.

The decommissioning approach will differ from place to place, but it is possible to make some general statements that apply to many facilities. This is initially developed in Section 2.1 by considering the particular issues faced by small facilities in general. The resources that are required for safe and effective decommissioning are identified in Section 2.2, and their optimized utilization is discussed in later sections of this report.

2.1. IMPLICATIONS OF FACILITY SIZE ON DECOMMISSIONING

In principle, the challenges faced in the decommissioning of any nuclear facility have much in common. The main aspect that discriminates between nuclear facilities and other facilities using radioactive material is the presence of alpha, beta and gamma emitting radionuclides in the form of contamination or activation of structures, equipment and work areas. Other hazards will also be present. These ‘conventional’ hazards, together with other design features, may make the decommissioning of any industrial premises difficult and costly. The techniques developed to deal with such issues in conventional industrial plants are equally applicable to nuclear facilities and facilities handling radioactive material. Henceforward, the term ‘facilities’ applies both to those facilities handling nuclear material and those handling other radioactive material, unless otherwise specified.

There are some specific aspects of small facilities that may require a change in emphasis from the decommissioning of large fuel cycle facilities and nuclear power plants. These include the following features, which are not necessarily independent:

(a) Scale:
   (i) Economies of scale will be limited, which may raise costs relative to large facilities;
   (ii) There will be less flexibility in a small decommissioning project, and hence if a delay is experienced in one area, it is more likely to delay the whole project;
   (iii) Space limitations may restrict work, due to a shortage of laydown areas, changing areas, etc.

(b) Radiological hazard:
   (i) Relatively small source terms should lead to relatively small hazards, risks and waste streams;
   (ii) There may be a wider range of nuclides than in large facilities, depending on the work previously undertaken at the facility.
(c) Resource limitations:
   (i) Regulations may be inadequate, due to a previous lack of need;
   (ii) The small size of the project may make specific technology development or procurement unattractive;
   (iii) Records of the facility may not have been transferred to the operator by the designer;
   (iv) The investment needed for infrastructure may seem prohibitive to meet the needs of a small facility (e.g. provision of a waste disposal site).
(d) Comparable facilities:
   (i) There may be many such facilities in operation throughout the world to act as models for decommissioning;
   (ii) Extrapolations from one facility to another may be difficult, due to local differences in operations.
(e) Cost estimation:
   (i) The one-off nature of some facilities means that cost estimation will need to be done on a site specific basis;
   (ii) As there are relatively few tasks in decommissioning a small facility, costing errors in one area will have a relatively high impact on the total cost, potentially leading to relatively high cost uncertainties.
(f) Management:
   (i) With a small staff complement, management of the project should be more focused;
   (ii) There will be limitations due to an incomplete set of skills among the staff;
   (iii) The job size may mean low interest from contractors;
   (iv) The administrative burden from QA arrangements, etc., may become out of proportion to the size of the project.

The capability to deliver a project in the context of these features will be related to the availability of resources.

2.2. IMPACT OF RESOURCE LIMITATIONS

Any decommissioning project or task requires that adequate resources be available as dictated by the requirements of the various activities. The timing of resource availability can be crucial to project success, allowing the optimization of interdependencies and logistics within the project schedule. The specific resources to be called on will depend on the facility in question as well as on the final goal of the decommissioning project. It is important that this goal is clear and that the activities are directed by an effective project management approach.

The resources required for decommissioning can be varied in nature. Although the term ‘resources’ is often used to mean human resources or funds, these alone are insufficient to achieve project success. It is true that a shortfall in other resources may be resolved by the application of the effort and purchasing power that plentiful human and financial resources can provide, but in many research reactors and other small facilities these will also be in short supply. An awareness of the total resource requirement will enable strategy, plans and implementation to be optimized.

The following list presents examples of the resources required for decommissioning, which are interdependent in some cases:

(a) Legal and regulatory: Decommissioning regulations, clearance criteria, discharge authorizations, delicensing criteria and transport regulations.
(b) Infrastructure: Waste or spent fuel storage and disposal facilities, transport containers and active drainage.
(c) Financial: Funds, cash (income, loans), cost estimates, system for control of funds used, and auditing of programmes and plans.
(d) Organization: Leadership, structure and a project delivery culture.
(e) Systems: Project management systems and data and records management.
(f) People: Staff members, contractors, knowledge, skills, experience, motivation and incentive programmes.
(g) Safety competences: Safety assessment, ALARA (as low as reasonably achievable) studies, HAZOPS (hazard and operability studies) and other hazards analysis, radiological protection, industrial safety and risk assessment.
(h) Technology: Instrumentation, ventilation systems, dismantling techniques, decontamination and radioactive waste processing.
(i) Stakeholder acceptance from: Regulators, communities, staff and owners.
(j) Learning: Processes for retraining, contractor familiarization and overall learning from experience.

For those States that do not enjoy the benefit of a nuclear power generation programme, little reliance can be placed on an existing nuclear infrastructure to support the decommissioning of small facilities that may be already shutdown or are nearing the end of their operating lives. Similar difficulties may apply with regard to small facilities even within States having nuclear power plants if they are significantly different in character.

The symptoms of resource limitations may include the following:

(i) An insufficient legislative framework;
(ii) Inadequate plans and preparations in terms of timeliness, detail and quality;
(iii) An operations or research culture rather than a project delivery culture;
(iv) Absence of a project management capability;
(v) Lack of the essential competences and skills needed;
(vi) Unavailability of necessary equipment and methodologies;
(vii) Inadequate knowledge of operating history in so far as design records, events or institutional memory are concerned;
(viii) No mechanisms to learn from experience of others or to exchange information;
(ix) Unavailability of interim and final storage capacity for the waste generated;
(x) Lack of reliable and sufficient financing.

3. DECOMMISSIONING STRATEGY SELECTION

IAEA recommendations are that all redundant nuclear facilities should be decommissioned in a safe and efficient manner [7]. A systematic approach to the development of strategies for decommissioning is essential. Investment in planning activities, initiated well before shutdown, will reduce decommissioning costs and shorten the decommissioning schedule.

Ideally, preliminary plans should be prepared for the decommissioning of a nuclear facility at the design stage [8–10], but for older, first generation facilities this was rarely the case. It is now a widely accepted regulatory requirement [7] that preliminary decommissioning plans should be prepared at the design and construction stage. These plans should be regularly revised and developed during the operating life of the facility to reflect the current status of the plant, and a final decommissioning plan should be prepared before permanent shutdown.

Where there are probable difficulties due to the unavailability of resources, planning can identify these shortfalls so that a practical way forward can still be developed. This could include deferral awaiting eventual access to additional resources to complete the decommissioning project. A good plan is required for estimating the project cost and to enable an understanding of the drivers of the cost. In an environment of limited financial resources, a good understanding of what drives cost is essential to efforts to reduce these and to enable more to be achieved with the available funding.

The evaluation of options for a decommissioning strategy should be performed by considering a wide range of issues. The fundamental options are discussed in Section 3.1. The major factors affecting the decision between these are covered in Section 3.2. Section 3.3 lists some common types of facility and the characteristics that would allow a graded approach to decommissioning. Techniques to assist in selecting between options are presented in Section 3.4.

3.1. STRATEGIC OPTIONS FOR DECOMMISSIONING

The three fundamental strategic options for decommissioning facilities are immediate dismantling, deferred dismantling and entombment. Each of these is detailed in the IAEA guidelines on decommissioning strategy given in Ref. [8] and discussed below in the context of the influence of resources availability. It is also possible to conceive of strategies that are intermediate between these fundamental options (e.g. periodic dismantling over a long period). Such approaches may be well suited to particular situations, for example on a multi-facility site or in a State with unpredictable availability of resources. The specific local characteristics should be used to determine the optimum approach.

3.1.1. Immediate dismantling

The immediate dismantling strategy covers the situation where a facility is fully decommissioned soon after the end of operations. It is generally preferred when no worthwhile benefit will be achieved from radioactive decay. It imposes the largest requirement for immediately available funds and other resources, particularly if it includes unrestricted site release.

This option may be particularly suitable for small facilities with a nuclide inventory that does not require highly sophisticated technology to meet the safety requirements in a well regulated environment. It will also be attractive for one of a kind projects that are heavily reliant on the knowledge and ongoing availability of operators [11]. A constraint is that the waste management plan must be able to deal with the early generation of substantial quantities of decommissioning waste. For research reactors and other small facilities, a concerted and relatively short project can achieve the final site end state.

3.1.2. Deferred dismantling

This option requires sufficient early dismantling to allow conversion of the facility to a safe enclosure (for research reactors) or adequate measures to bring other small facilities into similar stable conditions. In both cases final dismantling is deferred to a later date with an intervening period of low cost surveillance and maintenance to guarantee safety. For research reactors this usually consists of the prompt dismantling of accessible peripheral parts of the plant while leaving the activated reactor core as a safe enclosure. The deferral period is usually set either to allow the decay of short lived isotopes or the availability of waste disposal facilities. However, extended periods of care and maintenance during the deferral may be costly.

Inadequate resources may lead to deferred dismantling by default. Nevertheless, the transition from operation and the preparations for safe conditions demand immediately available funds and other resources. Surveillance and maintenance require continuous if lower funding during the deferral period. The total cost of deferred dismantling is usually comparable with or higher than immediate dismantling, but the cash flow requirements may be easier to provide, because the majority of the costs are deferred to a future date. Accounting practices may affect this if future cash requirements are discounted. Although in time financial resources may have grown, other resources, such as plant knowledge and condition, may have degraded. A complete picture of the implications of deferral needs to be developed on a facility specific basis.

3.1.3. Entombment

The in situ disposal of a facility is known as entombment. Due to the need for immediate financial resources, inadequate funding may preclude or impact on entombment as an option, even if regulatory authorities accept this strategy.

This option is attractive for smaller, one-off projects on grounds of expediency and cost reduction, but has not been broadly utilized by Member States as a decommissioning strategy [12, 13]. Entombment was a viable decommissioning strategy in the early years of the nuclear era, being practised in a few States [14–16]. However, environmental concerns in particular have limited the practice in recent years.

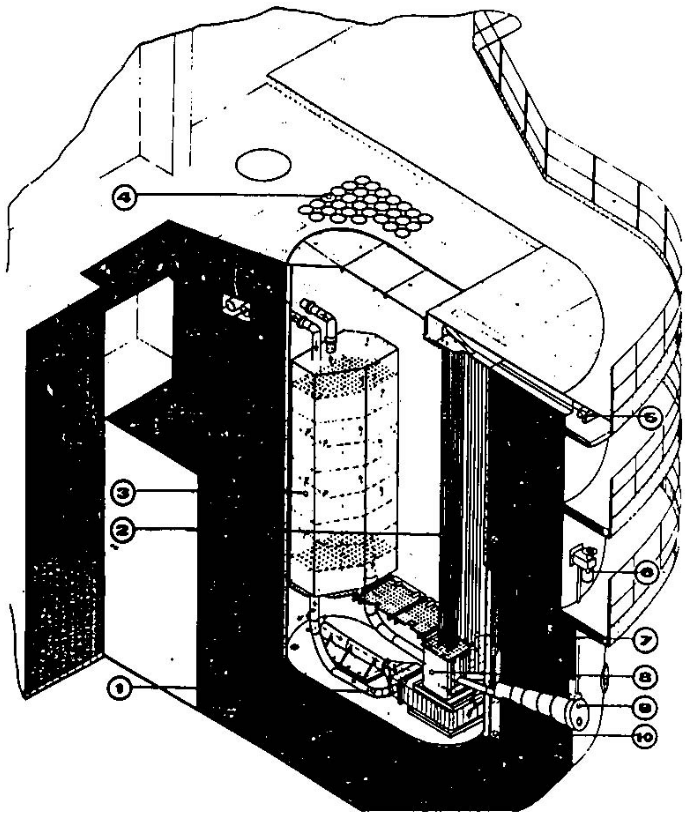

FIG. 1. View of the nuclear reactor tank, IRT, Georgia. 1: pressure pipeline of the primary circuit with ejection pump. 2: vertical channels of emergency protection and control rods. 3: hold-up tank. 4: dry channels for storing radioactive samples and waste. 5: engines of control, automatic and emergency protection rods. 6: slide valve of horizontal experimental channel. 7: vertical experimental channel. 8: reactor core. 9: horizontal experimental channel. 10: heat screen of biological shielding.

