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Considerations on Decommissioning in the Design and Operation of Research Reactors

CONSIDERATIONS ON DECOMMISSIONING IN THE DESIGN AND OPERATION OF RESEARCH REACTORS

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FOREWORD

In the early days of nuclear research reactors, the design and operation of various reactor systems was given much attention. However, very little consideration was given to decommissioning. In fact, the decommissioning of large research reactors or even small research facilities has proven to be more challenging than anticipated. It has been expensive, time consuming and to some extent hazardous, and has generated considerable amounts of radioactive waste.

The transition from an operating nuclear facility to the implementation of ‘end of life’ activities is a critical stage. Several organizational and technical modifications are needed to ensure that the facility can meet the decommissioning objectives and requirements during the transition period. A variety of activities need to be planned and performed both to implement the transition and to prepare for the decommissioning of the facility. Experience has shown that it is essential to start with preparations for decommissioning as early as possible, ideally during the design stage of the facility or at least during operation. Planning is the key to minimizing delays and undue costs, optimizing personnel and other resources, and initiating preparatory activities in an organized, timely and cost effective manner, with the overall objective of ensuring a safe and efficient decommissioning process.

The purpose of this publication is to provide practical guidance and information on decommissioning aspects for designers and operators of research reactors.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

According to data available in the IAEA Research Reactor Database (RRDB) [1], 840 reactors and critical and subcritical assemblies have been built in 70 countries for civilian applications.

By July 2024, 226 research reactors worldwide were in operation, 12 were under extended shutdown, 54 were under permanent shutdown awaiting decommissioning, and 69 were undergoing decommissioning. For a few research reactors under extended shutdown, there were plans to restart operation, but for the majority of them and for those under permanent shutdown, clear plans for their future do not exist. Additionally, around 70% of the operating research reactors are over 40 years of age and will soon become candidates for decommissioning.

Several IAEA publications encourage Member States to identify and implement good practices during operation to plan and facilitate decommissioning in accordance with the IAEA safety standards. Issues need to be managed effectively by Member States to ensure that research reactors are adequately prepared (and documentation is up to date) before dismantling and demolition activities are initiated [2, 3].

The characteristic variations of research reactor properties in the design, materials used for construction, size, power level, history of utilization and experimental facilities, in addition to modifications of the original designs during the operating lifetime, pose unique technological challenges for decommissioning. Furthermore, the complexity of the decommissioning processes presents serious concerns relating to the adequacy of safety documents, operation and maintenance (O&M) of systems and components, radiation protection programmes, characterization of the facility, and of training and qualification of personnel, and requires knowledge sharing and good technical documentation.

For many research reactors, preparations for decommissioning need to be improved and strengthened during the operation stage. This includes an effective management system, assurance of the necessary funding, configuration management, records keeping, specific maintenance activities, modification and operating procedures, experimental facilities, characterization methods and training programmes, as well as research and development (R&D) activities on specific materials to be used.

The participants of an IAEA workshop on the topic of decommissioning planning, held in August 2018 [4], recommended preparing a technical publication on good practices during the operation stage that would facilitate decommissioning. The Technical Working Group on Research Reactors

(TWG-RR) recommended that the IAEA continues supporting Member States in preparing research reactors for the decommissioning stage [5]. This also applies to current and expected refurbishment and modification projects of existing facilities as well as to the design of experimental facilities.

The IAEA has issued several publications on topics relating to the transition from operation to decommissioning of nuclear installations in general (see, for example, Ref. [6]) and the decommissioning of research reactors with an emphasis on the optimal use of resources (see Ref. [7]). This publication complements existing resources that provide guidance to Member States on the preparation for decommissioning during the design and operation stages. It also proposes modern tools to help manage the transition from operation to decommissioning.

1.2. OBJECTIVE

The purpose of this publication is to provide guidance on considerations relating to decommissioning during various stages of a research reactor's lifetime, including how to manage the transition from operation to decommissioning, which in many cases extends to several decades. The guidance provided in this publication on how to prepare for and facilitate decommissioning is based on good practices, examples and lessons learned.

Guidance and recommendations provided here in relation to identified good practices represent expert opinion but are not made on the basis of a consensus of all Member States.

1.3. SCOPE

This publication covers various factors that need to be considered during the design and operation of research reactors and during the transition period in preparation for decommissioning. The publication addresses the considerations to be taken into account during the initial stages of the facility, such as construction, and during ongoing operating activities, such as maintenance. Furthermore, it covers regulatory and management aspects relating to these topics. The practical guidance and information provided in this publication is intended for use by individuals and organizations responsible for the design and operation of research reactors, regulatory bodies, technical support organizations and other interested parties.