Entombment is perhaps best suited where the facility is situated far from populated localities, in an area where the geological and hydrological characteristics are potentially suitable for construction of a near surface repository. Such situations occur, for example, in the far north of the Russian Federation, near Norilsk [17]. Another example of entombment is the IRT reactor in Georgia (Figs 1 and 2), although this strategy is not seen as a permanent solution by the Georgian operator. Additionally, a pragmatic approach to entombment of residual hot spots following decontamination of a small facility in Cuba is described in Annex I.C on the CD-ROM. In this case, expenditure of additional resources on further decontamination and the production of

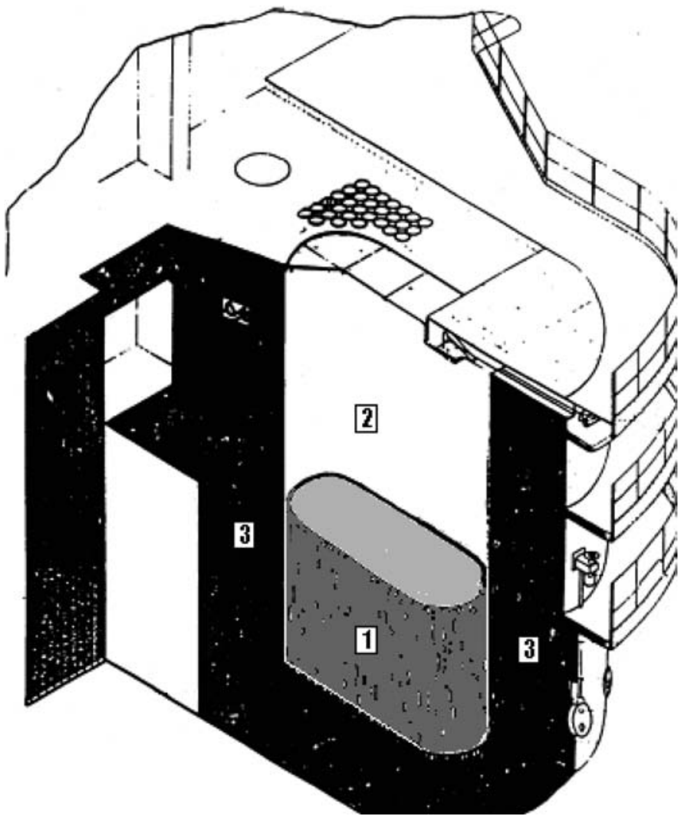

FIG. 2. The tank of the nuclear reactor after concreting. 1: grouted lower part (about 20 m³) of the reactor tank. 2: free part (about 35 m³) of the reactor tank. 3: reactor biological shielding.

additional waste were judged unwarranted given the minimal additional risk calculated. This approach was endorsed by the local regulator.

In general, entombment may be a viable decommissioning strategy for States needing to decommission a single facility and not having the resources to develop or obtain the infrastructure required for dismantling and waste disposal.

3.2. FACTORS AFFECTING THE CHOICE OF DECOMMISSIONING STRATEGY

The decommissioning strategy adopted will vary according to a number of considerations — the national policy of the Member State, the availability of waste disposal routes, the radiation protection policy, cost and funding considerations, site specific factors, etc.

The key influences on the choice of decommissioning strategy with respect to the various resources required to achieve decommissioning are discussed in this section. Table 1 summarizes the relationship between strategy options and resource availability. Within the table a distinction is drawn in places between short term resource requirements — occurring soon after facility shutdown — and long term requirements relating to effects many years later.

3.2.1. Financial requirements

The decommissioning strategy will have to be decided upon recognizing uncertainties in the availability or timeliness of funding. Inadequate decommissioning funding may be due to the lack of a legal framework requiring establishment of such funds, an early shutdown so that insufficient funds have been raised, a devaluation of funds or even their diversion to other purposes.

Private sector facilities typically pay a share of the decommissioning costs from the product produced by the facility. The decommissioning of state owned facilities is often paid for from public budgets, although where services are rendered to other organizations the fees for the services or products can be directed into a dedicated fund [18].

In cases where earmarked funds are not sufficient, government owned facilities might receive additional funding from the State budget, but this may not be available for a private sector facility. However, the legislative framework in the context of a deregulated market (electricity generation, isotope production, etc.) may impose restrictions on government aid, resulting in constraints even in the case of government owned facilities [19].

For government owned facilities, or indeed others, funding of decommissioning activities may come from finite annually fixed budgets. Thus, in addition to the absolute size of the funding, the rate at which it is made available may also be a constraint on the rate of work that can be achieved, limiting the choice of strategy and tending to a postponement of work. Overall, the availability and adequacy of financial resources may be a significant constraint on decisions on decommissioning strategy.

3.2.2. Human resources

Where work may be planned to use existing staff and internal resources, this may well favour the selection of a strategy with substantial early dismantling while the resources are still available. Other human resources

TABLE 1. RELATIONSHIP BETWEEN DECOMMISSIONING STRATEGIES AND RESOURCE AVAILABILITY

Resources affecting strategy	Fundamental decommissioning strategies		
	Immediate dismantling	Deferred dismantling	Entombment
Financial requirements	Short term: High Long term: Possibly still substantial if waste has only been stored	Short term: Medium for preparations Medium term: Very low Long term: High	Short term: High Long term: None
Human resources	High: Can also utilize remaining operational knowledge	Need to rebuild team after deferral	As immediate dismantling
Source term and dose rates	High	Final dismantling lower, dependent on dominant nuclides	High, but avoid access to highest dose areas
Technology required to achieve safe conditions	Sophisticated technology may be required to perform the dismantling work under safe conditions	Short term: Some technology required, for example operational waste recovery Long term: Similar tasks to immediate dismantling, but lower doses may allow simpler techniques	As deferred dismantling, short term
Waste storage and/or disposal	Short term: Waste needs to be disposed of or stored Long term: Waste disposal if previously stored	Short term: Remove simple assessable sources Long term: Waste needs to be disposed of	Short term: Remove simple assessable and long living sources

TABLE 1. RELATIONSHIP BETWEEN DECOMMISSIONING STRATEGIES AND RESOURCE AVAILABILITY (cont.)

Resources affecting strategy	Fundamental decommissioning strategies		
	Immediate dismantling	Deferred dismantling	Entombment
Spent fuel (reactors)	In all cases, needs to be removed at an early stage		
Further use of site	The site can be used for other purposes after completing the decommissioning work If it is released under special provisions, further use may be restricted depending on the licence	Short term: Use of the facility is restricted by the licence Long term: As immediate dismantling	Use of site likely to be restricted to protect entombed facility

related factors that could affect the choice of decommissioning option include the availability and affordability of specialist contractors.

The planned closure of a facility may have an impact on the local community that surrounds and serves it, and may have wider reaching effects further afield for the supply of goods and services. The societal effects of plant closure therefore need to be carefully managed. While the effects are particularly acute for nuclear power plants, which have often been sited in areas of relatively low population, there may also be an impact from the decommissioning of smaller facilities [20].

During the build and operation phases of the plant, movements of personnel and material contribute to development of the local economy and infrastructure. Consequently, the local population will have some dependency on the plant for employment and as the customer for locally produced goods and services. The people and businesses concerned will have to adjust to a new reality and ideally would be given support in so doing. However, the decommissioning project may provide an injection of cash and expertise that, although of limited duration, may have some longer lasting benefits. In an area of limited resources, decommissioning plans may consider the maximum use of local labour to minimize social impact and also possibly a cash outlay, perhaps at the expense of a slower schedule than a contractor in a more industrialized State would achieve.

As described in Ref. [20], in the case of small facilities socioeconomic effects are likely to be limited to the staff and the status of the affected institution. Nevertheless, responding to these issues may have a significant influence on the decommissioning strategy.

3.2.3. Safety

In selecting the optimum decommissioning approach, the principal consideration during the selection of a decommissioning strategy must be adherence to the ALARA principle, since, irrespective of the level of resources available, safety must not be compromised.

For immediate dismantling, any perceived advantages must be weighed against the higher radiation doses to dismantling workers, since little time may have elapsed for radioactive decay. Immediate dismantling scenarios rely more heavily on increased levels of remote technology, due to the much higher radiation fields present. For deferred dismantling, consideration must be given to the long term structural decay of the facility, the continuing cost of surveillance and the possible increase in costs of waste disposal as regulations become more onerous despite the reduction in hazard resulting from radioactive decay. There is also merit in considering early decommissioning options while the operator organization is still in existence. In such circumstances, entombment might be a viable decommissioning option. Guidance is required to develop the criteria for entombment in terms of its acceptability and conditions for its use [12].

3.2.4. Spent fuel and waste management infrastructure limitations

The problems of a lack of spent fuel and waste management infrastructure are found in developed as well as less developed States. The greater the availability of infrastructure, the greater the flexibility, choice of options and reduction in project risk. For decommissioning option selection, deferral would often be preferred in circumstances where the volumes of waste produced by immediate dismantling would be unable to be accommodated by existing on-site or off-site facilities. The practical difficulty that ensues from these issues is one of the principal determinants of the selection of an immediate or deferred dismantling approach.

A compromise can be achieved at a cost, by the construction of on-site temporary storage for both radioactive waste and spent fuel. Early removal of short cooled research reactor fuel means that the delay normally experienced during the cooling period is removed, hence reducing costs. Despite the potentially significant costs (e.g. from the purchase of casks for spent fuel storage), these problems must be addressed, otherwise there will be a pause in the project and any plant left to deteriorate may develop into a potentially more expensive problem as time goes by. The on-site storage option, in effect, ‘buys time’ until an ultimate solution for the disposal of spent fuel and waste is determined. Some novel solutions to the problems have been found; for example, in Poland, where there are several small research reactors but no nuclear power programme, the reactor shaft for the EWA reactor at Swierk was planned to be converted into a dry storage vessel for spent fuel originally wet stored on the reactor site [21].

3.2.5. Reuse issues

Some facilities will be decommissioned with the aim of either replacing them with new facilities or reusing the site for other purposes [22]. This allows decommissioning costs to be offset by the release of assets that can be used constructively for other purposes and promotes the redevelopment of facilities and their sites. The planned use of the site after decommissioning is a potential strong determinant of the decommissioning strategy. Existing services, or simply the ‘tradition’ of the use of the site for nuclear purposes, may make reuse for another nuclear application attractive. This will drive the strategy towards a site condition that is consistent with the prospective new use of the site.

3.3. INFLUENCE OF FACILITY TYPE ON DECOMMISSIONING STRATEGY

The nature of a facility will have a significant effect on the selection of an appropriate decommissioning strategy. Table 2 lists the common types of facility and the implications of their characteristics on the decommissioning strategy.

The decommissioning of facilities in which nuclear fuel has been handled or used is generally more complex than for other facilities. Nevertheless, these facilities often have areas that approximate to the simpler facilities listed under item 1 in Table 2. In order to ensure the effective use of limited resources, it is recommended that a complex facility be divided up into areas based on the activities undertaken and then strategies used that are most applicable for those hazards.

3.4. OPTIONEERING[1] METHODS

An evaluation of the various decommissioning strategy options should be performed by considering the applicability and influence of a wide range of potential issues, with special emphasis on meeting safety requirements and the resources available at the time of implementing the decommissioning.

Option study methods such as cost–benefit or multiattribute type analyses provide a systematic and auditable means to aid the decision making process — although they can be demanding to apply. A simple approach using a ranking of the influence of key factors will probably be the most appropriate for almost all small facilities.

The use of some techniques will require some form of quantification of the impact of factors. Even in the case of factors such as cost or dose, there may be a limited knowledge of likely actual values. In these cases a judgement can be made, together with an estimate of the related uncertainty or more simply a ranking such as high, medium and low. Other factors that may be important to strategy decisions may not be apparently quantifiable at all. The

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[1] Optioneering: Identification and testing of options for the conduct of a project or activity in order to auditably determine the optimum way forward.

TABLE 2. RELATIONSHIP BETWEEN FACILITY TYPE AND DECOMMISSIONING STRATEGY

Type of facility	Remarks
1. Applications without any use of nuclear fuel	
Used sealed sources only	After removing the sources, radiological contamination is not expected A simple contamination check may be sufficient to release the area
Handled only short lived (<60 days) nuclides, for example nuclear medicine laboratories	Deferred dismantling may drastically reduce the effort because of the short half-lives of the nuclides used
Handled limited range of beta emitting nuclides without significant gamma dose rate (e.g. biological research laboratories)	Limited range of nuclides reduces measurement requirements — basic tests to confirm working and environmental safety are usually sufficient Defer if half-lives are short
Handled a wide range of well documented nuclides (e.g. radiochemical laboratories)	Knowledge of the nuclides used reduces the measurement task A graded approach can be used to confirm working and environmental safety, depending on the nuclide inventory and half-lives and their deployment
Accelerator facilities	Mostly short lived nuclides Dependent on nuclide vector, a graded approach can be taken Defer for decay if short lived nuclides dominate
Small facilities with unknown history or lack of records	Unknown nuclide inventory and vectors require more effort in detection and measurement Once characterized redefine as one of the above categories
2. Applications involving nuclear fuel	
Nuclear fuel cycle facilities	Activation is usually not a big problem Storage of some products, for example plutonium, may increase hazard with time, therefore discouraging deferment

TABLE 2. RELATIONSHIP BETWEEN FACILITY TYPE AND DECOMMISSIONING STRATEGY (cont.)

Type of facility	Remarks
Research reactors	Activation and contamination present Full analysis needs to be performed to determine strategy
Nuclear power plants	Dependent on situation

contribution of such factors in the decision process can be determined by an expert group based on a cross-section of opinion from interested parties, in a ranking as above, if required. Similarly, a quantified weighting of the various factors (i.e. their relative importance) can also be decided in this way.

The important output from the optimization process is not only the selected decommissioning option but also the ‘route’ as to how the decision was arrived at and the sensitivity of the results to assumptions made in the process. In contrast to decisions made on a personal judgement alone, a more formal optimization process has the advantage that the underlying assumptions can be stated explicitly, enabling understanding, debate and change, if appropriate. There is merit in involving stakeholders, including regulators, in some way in the option study process. Unspoken biases can thus be removed. Furthermore, once agreement has been reached on the important factors such methods can be used to pinpoint what information is needed in support of the decision process, thus minimizing data gathering costs.

Although option studies should seek to use simple methods to identify robust solutions, those with limited experience may need to draw on specialist skills and equipment from international organizations or the market place. The process will be iterative and will not necessarily produce a clear preferred option straightaway. In some cases, overwhelming national conditions will dictate the decommissioning strategy, leaving limited scope for more refined analysis [19].

4. MANAGEMENT OF DECOMMISSIONING PROJECTS

This section describes the management issues that will need to be addressed during the implementation of the decommissioning strategy. Project management assumes critical importance during the planning and implementation phases of all decommissioning projects. In particular, it becomes central to meeting time and cost constraints. Emphasis should therefore be put on the application of systems of management that are appropriate to the available resources. In the case of smaller facilities, the full spectrum of management systems may be neither available nor appropriate, and a pragmatic approach should be adopted [23]; for example, a small facility may have limited technical resources in terms of qualified and experienced persons. To make best use of this key resource it may be optimal to consider combined and/or part time roles for a range of posts — flexibility and multitasking providing the best utilization of the human resources available.

If there is no background in project delivery at a small facility it may be helpful to employ a project management professional — a person with a track record in managing projects to time and cost but not necessarily with direct nuclear decommissioning experience. This person could act as project manager in control of the project or in direct support of the established management of the facility, working with the staff with technical knowledge of the facility, its history and hazards.

The remainder of this section considers the major management issues to be faced in planning and implementing a decommissioning project, with the emphasis on smaller facilities.

4.1. RESPONSIBILITIES

The overall responsibility for safety rests with the site licensee and cannot be delegated to third parties such as contractors. The licensee will need to demonstrate control and that there is an adequate organization in place to continue to discharge the responsibilities under the site licence throughout decommissioning.

Safety management and QA systems are required for the decommissioning project. These should ensure that the safety function is independent from the decommissioning implementers. Arrangements in place during operation may be readily adapted to the decommissioning phase. These should include provisions for the management of radiological protection, release monitoring, off-site discharges and general environmental monitoring as well as the management of other hazards such as asbestos. Physical protection and safeguards functions should also be maintained.

4.1.1. Responsibility at the site or facility level

It will be the responsibility of the site management to ensure compliance with the licensing requirements of the national regulatory body. This may be in the form of a decommissioning licence or other form of regulatory control. In the absence of a full set of formal decommissioning regulations — as could be the case in States and institutions with a single relevant facility — control may need to proceed on a step by step basis. Although the relevant site manager retains overall responsibility for administering the site licence, he or she may delegate day to day control to a subordinate member of staff.

4.1.2. Responsibility at the decommissioning project level

Decommissioning is a multidisciplinary task that requires the appointment of a decommissioning project manager (DPM). The DPM will hold the executive and managerial responsibility for implementation of the decommissioning project after the handover from operations. Ideally, the DPM will have been involved in the production of earlier plans for decommissioning, which should now be promptly finalized based on the inventory of radioactive and other hazards at final shutdown. Ideally, the person selected should have an engineering background with either previous decommissioning and/or refurbishment project experience, but suitable experience could be from outside the nuclear industry.

The DPM will be responsible for the day to day management of decommissioning in accordance with the agreed strategy. The DPM will also be responsible for the implementation of the decommissioning tasks, plant maintenance, cost control and performance against project milestones. The allocation and control of health physics and other safety resources between the independent safety function and the DPM should be clearly defined in the QA arrangements. The DPM may delegate responsibilities for licensing issues.

The DPM has to be supported by others within an organizational structure, a possible example of which is given in Fig. 3. Other management structures are also possible and flexibility must be assumed to support local circumstances.

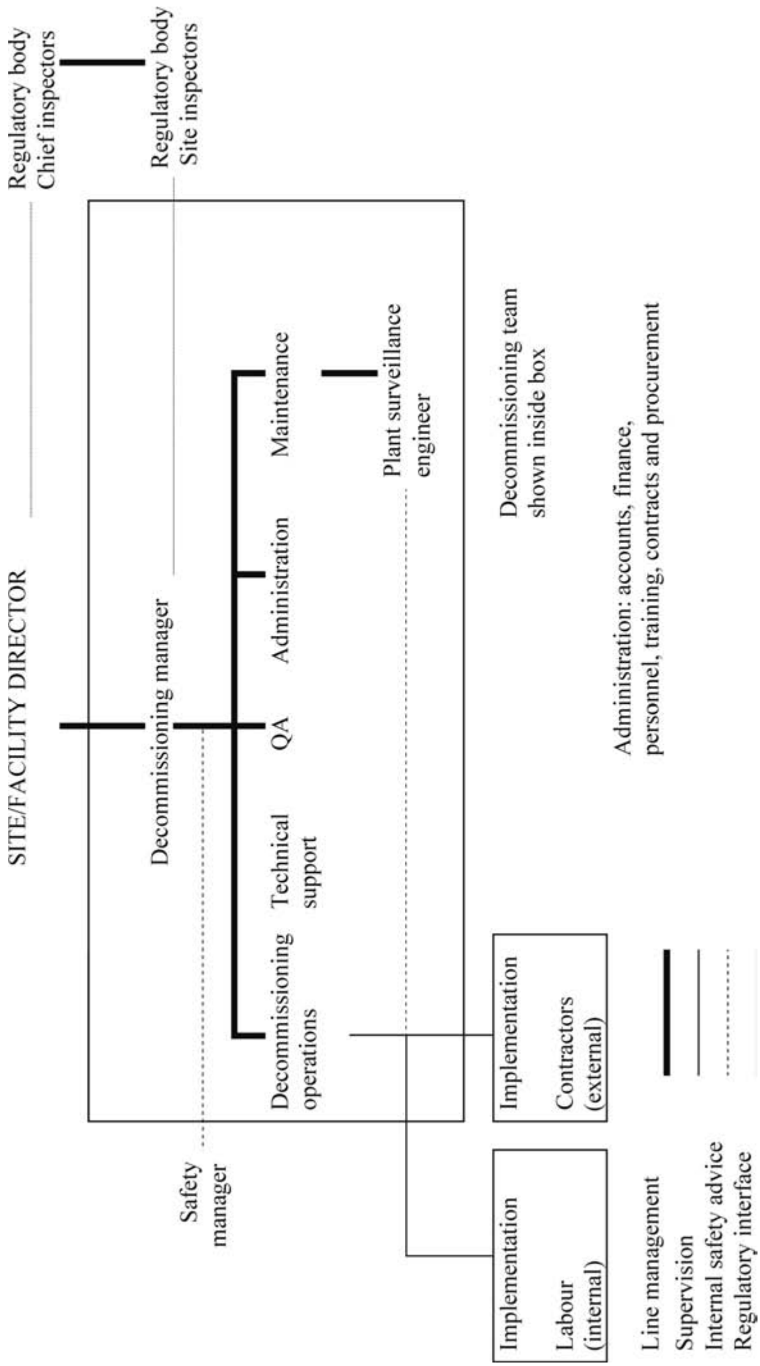

FIG. 3. National management organization.

4.2. PLANNING OF DECOMMISSIONING

The decommissioning plan is a key document used in defining and controlling the decommissioning project. It should be produced in a timely manner and in accordance with the requirements of the safety management and QA arrangements. In addition, a range of additional project management tools should be employed to further define requirements and to control and monitor the progress of the project — many of these will have been produced in a less detailed form to support earlier cost estimation and planning activities:

(a) A work breakdown structure (WBS) — normally in a hierarchical format that identifies tasks down to the lowest level thought appropriate and integrates them according to specific categories, for example dismantling activities, plant maintenance activities and procurement.
(b) A project schedule — normally in Gantt chart format — detailing tasks and durations and their interactions. This is an important tool for the monitoring and reporting of project progress and identifies the series of activities the achievement of which defines the minimum time to complete the project (the 'critical path').
(c) Cost estimates for the tasks to be performed.
(d) A resource plan to implement the tasks in the project schedule, detailing numbers of personnel and the skills required at each stage of the project, and to avoid peaks and troughs of demands for skills by allowing the adjustment of plans to smooth out these requirements.
(e) Method statements and work instructions defining in detail the nature, limits and controls for the tasks to be carried out.
(f) A risk management plan.

The effort in producing these items can be tailored to match the size of the project. However, it is essential that a decommissioning project has a disciplined approach to project management — to plan activities, monitor performance, control costs and feed back lessons learned. It is also important to recognize that decommissioning requires a different mindset from operations — the transition to a project management approach from research and development (R&D) or process type operations can be challenging for the existing management and workforce.

While much emphasis tends to be placed on the technical aspects of decommissioning, management aspects have generally received less attention. It is in the area of effective application of management techniques that decommissioning projects often fail to meet their objectives and suffer cost and schedule overruns, hence the importance of project control by the DPM and the management systems at his or her disposal.

4.2.1. Regulatory influences

A successful decommissioning strategy and implementation project require clarity in the regulatory requirements that have to be met. It may be that national regulations or regulators have not set criteria for decommissioning, or that all areas of decommissioning have not been adequately addressed. Planning has to take into account the resulting uncertainties. In this case, a good mutual understanding between the project organization and the regulator may lead to agreements that reduce the uncertainty and make the selected strategy more achievable. The lack of a clear position on material and site-wide clearance levels is a particular threat to the project schedule and budget.

For efficient decommissioning, the relevant needs of the regulatory system include:

(a) Safety assessment criteria for the decommissioning activities, including for any continued occupation of the site for safe enclosure, spent fuel or waste storage.
(b) Site release and licence termination criteria: covering site remediation requirements, including characterization of soils and groundwater, and the extent to which this is needed.
(c) Clearance and exemption levels for material arising in decommissioning in terms of overall radioactivity, specific nuclide limits and sampling methodologies.
(d) Criteria for restricted release/reuse of equipment and material (e.g. very low level contamination of concrete and soils for landfill).

In a situation where the necessary criteria are not available, there are likely to be strong arguments for postponing dismantling.

4.3. ENVIRONMENTAL AND HEALTH AND SAFETY CONSIDERATIONS

An optimized approach to the environment and health and safety is required during the removal of the radioactive inventory and other hazards from the facility. Decommissioning entails a controlled and progressive reduction in hazard as the radioactive inventory is reduced. It is essential that workers, the general public and the environment are protected during this work. For a reactor, this initially entails the removal of spent fuel, which usually accounts for over 99% of the radioactivity. In all facilities, a significant reduction in hazard can be achieved by a post-operational cleanup of sources, chemicals and other hazardous material. This is followed by decontamination and the removal of contaminated or activated plant equipment or material in the remaining structures.

4.3.1. Environmental issues

The environmental impact of a decommissioning project needs to be considered during the selection of a decommissioning strategy and its implementation in respect of the production of radioactive waste, its transport and any other factors that may effect the environment, including new facilities or processes to support decommissioning. Careful consideration of the environmental impact (e.g. from reuse or recycling of equipment and material, waste production or the use of consumables such as energy or water) may reap benefits in longer term cost savings if such considerations are incorporated into the planning phase for decommissioning. In general, compared with facilities such as nuclear power plants, the potential environmental impact from the decommissioning of research reactors and other small facilities will be proportionately limited.

4.3.2. Health and safety

Much experience has been gained in recent years in the area of optimizing the 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 and to improve overall health and safety. Conventional hazards will be met in decommissioning that were possibly limited or not present at all in operation. These need to be recognized in the detailed planning of work and, alongside radiological hazards, in determining an overall risk optimized approach. Internationally, the use of physical mock-ups, computer aided design (CAD) and similar systems has been recognized to be a major factor helping to reduce worker exposure (see Section 5.5).

Regulating and managing safety in a manner proportionate to the safety implications can assist in research reactor and other small facility decommissioning projects. Such an effective use of resources lies behind the IAEA's 'graded approach' [7]. In this case, the graded approach is the application of the safety requirements that are commensurate with the characteristics of the practice or source and with the magnitude and likelihood of the exposures. In more detail, the graded approach means a process of ensuring that the level of analysis, documentation and actions used to comply with a requirement are commensurate with: (a) the relative importance to safety, safeguards and security; (b) the magnitude of any hazard involved; (c) the life cycle stage of a facility; (d) the programmatic mission of a facility; (e) the particular characteristics of a facility; (f) the relative importance of radiological and non-radiological hazards; and (g) any other relevant factor [23, 24].

Research reactors and other small facilities are used for a range of purposes and hence require different design features and operational regimes. Design and operating characteristics may vary significantly, influencing the hazards to be managed in decommissioning. In addition, the need for flexibility in their use requires an appropriate approach to achieving the necessary safety requirements in both operation and decommissioning [25]; for example, regulatory inspections have to be flexible, as the plant configuration will be changing as decommissioning progresses. One US decommissioning project using a graded management approach is described in Ref. [26]. For activity concentrations exceeding standard clearance levels, a graded approach is suggested by the IAEA in Ref. [27]. The US Nuclear Regulatory Commission graded approach to enforce institutional controls for post-decommissioning restricted site use is described in Ref. [28].

It should be noted that the application of grading or concessions 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 minimization, although reduced cost may be a consequence. To select the least expensive strategy once it has been decided to shut the reactor down permanently is not the purpose of grading [23].