1.4. STRUCTURE

The publication consists of six sections, three appendices and four annexes. Section 1 presents a brief background and the objectives, scope and structure of the publication. Section 2 presents guidance on considerations for decommissioning during the early design and construction stages, and Section 3 presents guidelines on the considerations for decommissioning during operation of the research reactor. Section 4 provides guidance on managing the transition period from operation to decommissioning, while Section 5 provides typical regulatory considerations (e.g. the licensing process and oversight during extended shutdown and during the transition from operation to decommissioning). Finally, Section 6 presents the aspects relating to leadership and management considerations, relevant for this stage, followed by the appendices. The annexes present case studies of the preparations for decommissioning activities at facilities in selected Member States.

2. CONSIDERATIONS ON DECOMMISSIONING DURING DESIGN AND CONSTRUCTION

2.1. GENERAL

Considerations on decommissioning of research reactors refer to a variety of designs (e.g. TRIGA, pool type, tank type, tank in pool type) and a spread of nominal thermal power, from subcritical assemblies up to a few hundred megawatts. Moreover, the facilities are intended for different uses, which may include radioisotope production, neutron beam tubes, neutron activation analysis, neutron transmutation doping, medical therapy, fuel and material testing, validation of numerical tools and codes to perform reactor simulations, as well as the education and training of operators and students. Therefore, the construction and operation of a research reactor, whether large or small, involves interrelated disciplines and various configurations. The disciplines range from complex technical design and construction techniques, radiation protection, predisposal management of spent fuel and radioactive waste and disposal options up to environmental considerations and national policy [8].

Two requirements in IAEA Safety Standards Series No. SSR-3, Safety of Research Reactors [3], refer to the design for decommissioning of research reactors:

— Requirement 15: Features to facilitate radioactive waste management and decommissioning states that "**Special consideration shall be given at the design stage of a research reactor facility to the incorporation of features to facilitate radioactive waste management and the future decommissioning of the facility.**"
— Requirement 33: Design for decommissioning states that "**Decommissioning of a research reactor facility shall be considered in the design for the research reactor and its experimental facilities.**"

Paragraphs 6.92 and 6.93 of SSR-3 [3] list the considerations for meeting these requirements (reference omitted):

"6.92. In the design of the research reactor and its experimental facilities and in any modifications of them, consideration shall be given to facilitation of decommissioning. In accomplishing this, the following shall be considered:

(a) The selection of materials so as to minimize activation of the materials with regard to decommissioning and radioactive waste management and to provide for easy decontamination;
(b) Optimizing of the facility's layout and access routes to facilitate the removal of large components and the detachment and handling (remotely where necessary) of activated components;
(c) The predisposal management of radioactive waste (i.e. pretreatment, treatment, conditioning and storage of waste arising from operation and decommissioning of the reactor).

"6.93. Full details shall be retained of the design requirements and of information relating to the site and its final design, construction and modification, such as the 'baseline' radiological characterization, as built drawings relating to the facility's layout, piping and cable penetrations, as information necessary for decommissioning."

Furthermore, notwithstanding the type and size of the research reactor, each reactor is to be decommissioned at the end of its operating lifetime, and for this reason decommissioning needs to be considered by the designers of the reactor. A good practice would be to have the design reviewed by experts in decommissioning activities to ensure that provisions in the design will facilitate decommissioning.

2.2. DESIGN FEATURES TO FACILITATE DECOMMISSIONING

A research reactor with sufficient and well thought out features for decommissioning will need fewer resources and less time and will encounter fewer technological challenges than a reactor without considerations for decommissioning in its design. Research reactor design is primarily driven by the reactor's applications and utilization programmes; most research reactors combine several uses to meet the business programme.

Features to facilitate decommissioning were generally not considered in the research reactors that were designed and built several decades ago; decommissioning was seen as an activity that would happen far into the future and performed by a next generation of personnel. However, with the evolution of the IAEA safety standards, regulatory control and relevant social factors, awareness is increasing to take decommissioning into account at the design stage itself, to the extent possible, without compromising the safety and reliability of the research reactor.