In the USA, Argonne National Laboratory (ANL) and the Department of Energy (DOE) have embarked on a series of cleanup actions that strike a balance between the residual radiological risk to the public, the cost and the risk to workers conducting the remedial actions. Achieving unrestricted release at a given site following remediation requires almost complete removal of contaminants. Accomplishing this is often extremely expensive. In addition, this degree of stringency is usually unnecessary to ensure adequate protection of human health and the environment. The DOE and ANL were able to demonstrate that a very cost effective and low risk remedy could be implemented for three former radioactive waste storage vaults. Calculations of projected doses from the remaining radionuclides showed that only minuscule risk would exist from leaving the material in place. Substantial cost savings of approximately $2 million were realized by implementing decommissioning on the basis of acceptable residual risk rather than selecting an alternative requiring cleanup of the project site to its original conditions [29].

At the BR3 reactor decommissioning project in Mol, Belgium, some decommissioning activities can be carried out covered by a simplified work instruction. If a combination of criteria is met in terms of exposure, workload and material production, the authorization of the local representative of the regulatory body is sufficient [30].

4.4. COST ESTIMATION AND FUNDING

An estimate of the decommissioning cost is necessary from early in a facility's life in order to define the funding provisions that will need to be set aside for eventually implementing the decommissioning project. This cost estimate needs to be updated during the operating life of the facility to ensure that these provisions remain adequate. In due course the funds will be released for project implementation. The monitoring of expenditure versus budget will then enable performance against project plans to be established. Thus accurate and updated cost estimates are an important requirement from the beginning of life to the end of decommissioning (Annex I.H).

A variety of techniques are used to estimate decommissioning costs:

(a) Conventional bottom-up approaches based on the integration of task costs using the project WBS [31];
(b) Unit or parametric methods based on feedback from real jobs to adaptively modify unit costs [32];
(c) Computer models [33].

In addition, if contractors are to be used to perform some or all of the decommissioning, budget estimates and tendered costs can be obtained from them for the relevant activities.

Discounting of costs using fixed or variable discount rates may also be applied in the case of deferment projects where the costs will not fall due for many years. This approach assumes that funds set aside for future work can be invested to achieve real growth over the period until they are required to be spent. The prudence of discounting will be dependent on the historical and expected future economic stability of the State and on the investment climate.

In practice, a combination of techniques is likely to be used, but the conventional bottom-up approach based on a detailed WBS is usually the foundation. The more unique the task, the less likely specific experience from elsewhere or generic information from cost databases will be able to shortcut this approach. Factors can be included to account for slower working in radioactive environments compared with estimates from conventional demolition projects. The WBS should be defined as a hierarchy of work to be done, each large work area broken into smaller units of work at the next level down and so on until a sensible stopping point is reached at a specific task level. Costs can then be assigned at that task level in terms of labour, plant and material. Integration of the various tasks up the hierarchy is facilitated by using a unique numbering system or 'cost code' to build up estimates in various rolled-up categories as needed for control and monitoring purposes.

An initial project cost (the base cost) determined from the WBS can be adjusted by adding allowances for contingencies and risks. Contingency is added to the base costs to reflect an estimating uncertainty dependent on the level of cost definition; for example, low uncertainty typically ±5%, high uncertainty typically ±50%. Contingency assumes that the WBS is adequate in structure (i.e. it reflects the tasks being carried out).

In contrast, the risk budget is an allowance for the planned work (i.e. the WBS) not accurately reflecting the actual work to be done, usually due to unexpected situations such as a delay in a regulatory authorization. An assessment of risk is made by identifying potential deviations, judging their likelihood and estimating the schedule and cost implications (see Section 4.5). Some risks will have favourable outcomes and some unfavourable, creating a 'cancelling' effect that can be investigated using statistical methods such as Monte Carlo simulations to define the most probable outcome in terms of cost and schedule, with ranges related to appropriate confidence limits. However, in a small facility the issues are unlikely to be sufficiently complex to warrant such an investment and a simpler approach is likely to be sufficient.

It should be noted that contingency funding and cost and schedule risks can become obstacles to timely decommissioning. Money being held in a contingency account may be not available for use by the project, while inadequate risk analysis may place too much importance on certain risks while underestimating the potential impacts of others, leading to a loss of credibility for the project. To address this issue, the contractor responsible for the Fernald decommissioning in the USA developed a graded approach to identify various risks associated with the scope of the work and the level of mitigation appropriate to each risk. Using a variety of tools, project teams identified, quantified (within a rough order of magnitude cost estimate) and established the probability of occurrence of all potential risks in their area of responsibility [34].

Overall, cost estimates are worth revisiting on a periodic basis since increased knowledge can reduce both the contingency and the risk margin, hence reducing the fund provisioning required.

Realistic cost estimation that reflects the actual local conditions is particularly important if limitations on funds are severe. Initial funding for the project may be difficult to obtain, there may be limitations on the funding available in a given year and funds for any subsequent cost overruns may be increasingly difficult to obtain. Moreover, cost reduction campaigns can only be based on a good understanding of the sources of the costs. It is essential that a formal process for cost estimation is adhered to and training given as necessary to develop expertise as required. Underestimating the cost may lead to the project stalling with the facility in a less favourable condition than it was before decommissioning started.

In some other cases, facilities may need to be decommissioned, but funding is not available [19]. Smaller projects may also be conducted in an environment in which funds are released in relatively small amounts and the size of the funds to be released for the next period is not known until shortly before that time. In such cases the scheduling and cost estimate of the project need to reflect the likely budget profile, with significant schedule and cost risk allowances made for deviations. Releasing funds in this way may be unavoidable in some States or situations but will inevitably lead to a higher cost, longer project due to the inefficiencies generated.

One example of the role of a funding profile (variation of spend with time) in cost effective decommissioning is given in Ref. [35]. In that project the savings resulted from use of a five year flat funding profile as opposed to an eight year funding profile that had a dramatic increase in funding in the final three years. Besides any other issues, there are human resources advantages in a relatively flat, or monotonic, profile, as people and skills cannot easily be turned on and off.

4.5. PROJECT RISK MANAGEMENT

Risk management is routinely used in many industries to identify project risks, evaluate their consequences and try to remove or minimize their impacts. It should cover not only technical issues but also commercial, managerial and stakeholder related issues. The technique of risk management is typically applied in a stepwise fashion:

(a) Project scope definition — define the objectives of the project and assumptions made.

(b) Risk assessment process — identify potential project risks (and opportunities) and estimate their probability.
(c) Risk analysis — assess what impacts the risks could have on the project scope, costs and schedule.
(d) Risk mitigation — define how to manage the risks and identify who will be responsible for these actions.
(e) Risk monitoring — periodically review and modify the risk management approach.

A risk register can be constructed to bring the above information together, detailing the risks and impacts and those persons responsible for their control or mitigation. The register should be revised throughout the project by a process of iteration. Access to experience from similar projects can increase the accuracy and value of the process. Examples of risks that might need to be taken into account in the risk register might be:

(i) Non-acceptance of a safety document by a regulator (hence requiring more time and cost);
(ii) Accidents (causing lost time);
(iii) Discovery of hitherto unknown levels of radioactivity (requiring more detailed characterization surveys, hence increasing time and cost);
(iv) Changes in person effort requirements due to slower working than anticipated.

4.5.1. Managing stakeholder risks

Stakeholder relations are a potential source of risk to the delivery of a decommissioning project. Key stakeholders include funding providers, municipalities, planning authorities, the various regulatory bodies, the general public (local community), ‘pressure groups’ and other interested parties. Their early involvement with the project can ensure a good working relationship and develop trust. In addition, including stakeholders in planning and status sessions allows the project team to get input to, and the understanding or support of, the project approach.

This issue is as important for small facilities as for large ones. The public may have had no awareness of the existence of a longstanding facility until decommissioning is announced. Concern may be aroused if it is realized that the site may be used for extended spent fuel or radioactive waste storage or disposal. In a State with little in the way of facilities, there will probably be a need to recognize that the stakeholders need to build up knowledge and experience. Their own resources may also be limited. Having a more informed regulator allows project reviews to be better focused on the technical issues instead of seeking additional information or explanations about the project. A better informed local authority may assist in obtaining the necessary permits in a timely manner. Experience of stakeholder interactions in the decommissioning of the Oak Ridge National Laboratory and other facilities in the USA is described in Ref. [36].

4.6. HUMAN RESOURCES FOR A DECOMMISSIONING PROJECT

Experience gained by staff during the operational life of the facility, while invaluable as a starting point for decommissioning, will generally require strengthening in selected areas. New skills will be required to manage the project from planning to completion and to liaise with the various stakeholders that have an interest in the project, for example owners, regulators and local interests. A question then arises of how to identify and source the new expertise required. A summary of the various options is given below:

(a) Use of in-house expertise supported by appropriate training initiatives. The skills, knowledge and behaviour of existing staff can be developed, although there may be difficulties in retaining key staff. For a small decommissioning project, multiskilling can be utilized to enable efficient use of in-house expertise and resources. Additionally, there may be retired staff available who may consider part time working if the project demands do not require a full time commitment. However, economies can be gained by retaining key operational staff during the early phases of decommissioning via, for example, IAEA sponsored training programmes using expert missions, workshops and the secondment of selected staff to decommissioning projects elsewhere, in bilateral and/or regional programmes. Such external training gives access to lessons learned from experience gained at similar facilities elsewhere. As the project runs and requirements change, arrangements need to be made to continue the staff's acquisition of new skills through training, etc.

(b) Identification and utilization of national expertise from outside the project. If it is possible to supplement the team with additional skills that are not available internally, via the contractor market or by secondment from other projects, this should be considered where affordable. Such expertise may exist depending on the level of nuclear development present within the State. General engineering and project expertise may be identifiable, but the experience and requirements to work to the exacting safety standards required in the nuclear field may be lacking, hence bringing into question the philosophy of following this route without substantial re-education. While the overall responsibility for the safety of decommissioning operations will continue to rest with the licensee, a developed system of regulation will require demonstration that where contractors are employed they are suitably qualified and experienced to perform the tasks being requested.

(c) Identification and utilization of international expertise. There is an increasing availability of specialist decommissioning contractors that operate either on a regional or international basis. The use of such organizations is commonplace in many industrialized States and has largely superseded the virtual monopoly of governmental organizations on decommissioning planning and operations. This demonstrates the development of decommissioning into a mature commercially driven sector since the 1980s. Such specialist decommissioning contractors bring project management skills and the ability to accept the commercial risk of completing decommissioning work to time and budget. However, it has to be said that such services come at a price that may be prohibitive for States or institutions with very limited financial resources or where local costs are much lower than international rates.

In the case of one of a kind projects, this approach has definite attractions if most of the project risk can truly be passed on to a contractor that has the experience and competence to manage the risk more effectively than the operator. It should be noted, however, that the overall responsibility for the safety of the decommissioning process cannot be delegated and sits firmly with the licensee. In the same way, the use of external contractors requires other skills in the licensee’s team, such as contract management skills as well as the engineering competence to act as an informed purchaser. This important topic is expanded in the following section.

4.6.1. Managing the use of decommissioning contractor organizations

Contractors can have an important role to play in the decommissioning process. If an experienced contractor infrastructure is not available on a national basis, a number of contractor organizations that operate on an international basis and that are able to provide services from consultancy through to turnkey decommissioning are available. Successful project management requires the development of a clear scope for the work. If the contract specifications are not clear and fixed, project budgets and schedules will be threatened by variations and reworking. Such weaknesses also carry the risk of generating claims from the contractor (and client) that can lead to commercial wrangles, distracting both parties from the real purpose of the project. The uncertain nature of some decommissioning projects leads to difficulty in work specification, often making fixed pricing difficult. To avoid conflict and cost overruns it is worth considering a shared risk approach for parts of a project that cannot be accurately specified in scope at the outset. This may include target cost or incentivized contracts; for example, the contractor tenders a price for the work but agrees a bonus for early completion (at overall reduced cost to the client) or operates at a limited margin for programme overruns.

The best value for money can often be obtained by seeking competitive tenders from a range of competent contractor organizations. This requires that the operator has sufficient knowledge of the job in hand so as to be able to specify the contract with clarity and detail. However, the capability of the prospective contractors to offer their own innovative approaches to deliver the required goal should not be constrained by this approach. It is important that the operator does not seek to transfer risk that the contractor is not competent to manage, as this will tend to lead to a focus on claims and conflict when things go wrong. Sometimes the lowest bid may be made by a contractor that has not recognized the real challenge in the task, and hence the operator needs to identify such a situation during the tender process. To do this the operator needs to be an adequately informed purchaser.

The culture required for the successful use of decommissioning contractors may not be well developed in all States and institutions. Third party involvement may also be considered as a threat to both jobs and working practices. However, if these challenges can be met, the use of decommissioning contractors may bring acceleration to schedules due to the experience they have. In practice, the deployment of large teams of contractor personnel is unlikely at a small facility. In the decommissioning marketplace, contractor activities under such circumstances have been centred largely on predecommissioning consultancy services.

Thus it may be appropriate to choose only key tasks for external contractor support. An example of this approach in a State with a single research reactor is given by Latvia [37]. International contractor expertise was sought for dismantling studies of the Salaspils IRT reactor near Riga. In this case immediate dismantling was preferred on the basis of a national strategy decision that the timely removal of the reactor was in the national interest, thus avoiding arguments on the intergenerational aspects of deferred dismantling. This project effectively utilized international support to upgrade decommissioning infrastructure such as the waste cementation plant procured by the IAEA (Fig. 4).

The more those involved work as one team pursuing a common goal, the more likely is project success. At the Barnwell nuclear fuel plant in the USA it

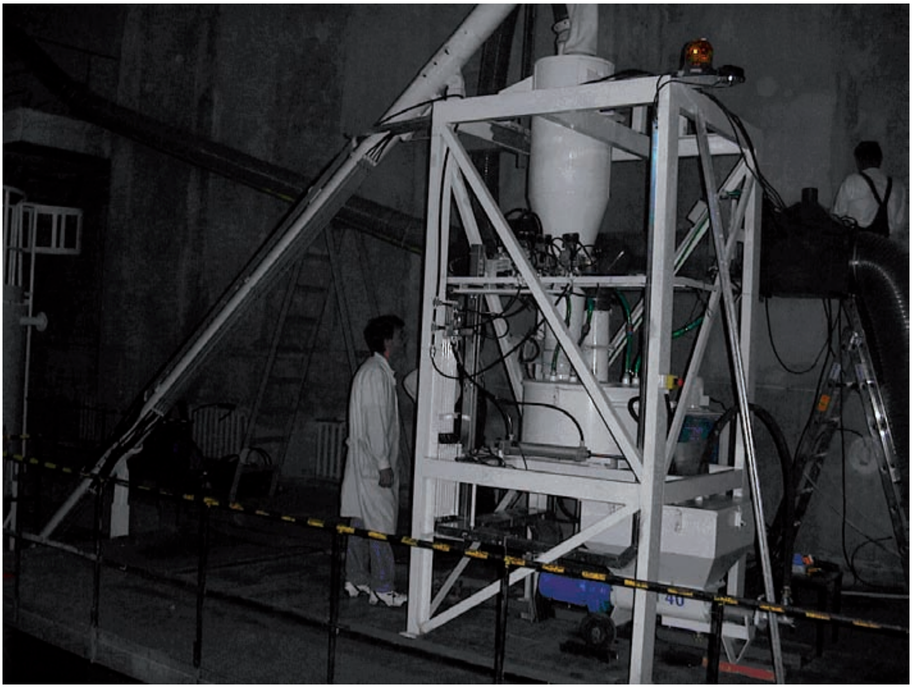

FIG. 4. Salaspils IRT reactor, Latvia. Installation of the cementation plant for decommissioning.

has been reported [38] that the success of a decommissioning project was due to excellent teamwork among the four organizations involved. This teamwork was based on trust and mutual respect and on the organizations working towards a common goal. Another factor was the client–contractor relationship, wherein the operator entrusted the contractor to act on its behalf with minimal pressure.

There are many examples of effective contractual arrangements in practice; for example, at Oak Ridge National Laboratory in the USA, an innovative contracting method was used to reduce project costs, improve safety performance and ensure management accountability. Relevant features included:

(a) Obtaining a multicontractor team;
(b) Using fixed price contracting;
(c) Providing an incentive for finishing under budget and within specified criteria;
(d) Applying a penalty for any cost overruns or unsatisfactory performance;

(e) Using technical experts to help streamline and focus procurement performance specifications, thereby simplifying the process and reducing cost estimates [36].

4.7. KNOWLEDGE AND COMPETENCE

In a situation of limited available resources the issues of staff knowledge and competence can become particular concerns, especially if decisions cannot be made quickly on implementing a decommissioning strategy. The longer the time between plant shutdown and the start of decommissioning, the greater the risk of the licensee losing employees through resignation or other reasons. The re-training of existing staff for new decommissioning tasks becomes critical in order to build on existing experience and plant knowledge and to develop new skills and behaviours relevant to the decommissioning project. The following sections detail the principal issues.

4.7.1. Knowledge retention

The nuclear industry is faced with the prospect of loss of ‘corporate memory’ as older people retire. The so-called tacit information carried in the minds of many experienced employees is an important resource to preserve in addition to the explicit information carried in documentation and databases [39]. The prospect of such loss is exacerbated by the widely experienced problem of insufficient numbers of younger scientists and engineers wishing to embark upon a career in the nuclear industry. This is in part due to the general downturn in young persons wishing to follow technical disciplines in higher education, but in States with only one or two small nuclear or related facilities there will understandably be little apparent attraction in joining an industry seen as having no future locally. Managers of facilities need to put succession management practices into place in anticipation of later problems, to encourage the development of new talent.

Knowledge retention applies equally both to individuals and record systems, so it is important not only that training and educational opportunities are identified but also that robust systems are developed under the QA programme for the retention and maintenance of records for future use.

There will already be a duty on an organization operating a facility with radiological hazards to ensure the existence and implementation of adequate arrangements for the training of those who have responsibility for any operations that may affect safety and as required under the decommissioning licence conditions or national and local rules and regulations [40, 41].

4.7.2. Learning from and working with others

An effective way of improving the productivity of decommissioning projects is to learn lessons from others with similar facilities that have carried out similar operations, or plan to do so. Capitalizing on such experience can save programme time and costs and avoid wasteful re-invention. There needs to be an appropriate willingness among staff to take on the ideas of others and an avoidance of a ‘not invented here’ outlook. The nuclear community is well linked through a variety of international bodies, agreements and programmes, conferences, workshops and training sessions organized via task groups or international bodies active in the field, including the IAEA. Participation in such training opportunities brings the benefits of shared experience and identification of successes (and problems), providing a knowledge base of lessons learned for the application of the many.

In addition, the decommissioning challenges faced for a research reactor or another small facility are likely to be similar to the challenges faced by those with similar facilities. There may be real opportunities to share not only experience but also equipment and techniques, reducing overall costs. Staff could be seconded to other sites to assist in their work and to bring back valuable personal experience for application at home. Such arrangements may be set up through organizations such as the IAEA or by bilateral contacts and agreements.

4.8. QUALITY ASSURANCE

QA is a management system that, if properly used, gives confidence in and provides documentary evidence of the outcome of a given task. It provides a rationale for the management and control of all the processes that constitute the project by defining how the processes are carried out, monitored and recorded. While some of the procedures used during operations will be carried forward into the decommissioning phase, many new ones specific to decommissioning will be required. The management discipline imposed by a system of QA, although initially expensive in terms of commitment and time to deploy, will allow improved efficiency in the longer term and will become an important driver in controlling costs. The QA management system and QA programme for decommissioning activities should be implemented as an extension of any existing system for operations before decommissioning starts and should be described in the decommissioning plan.

A small decommissioning project should adopt a pragmatic, fit for purpose approach that recognizes the importance of the activity to safety or other issues [42]. The quality system deployed should determine the minimum requirements for control of the processes and should not require an overly restrictive set of procedures that become difficult to deploy and that may not be used. Hitting the right note here is most important, since many QA systems fail because of lack of commitment from users who fail to see the merits of the system. Training in the value and use of the QA system is important to foster understanding and commitment by the users.

The system employed can span from documentation of existing procedures that have been employed over long periods but never formally recorded as such, to the preparation of new procedures for the decommissioning phase. The documents should be formally recorded and disseminated as procedures, work instructions, etc., and issued under the control of a designated person tasked with the administration of the system.

The procedures should be 'live' in the sense that they should be kept up to date. Audits will be necessary to ensure compliance with agreed procedures. These should include internal audits, preferably by someone from another branch of the organization. External audits may also be necessary to satisfy the requirements of regulators or others. Audits may also be undertaken of contractor's arrangements.

5. FACILITATING DECOMMISSIONING

This section discusses the activities that can be undertaken at research reactors and other small facilities to prepare for and implement decommissioning. It is organized as per the facility life cycle, from design to completion of decommissioning.

5.1. ACTIONS DURING THE PLANT DESIGN AND CONSTRUCTION PHASE

Designing for decommissioning is arguably the best long term facilitator of the decommissioning process [43, 44]. While this is a laudable objective, and directly relevant to the construction of new facilities, the reality is that this is only possible for existing facilities in the context of their modification and maintenance. Where practical to implement, small additional costs can eliminate substantial decommissioning costs. One such example is the reconstruction of Bulgaria's IRT-2000 reactor. New systems are designed and installed subject to an IAEA supported assessment of their decommissioning suitability [45].

In reactors, the trace elements that are always present in construction material will be activated in a neutron flux. The resulting radioactive isotopes contribute to operational doses (e.g. ^{60}Co) and can become significant for waste management (e.g. long lived isotopes such as ^{36}Cl from graphite and ^{14}C from most construction material). It may not be practicable or cost effective to eliminate relevant trace elements entirely, but care should be taken in construction material selection and samples should be retained for future analysis to support characterization campaigns for decommissioning; for example, the use of aluminium rather than stainless steel for research reactor containment tanks reduces the quantities of low and intermediate level waste (LILW), since all commercial stainless steels contain significant quantities of elemental cobalt (although most aluminium alloys contain some residual traces of cobalt).

Wherever possible, activation sources should be positioned away from concrete bioshields or other shield walls in order to reduce the quantity of activated concrete. Given the nature of the materials that make up concrete, it is difficult to source these so as to reduce activation [46, 47]. Neutron activation will occur up to a depth of many centimetres in concrete, thereby generating tritium (from $^{6}Li(n,\alpha)^{3}H$) as the principal radionuclide of activation. Although calculation methods are routinely used to estimate the masses of activated concrete, they become inaccurate in deep bioshield structures distant from the reactor core [48]. This is due to difficulties in accurately predicting the neutron flux. Design provisions can enable direct flux measurements to be made during operation. The resulting improved calculational accuracy means that less reliance needs to be placed on the removal and analysis of core samples, thus reducing the overall decommissioning costs. Additionally, removable activation coupons of construction material should be considered for facilitating later estimates of radioactive inventories. This gives a cost effective route for the collection of neutron flux data and can be used to support later activation calculations in support of decommissioning preparations, for example assessments of the waste category and quantities [49]. Finally, neutron streaming through voids can activate components but can also be avoided by careful attention at the design stage.

The design of all facilities should also include measures to prevent the spread of contamination during maintenance of the facility. Some examples of guidelines for the design of small facilities with effective contamination control are given in Refs [50, 51]. The design should ensure that the amounts of radioactive waste that arise are minimized and that all relevant parts of the premises are constructed, maintained and used in such a manner that they do not readily become contaminated. Any contamination that does occur should be able to be easily removed.

Other practical considerations at the design stage include taking care in the positioning of embedded and/or underground components. Their accessibility becomes limited once construction is completed; leakage to ground may occur and characterization becomes difficult and expensive. The use of such embedded systems should be minimized. Where they are unavoidable, consideration should be given to providing the capability to monitor them. Double containment systems are more expensive to install initially but reap rewards later.

Attention to these basic principles should be given in the design phase to each component of the facility.

5.2. ACTIONS DURING THE OPERATIONS PHASE

The safety and cost effectiveness of decommissioning can be enhanced if appropriate steps are taken in the conduct and recording of operations.

5.2.1. Refurbishments

The experience gained in plant refurbishment exercises generates useful information in support of future decommissioning tasks. These exercises are often equivalent to 'partial decommissioning', with the methodologies and equipment used, the dose uptake incurred and other experiences being valuable for decommissioning planning. This work will usually have been undertaken under normal operational conditions with radiation exposure rates that have not benefited from a long period of radioactive decay, hence requiring very close control of operations and dose uptake. Such work has been carried out on numerous research reactors — replacing defective components, cooling circuits or heat exchangers, changing core configurations and upgrading power output [52–54].

Generally, such tasks have been carried out by in-house engineering staff at the facility site, often with support from local subcontractors in States where sufficient nuclear infrastructure exists to make this possible. One example is the LWR-15 reactor at Řež in the Czech Republic [55]. At the CIRUS reactor in India, several part-decommissioning activities were carried out during the refurbishment. These activities were used to generate data, document the experience and lessons learned, and support initial planning for future reactor decommissioning. Similarly, the experience gained during the refurbishment of

PARR-1 in Pakistan will prove useful for better planning and execution of the future decommissioning of PARR-1 and other research reactors [54]. In Bulgaria the IRT-2000 research reactor in Sofia was refurbished for power upgrades and is now planned for reconstruction as a low power reactor [45]. Similar activities were performed in Latvia with an IRT type reactor [56]. Tasks accomplished ranged from specific component removal and replacement through to the replacement of the entire activated reactor core. Hence the refurbishment tasks have included many of the more difficult and potentially high dose operations that will be required ultimately during the final dismantling of these systems.

Unlike in decommissioning, refurbishment work usually generates only limited quantities of radioactive waste and does not place excessive demands on existing waste management facilities — the radioactive waste being stored on-site or disposed of at national facilities where this has been possible. Clearly, for further dismantling involving more significant quantities of potential radioactive waste (e.g. bioshield removal), the waste management challenge is greater, necessitating developed facilities and a policy on waste categorization and acceptance and clearance criteria.

Refurbishment experience reinforces the need to:

(a) Record and retain the knowledge from such refurbishment activities by means of documentation, databases and photographs;
(b) Estimate and retain cost information for use in decommissioning option studies and planning;
(c) Retain personnel with refurbishment expertise if possible, at least during the early phases of decommissioning;
(d) Draw on experience gained by others who have operated, modified or decommissioned similar systems;
(e) Prepare samples of used material for irradiation in the core area to obtain activation data for material, if possible.