Reference [8] compiles lessons from decommissioning and remediation projects of nuclear facilities up to 2010 and provides information on the design related lessons identified. Some of these considerations are developed in the following paragraphs:

- Initial identification of structures, systems and components (SSCs) that are likely to become activated or contaminated and thereby give rise to radioactive waste;
- Easy access for component disassembly and removal;
- Inclusion of barriers to prevent release of contamination;
- Adaptation of auxiliary facilities and services, such as electricity and ventilation systems, and the assignment of areas of the facility for activities not frequently performed during operation (e.g. disassembly, decontamination);
- Provisions to ensure that external non-nuclear systems and services do not become contaminated.

Consideration needs to be given to the design of items, such as active drains or pipes, that might pass through conventional non-active areas (i.e. piping radioactive liquids across the site needs to be minimized or avoided). Nevertheless, if such pipes are required, they have to be double contained with monitoring and leak detection. In any case, active and non-active drainage systems need to have a clear separation.

Some facility design factors will have cost and programme implications for design and construction as well as for operation and reliability, and these may tend to push the design in opposite directions. For example, providing desirable features for decommissioning may conflict with optimum performance criteria and/or functional design for operation. Examples include the use of modular shielding, improvement of access provided specifically for final dismantling, provision of special features in pipework layout (e.g. design to avoid radioactive crud deposition) and the minimization of embedding items in walls and floors. Potential radiation doses from unshielded SSCs have to be addressed in the design itself.

Provisions that directly help during decommissioning are the following:

(a) Designing structures for long term integrity;
(b) Containing and monitoring spills and releases of radioactive materials;
(c) Avoiding transport of contaminants.

A clean-up criterion at the end of the operating lifetime and during decommissioning has to be considered during the design, and necessary provisions have to be available. Consideration has to be given to all possible features and a record made of their disposition [9]. For future facilities, especially on new sites, the goal of design for decommissioning might be to permit dismantlement several decades earlier, without protracted safe enclosure [10], and the ultimate free release of the site.

The inclusion of persons with a previous professional background in decommissioning and waste management in the teams for design and procurement is a method of ensuring that beneficial features are incorporated in new designs. The tables in Appendix II and III highlight the detailed features that provide an important tool for this process. Additionally, training on decommissioning concepts for key participants in the process, such as designers and policy makers, is essential. In particular, States investing in the first research reactor need such training and access to experts to ensure all aspects of decommissioning and associated radioactive waste management are properly considered. Training is available from international organizations (e.g. the IAEA).

The design of SSCs needs to aim at minimizing the holdup and deposition of radioactive liquids, gases and particulates. SSCs have to be designed, as much as possible, to avoid stagnant points, bends and pockets where activity can accumulate. Moreover, sufficient access to and provision for removal of radioactive liquids and gases and radioactive particulates may also be incorporated in the design of the SSCs.

There may be instances where the judicious use of remote equipment is the best solution. Therefore, the use of remote handling techniques to remove active items might be considered and suitable provisions be made in the design for their later application.

In conclusion, early design considerations for decommissioning might include the following aspects:

- Provisions for the handling and storage of decommissioning waste at the site;
- Provision of facilities for characterization, decontamination and dismantling;
- Provision of easy decontamination surfaces during operation;
- Provision of early leak monitoring and detection systems to prevent the spread of contamination;
- Provision and access of material handling devices such as cranes for the easy removal of SSCs and the possible use of remote cutting or use of robotics;
- Use of modular designs;
- Optimization of SSC design to avoid excessive use of materials such as shielding;
- Minimization of penetrations and crevices in which contaminants can be trapped;
- Minimization of the creation of cracks or flaws in which contaminants can be trapped, by selecting materials in SSCs in accordance with the mechanical and chemical stresses that they are expected to undergo throughout their operational lifetime;
- Provisions for the implementation of an effective maintenance and ageing management programme.

2.3. INITIAL DECOMMISSIONING PLAN

Design for decommissioning is an important concept for a broad range of interested parties, including policy makers, designers, vendors, constructors, prospective owners, operators and regulators. Planning that addresses the entire lifetime of a facility is suggested. A key element of this planning is the initial decommissioning plan, which has to be prepared at the commencement of design work in order to record the outline strategy and all relevant design aspects and features beneficial to later decommissioning [8].

An initial decommissioning plan should take into account potential decommissioning strategies, ideally opting for immediate dismantling following the final shutdown, contingent on the availability of waste repositories. The recognized decommissioning strategies being considered by different countries are:

— Immediate dismantling after the final shutdown;
— Deferred dismantling (i.e. engineered safe enclosure for a specified period, followed by the final dismantlement);
— A combination of both strategies.