Typical lessons learned from surveillance and maintenance activities in the course of decommissioning and strategies resulting in cost savings are reported in Ref. [57]. Although clearly not drawn from the decommissioning phase, Ref. [57] illustrates the nature of similar information that could be drawn from operation.

5.2.2. Contamination control

In any facility, the spread of contamination may have been an operational problem, as it is an important issue for safe facility maintenance. Decontamination exercises will prevent buildup of radioactivity and alleviate later problems. General housekeeping activities should be employed using routine monitoring surveys to identify and remove contamination hot spots. As in other applications, commercially available equipment can be a relatively cheap option, for example non-nuclear cleaners with HEPA (high efficiency particulate air) filters can be used for cleaning purposes (Fig. 5).

Contamination of soil and groundwater can significantly influence the decommissioning strategy. Decommissioning a facility to unrestricted release standards may require such an expensive ground remediation programme that it comes to dominate the total decommissioning cost [58]. Operational experience of contamination control in some facilities is given in Refs [49, 59].

Experience indicates that the following contamination control aspects should be considered in the operational phase:

(a) Control of radioactive material;
(b) Workplace monitoring;
(c) Stack and area monitoring;
(d) Radiation safety training;
(e) Development of ALARA programmes;
(f) Radiation dose reporting.

Contamination issues can be considered in the early planning of decommissioning based on data from sampling tests and analysis of historical records.

5.2.3. Records

Information will be generated during all phases of the design, construction and operation of a research reactor or other small facility, much of which will be useful during the decommissioning phase. In the case of smaller facilities that may have been used predominantly for research purposes, a low priority may have been given to the documentation and general maintenance of records of structural and operational changes that were made during the history of the facility. Such record keeping should be instituted as an integral part of the overall management process for the facility. Changes in the use of the facility, additional equipment, modifications to the design and power upgrades may have been routine for research reactors and, where relevant, other small facilities. These would have a direct bearing on planning for the decommissioning phase.

Original, as-built drawings may be neither available nor readily obtainable, being retained by the designer or architect–engineer organizations

FIG. 5. Decontamination activities during refurbishment of the SRR's spent fuel pool.

that designed the facility decades before. Such organizations may no longer be in existence in the same form, compounding the problem. These factors point to the need to set up and maintain a records management system (RMS) for records that do exist and to ensure that a QA system is instigated to record operational details to support future decommissioning activities. Guidance on developing an RMS and on the advantages of various media for records storage is available in Ref. [60].

Gaps in knowledge due to missing records can be at least partly closed through surveys or by obtaining relevant data from similar facilities. It is valuable to build up knowledge of experimental rigs and devices and their locations, contamination incidents and subsequent cleanup operations, and plant events that may have led to the spread of contamination. Interviews with older staff, including those who have retired, can be useful in recording events that may have left legacies that are no longer apparent.

For research facilities, the configuration of the plant may well have been under constant modification as new experimental rigs were introduced and older ones removed. In such circumstances, photography is a cheap and effective way of recording the various configurations — in particular, digital photography is a cost effective way of cataloguing the various changes that can be stored on CD-ROM.

5.3. TRANSITION FROM OPERATIONS TO DECOMMISSIONING

The transition from operations to decommissioning requires early planning to cope with both the organizational and the physical changes that will be required. During this phase the facility has to be readied for dismantling or safe enclosure. Earlier exercises in preparing decommissioning plans must now be finalized. It is important that a team to manage decommissioning activities be established early during the transition period. For a small project this does not mean that a large number of staff will be required, but rather that selected members of the existing operations team are reassigned, supported by expertise from elsewhere where this is available, for example for cost estimation and project scheduling work.

The principal objectives of the transition stage are to reduce hazards and to lower operations and maintenance costs. Equipment that will no longer be required to support the decommissioning phase may be deactivated. Systems for which the full capability is no longer required for decommissioning can be modified to cope with the lower demands imposed by decommissioning. However, although the full capabilities of ventilation plant may no longer be required, additional ventilation arrangements may be needed to aid contamination control in the decommissioning phase. Further cost savings may be achieved by selective staff reductions, reduction in power and other services, reduced maintenance requirements, reduction in consumables and the recycling or resale of plant that is no longer required.

A research reactor or other small facility will not require the same level of transition activities as for a larger facility such as a nuclear power plant. However, a number of preparatory works still need to be carried out that typically include finalizing decommissioning plans and reducing or removing the more mobile nuclide inventory; for example, spent fuel removal (see Section 5.3.1), decontamination, operational waste treatment and the taking of measures to prevent the spread of contamination. Furthermore, a variety of other housekeeping tasks should be tackled to reduce hazards and to prepare areas for later decommissioning [61]. Figure 6 shows one example of the cluttered environment of a research reactor typically resulting from a number of experiments and measurements. Comprehensive housekeeping prior to the start of decommissioning is essential to simplify later work. Installed systems need to be reviewed selectively for retention, de-activation or removal.

There are a number of factors that could compromise progress in States and institutions with limited resources:

(a) Funding to support transitional work may be required over and above that allocated in the operating budget — such funding may be unavailable.
(b) New techniques may be required for which neither funding nor expertise is available locally, for example for cooling circuit decontamination.
(c) Lack of regulations relevant to decommissioning may generate a hiatus in the transition, thereby increasing costs as existing operational services are required to be maintained. This effect may be compounded further by unclear responsibilities for decommissioning.
(d) The transition period may be extended by a lack of firm decision making on the part of the facility owner, resulting in the need to maintain full operational staffing to comply with licensing requirements.

It will not be easy to refocus R&D staff to the task of decommissioning, as this is often seen as less of an intellectual challenge than previous work and, as

FIG. 6. Cluttered environment at a research reactor.

such, workforce morale may suffer. Inevitably, some younger staff may see their career prospects curtailed and seek alternative employment. This problem may be exacerbated by the difficulties in recruiting younger technical staff into the nuclear industry in the first place. A positive outlook has to be fostered by management, for example by emphasizing the value of the new skills that can be developed by involvement in a decommissioning project.

While it may be appropriate to release some older staff, it is essential to maintain key skills to support the early phases of decommissioning, particularly those involved in engineering and health physics support services. This requirement must be supported by the retention and maintenance of essential plant documentation as well as reconstructing or making provisions for any missing documents (see Section 4.7). To supplement the existing facility documentation, extensive use of former employees has been invaluable at the Oak Ridge facility for determining the potential hazards there. These former employees have been able to identify and locate additional documentation and to provide details on past facility operations, mishaps and incidents [36].

5.3.1. Spent fuel management

Spent fuel is a significant issue in research reactor decommissioning. Internationally, research reactors have generally been sourced from the USA (e.g. TRIGA or Argonaut types) or from the former Soviet Union (e.g. IRT (pool) or VVR (tank) types). On-site storage of spent fuel in at-reactor facilities is commonplace, with away from reactor facilities generally not used. In some instances, the entire charges of fuel utilized since reactor startup are still stored at the reactor site. Recognizing that in many cases high enriched uranium was used in the early designs, policies have been developed to enable the return of spent fuel to suppliers on grounds of non-proliferation. This has been achieved for US supplied fuels under the US Foreign Research Reactor Spent Nuclear Fuel acceptance programme of 1996 and, more recently, for fuels supplied by the Russian Federation, under the Russian Research Reactor Fuel Return programme of 2003 [62]. The spent fuel management options for research reactors in Latin America are described in Ref. [63].

Corrosion problems have become evident for aluminium clad research reactor fuels in long term wet storage. In some cases this has progressed to a point where there has been potential for loss of fission products to the environment [64]. Figure 7 shows that after a multi-year shutdown period, corrosion at the Vinča reactor in Serbia could be a serious problem. The absence of facilities for spent fuel management places increased strain on site based facilities that are not designed for long term storage — remedial work

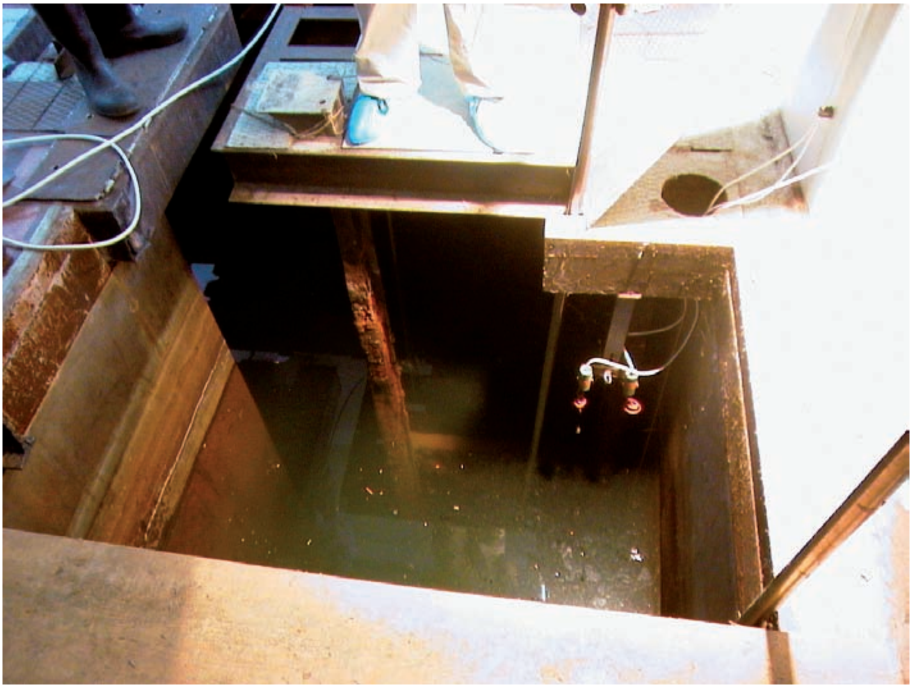

FIG. 7. Research reactor corrosion following an extended shutdown period.

being required on recirculation and ion exchange systems to maintain water purity levels.

A number of issues arise:

(a) Limited storage forces operators to increase pool capacity through spent fuel reracking operations, resulting in potential cooling and criticality issues;
(b) Cladding corrosion mechanisms require the sampling of pool water for the identification/isolation of failed fuel assemblies;
(c) Failed fuel requires prompt intervention and isolation to limit fission product releases;
(d) Large radioactive inventories of spent fuel are present in facilities that are often now in populated areas.

Fuel failures lead to increased fission product release and transport around cooling circuits, increasing the decontamination and cleanup challenge in decommissioning.

5.4. CHARACTERIZATION

Characterization is the most important technical step in the planning process [65]. Adequate resources need to be allocated to ensure that characterization is carried out in a timely manner. If problems are identified later during decommissioning, they can have a significant negative impact on the project cost and schedule. It is essential to produce an effective site characterization in terms of both radioactive inventory and the physical status of the facility. This is particularly true if the facility has been unused for some time and may be suffering from deterioration due to inadequate care and maintenance. One recent example of a predecommissioning characterization of a research reactor is given in Ref. [66].

Where deferred dismantling is intended, a structural survey should be carried out for components that are vital to the containment of the radioactive inventory in order to identify any work required to strengthen the structure for the safe enclosure period.

Both the selection and the implementation of a decommissioning strategy for a facility require knowledge of the radionuclide composition and the activation and contamination levels that have arisen during operation. In the case of facilities not capable of generating activation processes, this would be restricted to knowledge of the contamination levels [67].

In reactors that have undergone normal operations, the principal component of the radioactive inventory (apart from the spent fuel) is activated structural material. This may be estimated by a combination of calculation, measurement and analysis of samples. Where physical samples must be taken, the aim should be to minimize costs by using commercially available equipment. Figure 8 shows the drilling of concrete samples from the Austrian Astra reactor bioshield. Equipment was used that required only modest adaptation to work in a nuclear environment.

Contamination in a shutdown reactor results from radioactive releases from the fuel together with the activated products of corrosion and erosion that arise from operations. In contrast to activation, it is difficult to estimate the amount of contamination remaining inside a reactor, and hence a programme of sampling would normally have to be carried out. The following information is required:

(a) The principal nuclides present that need consideration for waste handling, transport and disposal;

FIG. 8. Core drilling tool at the Astra research reactor.

(b) The quantities, types and location of waste according to national waste categories and site release criteria;
(c) The radiation fields present, in order to decide which types of dismantling technology (remote, semiremote or manual operations) are appropriate during decommissioning;
(d) The radionuclide and radiation fields present, in order to decide which radioactive waste conditioning technologies are to be used.

A pragmatic approach may be adopted at a small facility by utilizing skills and plant knowledge developed by the local safety organization. Direct gamma measurements can be made using available (and hence familiar) equipment. Such direct monitoring can be used to characterize specific components for dismantling, consistent with national waste categories. Emphasis needs to be placed on the detailed characterization of components where waste categorization boundaries exist, since care must be taken not to overcategorize waste owing to the added cost involved. Conversely, undercategorization will lead to regulatory and environmental issues.