The factors to be considered can be grouped into the following three categories [11]:

(a) Policy and socioeconomic factors;
(b) Technological and operational factors;
(c) Long term uncertainties.

Evaluating these factors is particularly challenging, especially over extended periods. Given the variability in policies, different strategies are often chosen for similar facilities. For example, decisions, such as those regarding the availability of qualified staff, are heavily influenced by policy and this can support the argument for immediate dismantling after shutdown. Conversely, the absence of a repository for decommissioning waste might justify delaying decommissioning and maintaining a nuclear facility in safe enclosure until a repository becomes available. More commonly, deferred dismantling results from insufficient financial resources. However, immediate dismantling tends to facilitate a smoother transition and is generally more acceptable to the public, as deferral could lead to facility abandonment and compromised safety and security [11].

The selection of a decommissioning strategy during the design stage is important because it will have a direct impact on the proposed method of dismantling and, consequently, on the total cost. Many facilities are now being designed and licensed for operating lifetimes of up to 60 years, and when considering a safe enclosure option, the integrity of the containment enclosure system may need to be maintained for well over 100 years. Even if the immediate dismantling strategy is adopted, the entire design life required for structures, the containment system and safety components could be 70 years from the date of first criticality [8].

While a preferred decommissioning strategy has to be selected during the design stage of the reactor, it needs to remain flexible to adapt to changing circumstances. Nevertheless, future release from regulatory control after permanent shutdown, along with site clearance and site reuse, may be also considered during the planning and the design stage, to create a basic time frame. Guidance on how to refer to these periods can be found in several IAEA publications — see IAEA Safety Standards Series Nos SSG-47, Decommissioning of Nuclear Power Plants, Research Reactors and Other Nuclear Fuel Cycle Facilities [12], WS-G-5.1, Release of Sites from Regulatory Control on Termination of Practices [13], and GSG-17, Application of the Concept of Exemption [14].

2.4. SELECTION OF MATERIAL

In reactors, the elements that are present in construction material will be activated in a neutron flux. Minimizing the amount of activation products, particularly the long lived ones, is a major consideration, with an emphasis on minimizing exposure to operators and facilitating maintenance, which also facilitates decommissioning.

As an example, the use of commercial stainless steels containing ^{60}Co as a structural material for research reactor cores increases the quantity of long lived activation products. A design effort minimizing such trace elements in the SSCs exposed to neutron flux is required.

Owing to the low absorption of thermal neutrons, research reactors often use aluminium and its alloys in high radiation areas. This has a distinct advantage of avoiding the generation of long lived activation products, which facilitates decommissioning and management of the resulting waste. One approach could be to specify the maximum quantity of trace elements such as cobalt that give rise to long lived activation products. The designer may have to trade off the material properties required for safety and durability against facilitating decommissioning. For example, the use of stainless steel in a high neutron flux region (such as the structural material of the reactor vessel) cannot be avoided in some cases. Therefore, it is beneficial to keep samples and records of the composition of structural materials, including concrete composition and metals used for construction, as knowledge of impurities is necessary for estimating the radiation dose due to activation after long periods of irradiation during the reactor lifetime. Initiatives to continue the reduction of activation products and other hazardous materials in modifications and the design of new experimental facilities are suggested, but may pose difficult trade-offs involving additional costs, effects on operating life and system performance. Important considerations in meeting this objective include decay times, dose rates, total waste volumes, disposability and conventional health and safety. It is also important to select materials that minimize or resist corrosion and facilitate later decontamination. An example is the smooth metal lining of concrete tanks and sumps, which may contain potentially active fluids.

2.5. LAYOUT CONSIDERATIONS

Layout considerations are important in the general design approach. These include aspects such as easy access to the relevant SSCs and the physical separation of areas according to their radiological hazard. This will facilitate decontamination and possible segmentation or even the one piece removal of large active or contaminated SSCs as part of the dismantling process. If one piece removal is identified as useful in the design stage, pathways large enough for the removal of bulky material or components such as heat exchangers during decommissioning might be planned. Transport planning might be simplified by including airlock size to accommodate transport vehicles carrying this material. Therefore, the use of potentially radioactive tanks, vaults and sumps that are difficult to access (e.g. underground tanks) needs to be limited.

Site layout considerations have to include placement of on-site waste storage facilities to be used during dismantling operations, as well as provisions for interim storage of the spent fuel if it cannot be removed from the site immediately.

2.6. CONSIDERATIONS ON DECOMMISSIONING IN CONSTRUCTION

The following construction features may facilitate future decommissioning:

(a) Quality of technology and building surface finishes or coatings;
(b) 3-D modelling to support the construction process;
(c) Photographs and videos of as built SSCs;
(d) Design and installation of SSCs to minimize the deposition of activation products;
(e) Preserving samples of the material used for construction as well as physical characterization of SSCs;
(f) Modular construction.

Regarding features (a), (b) and (c), it is important to highlight that during the construction stage, many engineering details not properly addressed in the design drawings are generated. They normally relate to unexpected situations such as layout interferences; modifications applied during construction; and errors or details not fully addressed by sketches or drawings of the installation that need to be resolved at the site (e.g. joints, routing of cables and/or piping, layout of equipment, unmarked welds, supports, spacers). In many cases, details are hidden or covered by further works (e.g. embedded in concrete, shielding, structures or behind large equipment making them inaccessible during the O&M phase). Keeping 'as built' records, photographs and videos taken during installation is considered of vital importance for further analysis and decision making during preparation for decommissioning.

Considering the specific feature (d), problems occur at regions of low fluid flow and at low velocity areas or 'inverts' where deposits can build up and become hot spots. Changes of piping cross-section and pipe junctions can result in the build-up of deposits. Where invert sections of pipes and ductwork and junctions are unavoidable, consideration has to be given to drainage connections and inspection covers. Sludge deposition can be exacerbated (e.g. by solidifying in pockets in the pipework) when facilities are shut down for long periods or when they are finally shut down and there is a delay in the start of decommissioning [15].

Considering the specific feature (e), samples of the original structural material that is likely to be activated or contaminated would help in working out the radioactivity inventory and radiological characterization of the site, as well in estimating the operating life of the facility.

Considering the specific feature (f), difficulties in the removal of large, contaminated items by dismantling can be addressed by using design and construction in modular form. However, modular construction is likely to be more costly and may reduce reliability or integrity if prone to leakage or other faults. Therefore, certain trade-offs need to be considered.

3. CONSIDERATIONS ON DECOMMISSIONING DURING OPERATION

3.1. GENERAL

Key considerations in the preparation for decommissioning during operation include making appropriate arrangements to ensure that SSCs necessary to be in operation during decommissioning activities remain available and functional. This consideration needs to be incorporated in the ageing management programme of the research reactor, in accordance with IAEA Safety Standards Series No. SSG-10 (Rev. 1), Ageing Management for Research Reactors [16]. Examples of such SSCs include means of confinement, radiation monitoring equipment, long term cooling systems, lifting equipment and condition monitoring equipment.

3.2. CONFIGURATION MANAGEMENT

Configuration management is an important aspect of research reactor operation and is essential for the transition period to decommissioning [17]. Configuration management consists of:

- Design requirements or technical requirements derived from the applicable codes, standards, and regulatory requirements and design specifications of SSCs that describe what needs to be in the facility. In some early-era research reactors, the design basis or design requirements for many of the SSCs might not be available. In such cases, prior to the final shutdown, it is necessary to reconstitute the design basis for a configuration management system.
- Updated physical configurations of SSCs, in as built state, that have to meet the design intent.
- Configuration documents that describe how the facility was designed, constructed, operated and maintained and that contain all the information to indicate the current state of the SSCs. The documentation can be categorized according to facility processes (e.g. design, operation, maintenance, modifications, procedures, databases, training, procurement).

For research reactors with a long operational history, records pertaining to past experiments need to be retained. Similarly, records of experimental facilities that have been partially dismantled or removed from the site need to be retained.

Activities for dismantling SSCs are often the activities for their installation in reverse order. Clear records, including video footage and photographs in different stages of installation, are very useful for planning dismantling activities.

Configuration management includes changes in the design requirements, if any become necessary (and accordingly any changes in the physical configuration of the SSCs) and is reflected in the facility configuration documentation. Such changes in the design requirements may arise for several reasons, including changes in the safety requirements, regulations or licensing basis, results of periodic safety reviews, ageing management or new requirements from the initial decommissioning plan.

In a research reactor, it is common for equipment to be modified during the operating lifetime. These modifications may include the introduction or withdrawal of experimental facilities, which could be attributed to shifts in the utilization programme, equipment becoming outdated, changes in measurement devices, or enhancements to the instrumentation and control (I&C) systems.