If nuclide specific measurements are required, the expectations of the regulatory bodies need to be understood early so that the scope of the requirement can be specified. Hard to measure beta and electron capture nuclides may be determined by limited sampling and analysis to develop a ‘fingerprint’ that is characteristic of the nuclide mixture. Scaling may then be carried out utilizing gamma measurements to assess the activity of the beta and electron capture nuclides present [65]. Care should be taken in utilizing such techniques so that the results obtained are not overly restrictive. Limited sampling [68] may generate results that are not sufficiently representative of the contamination field as a whole. Fingerprint methods must be reappraised periodically to ensure that the nuclide vector remains accurate. Other practical matters include the following:

(i) In general, the number and extent of surveys should be kept to the minimum to ensure that the safety requirements for the planned decommissioning strategy are fulfilled;
(ii) Performing more than the bare minimum of prefinal status surveys, particularly for areas whose characteristics may potentially be changed by subsequent decontamination activities, simply results in additional surveys and costs;
(iii) Surveys should flow from areas whose decontamination could potentially contaminate other areas (e.g. ceiling areas) to those less likely to spread contamination (e.g. floor areas);
(iv) Effective integration of health physics (during both operation and decommissioning) and characterization functions will reduce overall project costs by eliminating redundancy and improving resource utilization.

Application of these and other key considerations to the decommissioning of a research reactor and other small facilities at the Battelle Memorial Institute, USA, is described in Ref. [35].

A statistical approach can be taken to minimize the number of measurement samples; for example, the possibility of measuring the entire surface of a stack may exist, but economic and industrial safety concerns make it unattractive. The effective use of knowledge about the plant can allow assumptions to be made to form the basis of a sampling regime. By sampling the surface using selective coring and measurement, the entire stack can be characterized in a cost effective manner [69]. Similarly, work performed at Saxton Nuclear Experimental Corporation achieved a saving of $5.5 million [70] by carrying out in the field triage survey screening to segregate soils into three categories based on the site release criteria.

5.5. SELECTING TECHNOLOGY FOR DISMANTLING AND OTHER DECOMMISSIONING OPERATIONS

The implementation of decommissioning involves a wide range of activities, such as characterization, decontamination, dismantling, the handling of radioactive and other hazardous waste and site remediation. Each of these operations is specialized in nature and needs a variety of technological solutions. Decommissioning technologies are now extensively developed, following a formative period starting in the 1980s during which both new techniques and adaptations of existing technologies (from the nuclear sector and elsewhere) were explored for application in the nuclear decommissioning field, for size reduction purposes, waste handling, etc. The associated development programmes were costly in terms of time and money. The general consensus is that effective technology now exists for most decommissioning activities and is in wide use [71]. Reviews are available of the selection of technologies for application to decommissioning problems in a systematic way [72, 73]. The European Commission has also developed databases of equipment performance and application parameters [74]. A checklist to aid technology selection is provided in the Appendix.

Substantial R&D should not be required to support the decommissioning of research reactors and other small facilities unless unique issues apply requiring specific technical solutions. Technological solutions are available from the international market, albeit at a price. High costs, commercial or licensing issues and the need for specialist knowledge may make equipment and techniques difficult or impossible to acquire and use. Hence, continued use of operational phase equipment, or non-commercial developments using readily available non-nuclear equipment or tools that can be easily manufactured in a local workshop all offer cost effective approaches; for example, existing facility cranes will often provide the necessary lifting and deployment capability for specialist tooling to be deployed inside a reactor vessel. Existing ventilation plant may also be utilized to support tenting or modular containments required to service decommissioning. Existing plant and services that support future decommissioning should be identified at reactor shutdown and maintained in a state fit for future use.

Simple, inexpensive and locally available technologies can also allow advantage to be taken of local labour costs, as opposed to States where automatic technology is used to avoid high labour costs. The adaptation of technologies from other industries for use in decommissioning activities has been successfully applied on several projects. An example of this is the application of an aviation technology for removal of waste packages from a former nuclear facility in the USA [75].

For States with single facilities, the resources and infrastructure for sophisticated decommissioning technology development are unlikely to be available or warranted. Prevention of radiation exposure of workers may require the use of remote technologies or robotics, but these should be selected only where truly essential, as they may increase costs disproportionately. In these circumstances, advice can be taken from other facilities or the marketplace, or from international organizations such as the IAEA.

Semiremote methods often offer a safe but cheaper, quicker and more appropriate option than fully remote operations. Long handled reaches with simple end effectors may have been routinely used in operations and can be readily adapted for both size reduction and handling operations when supported by closed circuit television for viewing of the work area. The use of manual or semiremote technologies is generally sufficient in deferment strategies where sufficient time has elapsed to enable the key radionuclides to decay to manageable levels. In contrast, immediate dismantling may rely more heavily on remote technology, due to the much higher radiation fields present. Perfecting a simpler solution will invariably be more cost effective than spending money on a high tech solution [76]. The use of complex and expensive solutions should only be considered when absolutely necessary, for example where high radiation environments dictate.

In some situations it may be better to remove large components intact rather than to dismantle them. This approach has been used in the refurbishment and decommissioning of research reactors. Examples include the removal of the JRR-3 reactor in Japan [77] and the removal of the EWA reactor tank in Poland [78].

The choice of methods must be justified in terms of dose uptake and hence compliance with the ALARA principle. A dose budget should be determined based on analysis of the proposed tasks and taking account of the number of workers, occupancy times and radiation fields involved. Care should be taken to account for all tasks, including maintenance of equipment that becomes contaminated during operations. Contingencies must be allowed for unforeseen occurrences such as equipment failures and accidents. The collective dose incurred during the dismantling of core components of the research reactor at the University of Virginia in the USA was reduced 30-fold by using divers to remove activated components in the reactor pool [68].

Dismantling procedures should be practised wherever possible using test pieces and mock-ups that mimic the components being dismantled to test the equipment being used. By using such rehearsal training methods it is possible to optimize deployment methods, thereby minimizing working times in radiation fields and developing a better understanding of the failure modes of equipment prior to active deployment [79]. Figure 9 shows a detail of Georgia's IRT reactor mock-up.

Other simulation techniques used in task design and training include the use of three dimensional models generated using CAD or similar techniques. Such models are used to accurately simulate the relative spatial positions of components, access ways, personnel and tooling on a screen. Although the computer images often prove to be expensive to generate, the advantage they hold over mock-ups is the multiple reuse that they allow. As well as tools for the development of technical solutions, they can be used by operatives, similarly to mock-ups, to familiarize themselves with plant layouts and equipment operating envelopes prior to exposure to a live working environment; for example, VISIPLAN was developed in parallel with the decommissioning of the BR-3 reactor at Mol, Belgium, as simulation software to optimize occupational exposures and other parameters in decommissioning activities (Fig. 10) [80]. For small and very small facilities where the number of components and potential sources is limited, the good practice approach is usually sufficient to achieve an optimum, and simulation software would only be considered for particularly challenging situations, if at all.

One possibility that has been successfully used in some States is to utilize existing military technology in the nuclear decommissioning industry. Various technologies, ranging from sensors, to materials, to remote control vehicle design, that have been developed for military applications can be implemented to meet the challenges that face the nuclear industry. In particular, it has been observed that optimized human–machine interfaces for tele-operated control

FIG. 9. Mock-up of grouted IRT reactor in Georgia.

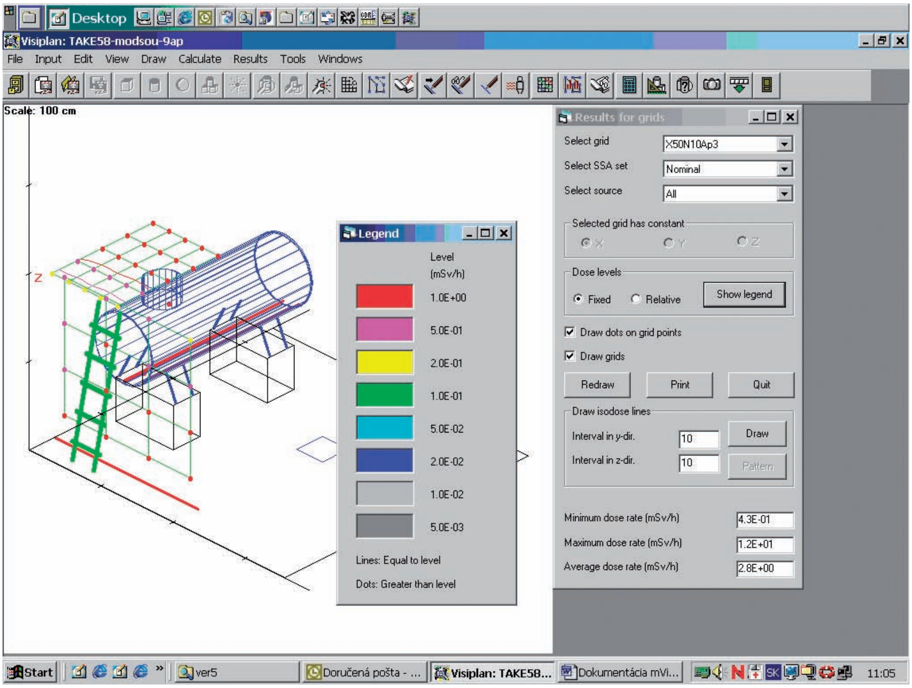

FIG. 10. VISIPLAN application.

of remote platforms can reduce time and operator errors when compared with standard hand controller devices [81].

A description of the decision making approach in selecting decommissioning technologies is given in Ref. [35]. The project includes a research reactor together with other nuclear installations. As one example, it was found that the use of low cost vacuum grit basting proved to be a cost effective decontamination technology. The experience of selection of technology for decommissioning activities in Estonia is reported in Ref. [82].

A summary of the lessons of employing innovative techniques in nuclear facility decommissioning in the USA is given in Ref. [83]. The implementation of innovative decommissioning techniques was based on the following lessons:

(a) It is safer to limit the size reduction of decommissioned components;
(b) Decontamination can reduce the costs associated with waste packaging, transport and disposal;
(c) Investigation and characterization often eliminate myths that surround historical operations, allowing safe work planning based on facts;

(d) Use of fixatives and fogging can eliminate potential exposure to airborne contamination;
(e) Generally available demolition techniques are often directly applicable to nuclear and radiological projects;
(f) An open and streamlined regulatory process encourages active participation and support from regulators and the government, thus encouraging working teams.

Typical experiences of a range of relevant decommissioning techniques are provided in Annex I.

5.6. WASTE MANAGEMENT

Waste management is a critical part of the decommissioning process. Managing significant quantities of decommissioning waste requires careful planning and implementation by a dedicated organization. The material produced by decommissioning needs to be managed recognizing the requirements and categorization of waste by the national authorities. Small facilities with limited resources do not usually have comprehensive waste management systems corresponding to all the requirements of the national waste management policy and specifically may have the following weaknesses:

(a) Limited waste treatment facilities;
(b) Poorly developed waste characterization system;
(c) Limited decontamination possibilities;
(d) Lack of radioactive waste transport packages and vehicles;
(e) Unskilled staff doing the dismantling and waste management.

These limitations make waste management difficult at small facilities without support from outside.

The decommissioning of the Salaspils research reactor in Latvia (see also Annex I.G) provides an example of how a waste management system was established at a small facility in a State with only one nuclear facility [49, 58]. The following features were found to be important:

(i) A material testing laboratory was established and equipped for characterization of material arising from decommissioning.
(ii) Use of simple decontamination methods. Vacuum cleaners, hot spot removing via drilling, scrabbling and shaving, brushing and wiping, and decontamination of stainless steel in oxalic acid solution. Planning of

decontamination was performed taking into account cost–benefit analysis principles.

(iii) Material and objects after free release were managed by external contractors (in many cases contractors also performed dismantling of conventional systems and components).

(iv) Radioactive waste was conditioned in concrete containers. Liquid radioactive waste from special canalization tanks was used for the preparation of cement/water mortar to prevent the discharge of liquid radioactive waste to the environment.

(v) Special concrete container tests were performed to assess compliance with national radioactive waste transport regulations.

(vi) The national waste repository was upgraded for decommissioning purposes.

(vii) Characterization and associated sorting of material can significantly reduce waste management and decommissioning expenses.

(viii) The strategy for reuse of the site significantly decreased the quantity of material arising.

In considering waste processing to reduce waste disposal and/or storage costs, savings based on volume reduction need to be weighed against increased processing costs. Volume reduction becomes more cost effective as disposal costs increase. Uncertainty over the final destination of radioactive waste makes more difficult the cost–benefit analysis required to justify waste processing. The same analysis will also be needed to assess the options for decontamination to allow recategorization of waste either for category reduction or for free release purposes.

A further option is to store radioactive material to enable decay so that it can be disposed of as a lower category or even be free released. The appropriateness of this route will depend on the activity and nuclide content as well as the availability and cost of storage and disposal of relevant category waste.

5.6.1. Recycle and reuse of material

There are strong economic and environmental incentives to minimize the generation and release of decommissioning waste. In States with few nuclear or radiological facilities there may not be specific regulations on clearance of material. This shortcoming needs to be remedied before the start of the decommissioning project, otherwise the project will be at risk from regulations promulgated later or else some material will be unnecessarily managed as radioactive waste. Material that cannot be conditionally or unconditionally released or reused will have to be treated as radioactive waste. Waste minimization seeks to avoid, as far as reasonable, the production of these undesirable by-products, which are often costly to manage; where they are unavoidable, steps are required to minimize their volumes [84].

Economic and environmental considerations are major driving forces when considering recycling and reuse versus disposal of radioactive and inactive material. Some level of optimization is an inherent part of determining whether recycle and reuse practices can be applied in a particular case or at a particular facility [67, 85].

Examples of the reuse of cyclotron facilities are reported in Refs [86, 87]. In these cases the recommissioning of the radiation facility significantly influenced the overall whole decommissioning approach.

The costs of radioactive waste management are a significant element of the overall decommissioning costs and may dominate in some cases [88]. Seeking an optimum balance between decontamination and dismantling costs and waste disposal costs as well as minimizing waste disposal costs has been a continuing effort at the Battelle Columbus Laboratories decommissioning project, which includes a research reactor, a critical assembly and many other facilities. More information on this project, including cost–benefit criteria for waste dispositioning, is given in Ref. [35]. Disposition of very low level waste in landfill is described in Ref. [89].

5.6.2. Reuse of sites

Reuse of a site is consistent with the concept of sustainable development. It combines economic development with conservation of natural resources such as land and may reduce the scale of the cleanup and final survey required at the end of the decommissioning project.

Realizing the potential for equipment and site reuse requires the adoption of a stepwise approach by:

(a) Identifying resources and facilities, material or equipment suitable for recycling or reuse at the site;
(b) Assessing the markets and opportunities for reuse;
(c) Removing or reallocating equipment or buildings for alternative use;
(d) Restoring the landscape, amenity or functional value of an area of land so that it can be redeveloped.

In order to maintain cost effectiveness it is necessary to limit cleanup targets to levels compatible with the planned future site use [35]. Furthermore, limiting the extent of physical dismantling and decontamination work to structures that will not be reused will minimize expenditure. An early

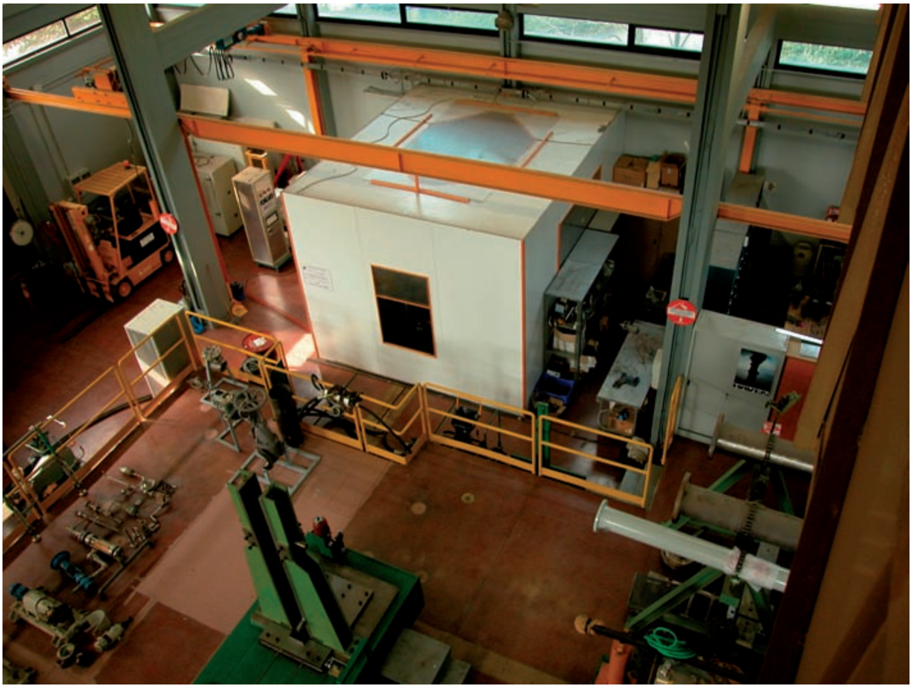

FIG. 11. The Montecuccolino RB-2 reactor after decommissioning and conversion to a mechanical test workshop.

identification of the decommissioning end point, based on the planned site use, will allow the maximum redevelopment potential to be realized. The site may then be transformed into new industrial, commercial, recreational or residential property, possibly with some portions of the facility with functional value retained, and structures and equipment being retained and reconfigured for the new purpose. Ownership of the site would be transferred after the elimination of radiation and other hazards consistent with the protection of human health and the environment, the cleanup goals being set by the proposed new use of the site. An added social advantage is that new economic activity replaces economic activity lost by closure of the facility in question.

Experience in site reuse is presented in Ref. [22]. One case of interest was the Risley research reactor in the United Kingdom. In the course of decommissioning, the site was marketed and eventually sold in 1996 for use as distribution warehouses. The proceeds from the sale represented about 60% of the cost of decommissioning and delicensing [90]. Another case was the RB-2 reactor at Montecuccolino, Italy, which was converted to a mechanical test workshop (Fig. 11). The FR 2 reactor at the Karlsruhe Research Centre in

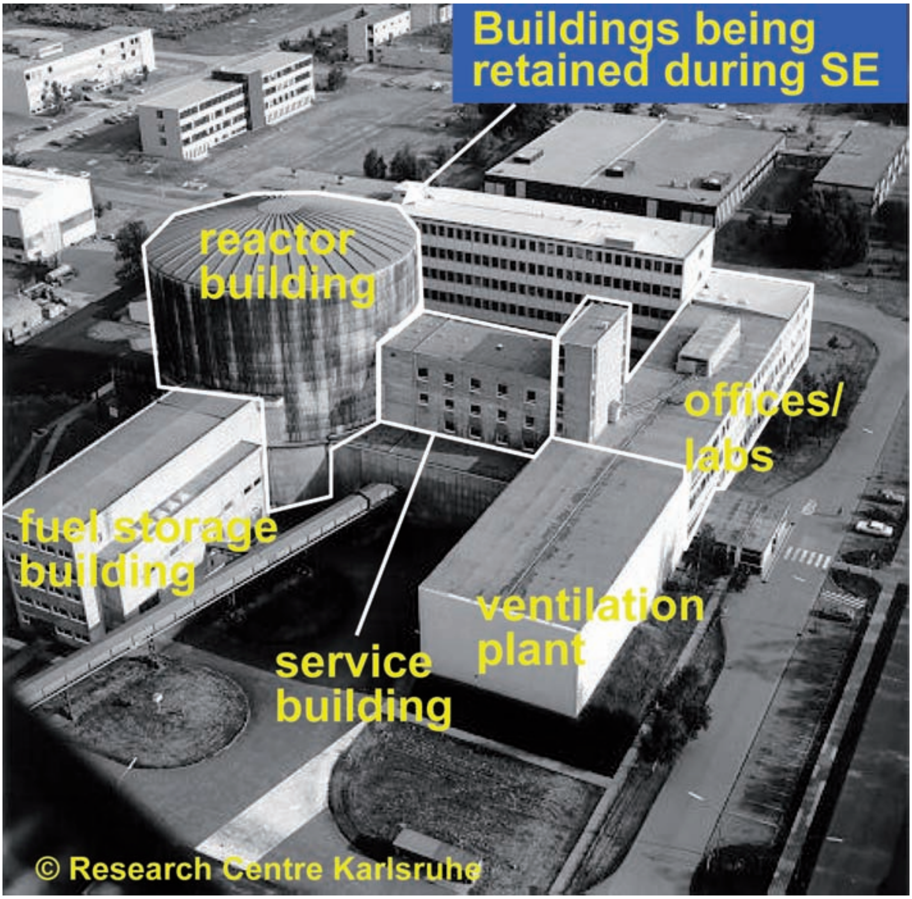

FIG. 12. The FR 2 reactor at the Karlsruhe Research Centre — buildings in safe enclosure.

Germany was converted to a museum pending radioactive decay and eventual dismantling (Fig. 12).

6. CONCLUSIONS

The decommissioning of research reactors and other small facilities is readily achievable. It requires adequate planning, the use of commonly available technologies and methods and the effective management of project delivery.

Decommissioning of such facilities may be made more difficult due to limitations in the availability of the necessary resources. The resources required for decommissioning are varied in nature and go beyond simply numbers of people or amounts of available funding. Experience gained in the wider decommissioning industry needs to be applied in a fit for purpose and cost effective manner, utilizing the resources that are available.

The size of a small facility, or the absence of a local or national nuclear industry, can mean that all necessary resources are not present. Where this has been recognized in the amount of funds provided for the decommissioning, allowance will have been made to make the necessary infrastructure investments and/or purchase support from contractors.

In many States or institutions such an approach will not be possible. Where funds to procure support are very limited they should be used where they have the greatest impact — usually in strategy selection and other similar front end activities. International support, for example from the IAEA, can be a means to build local capability in decommissioning issues and in being an informed purchaser.

Staff numbers at smaller facilities are inevitably relatively low. Where financial resources are limited there are advantages in retraining staff so that their new skills, coupled with their knowledge of the facility and its history, can be applied to decommissioning.

However, the project delivery context of decommissioning requires different skills and behaviours to those commonly found in the operation of research reactors and other small facilities. It is essential that a project structure be established, led by a competent project manager, to guide all staff in the new task to hand.

A project on a hazardous site requires work to be performed in a safe manner within established procedures and other controls. These should be proportionate to the hazards, number of people and size of the project. The safety management, QA and other control systems and processes should be designed to be adequate for the task, and not simply brought across from a large scale decommissioning project such as that for a nuclear power plant. This will naturally lead to a more optimized use of limited staff and other resources.

The size and complexity of the project should be minimized. Simple manual methods should be used where they can be used safely and cost effectively, and costly and complex automated and robotic applications should be avoided where at all possible. The end point should be defined to suit the future plans for the site, and more work should not be carried out just because it is possible. Equipment and other material arising should be reused or recycled to minimize the demands on radioactive waste disposal facilities, while recognizing that the cost of processing facilities and techniques may not be justified where there are only small quantities of material involved.

Whereas the achievement of decommissioning with limited resources is a laudable aim that should be pursued, regulatory compliance and safe ways of working remain essential. Decommissioning tasks should not be undertaken where resources are insufficient to deliver the necessary standards of safety.

Appendix

CHECKLIST FOR TECHNOLOGY SELECTION

General:

(1) What has the predecommissioning characterization survey shown in terms of radiation and contamination fields? What level of technology is suggested: fully remote, semiremote or manual (hands-on)?
(2) What is the scale of the decommissioning problem? Are the tasks to be performed ‘one-off’, small in scale or do they entail multiple, repetitive tasks where an economy of scale approach will repay investment costs by using specialist, commercially developed equipment?
(3) What are the safety implications of use of the technology? What is the estimated dose uptake in man-Sv for its deployment on the selected task and associated maintenance regimes?
(4) Is the local operator base adequately skilled to deploy and support the technology selected?
(5) What are the waste management implications of the technology? How much secondary waste will be produced? Is the equipment capable of being decontaminated cost effectively so that it can be reused or does it have to be committed to a waste stream?
(6) What are the conventional safety concerns associated with the equipment?

For in-house developed technology:

(1) Is the local skill base capable of producing a solution to the problem?
(2) Can existing equipment be adapted cost effectively for the decommissioning purpose?
(3) Would in-house developed technology be useful for other projects? Is there merit in development for wider application by developing a skill base?

For commercial equipment:

(1) How does the cost of commercial technology compare with a possible in-house developed solution?
(2) How does the cost effectiveness of the technology compare with that of other competing technologies?

(3) Can the technology be reused elsewhere or project costs shared with another project?
(4) Does the commercial technology have a proven track record in the particular application selected? What is the experience of others and can they be consulted?
(5) What is the anticipated serviceability of the technology? What are its failure modes? What dose would be incurred from routine and breakdown maintenance?
(6) What support from the supplier is available locally in the event of operational difficulties? At what cost?

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CONTRIBUTORS TO DRAFTING AND REVIEW

Abramenkovs, A.	State Hazardous Waste Management Agency, Latvia
Allcock, C.	British Nuclear Group, United Kingdom
Benitez-Navarro, J.C.	Centre for Radiation Protection and Hygiene, Cuba
Boing, L.E.	Argonne National Laboratory, United States of America
Cato, A.	Tekedo AB, Sweden
Cornejo, N.	Centre for Radiation Protection and Hygiene, Cuba
Cross, M.T.	United Kingdom Atomic Energy Authority, United Kingdom
Dadoumont, J.	Belgian Nuclear Research Centre (SCK•CEN), Belgium
Fasten, W.	QSA Global GmbH, Germany
Harriague, S.	National Atomic Energy Commission, Argentina
Hryczuk, A.	Institute of Atomic Energy, Poland
Laraia, M.	International Atomic Energy Agency
Le Goaller, C.	Commissariat à l'énergie atomique, France
Lindskog, Staffan	Tekedo AB, Sweden
McIntyre, P.J.	International Atomic Energy Agency
Negin, C.A.	Project Management Corporation, United States of America
Oelgaard, P.	Danish Decommissioning, Denmark
Podlaha, J.	Nuclear Research Institute Řež, Czech Republic

Rao, D.V.H.	Bhabha Atomic Research Centre, India
Selgado, M.	Centre for Radiation Protection and Hygiene, Cuba
Sjöblom, R.	Tekedo AB, Sweden

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There are large numbers of research reactors and many more small facilities utilizing radioactive material worldwide, some of which are coming to the end of their operating lives and will require decommissioning. This report provides guidance on the safe and efficient decommissioning of such facilities by: providing practical and specific guidance to assist in the planning and implementation of the decommissioning of small facilities in which radioactive material has been used; guiding the development of a decommissioning strategy, making optimal use of available resources; encouraging a timely, well planned approach to decommissioning; and evaluating decommissioning experiences and refocusing these towards a pragmatic approach meeting the needs of countries and institutions with limited local resources.

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