The objective of configuration management is essentially to maintain the consistency between the design requirements, the physical configuration and the documentation.

The management process needs to include modification and change control to ensure that physical configuration is correctly reflected in the records. Configuration management has to identify the factors that could affect the decommissioning of the research reactor, such as radiation hot spots, radiation spills, SSCs removed from service or new additions or changes to existing SSCs. The transition period from operation to decommissioning poses challenges to configuration management as some of the SSCs remain operational while others are non-active or removed, resulting in continuous configuration changes. Therefore, records of the physical configuration of the facility, including records of the experimental facilities, have to be kept and always updated to demonstrate the current configuration.

3.3. MAINTENANCE, SURVEILLANCE AND AGEING MANAGEMENT PROGRAMME

Most of the provisions for an effective maintenance programme, such as ease of access, ease of replacement and adequate handling of equipment and tools, also aid in the transition to decommissioning process. The maintenance and monitoring processes in a research reactor consist of work procedures, checklists, data collection and observations on various activities during operation. The experience gained during the maintenance activities is useful for the eventual transition to decommissioning. The format and content of maintenance procedures, such as the removal of equipment from the facility and its transport to a maintenance workshop for overhauling or its removal from service for disposal, would be similar to the procedures prepared for the final shutdown. Although the objectives are different, the maintenance procedures used for the transition to decommissioning could be modified to suit the new objectives. Procedures for maintenance activities should take into account that the SSCs will eventually need to be decommissioned. Therefore, they should be modified in a way that facilitates a more straightforward and smoother process in the future.

The following points need to be considered:

— The spread of contamination has to be kept to a minimum by controlling any spillages, zoning the radiation areas, making decontamination facilities available, avoiding cross-contamination between different zones and checking and decontaminating SSCs that are possible to decontaminate. The overriding aim of decontamination during operation of the research reactor is to minimize the amount of radioactive waste arising from decommissioning. The decontamination process could be different for regular maintenance activities during operation, when SSCs need to be preserved to deliver their function, while at decommissioning, SSCs will be disposed of. This difference could allow the use of harsher chemicals or alternative decontamination processes.

— The use of tools for maintenance and how they can be adopted for decommissioning.
— The maintenance programme has to take into account that some of the SSCs will stop functioning once the decision is made to permanently shut down the research reactor. Some SSCs will need to be kept in operation for a while longer before they are taken out of service, while other SSCs need to continue in service until the end of the decommissioning process. Therefore, a programme that includes the frequency of preventive maintenance and condition monitoring, spare parts management and SSC replacement needs to take the required life of SSCs into account. Moreover, as the 'recycle and reuse' principle reduces the amount of waste to be managed, a good maintenance programme has to take this into account and earmarks the SSCs that are considered for this principle.
— The ageing management programme has to include appropriate arrangements to ensure that the equipment and SSCs required to perform the decommissioning activities (e.g. means of confinement, radiation monitoring, long term cooling, lifting equipment, condition monitoring equipment) remain available and functional [15].
— Maintenance procedures need to identify information that is relevant to the period of transition from operation to decommissioning. A mechanism has to be developed and implemented to retain such information for future use by the decommissioning team, which could be different from the O&M team. Records can include the facility's logbooks, equipment history cards and maintenance reports that cover key observations, video footage and photographs that could be used for training and future decommissioning of the facility.

3.4. MODIFICATIONS, REFURBISHMENT AND MODERNIZATION

One of the major challenges faced by many States is the decision on whether to take up a large refurbishment and modernization project for long term operation or to move towards the final shutdown of the research reactor for decommissioning. To arrive at an appropriate decision in this case, a cost–benefit analysis that considers both options, together with the expected life extension and the State’s strategic planning, is necessary. Currently, most research reactor operating organizations are likely to perform modifications and refurbishments and undertake modernization projects to secure services for users and stakeholders in the medium term. The reasons for refurbishment or modernization, as concluded from SSG-10 (Rev. 1) [16], could be to overcome obsolescence, changes in the utilization plans or in the safety requirements or regulations, or to extend the operating life of the research reactor for a reasonable cost. These projects might be very diverse in nature and may take up to several years.

Most modification, refurbishment and modernization projects involve partial decommissioning processes. During these projects, a few SSCs are removed from service and deconstructed, generating both conventional and radioactive wastes. The explicit details, as-built drawings, records and experience from such projects, especially the lessons identified, need to be clearly documented and preserved as input for future decommissioning plans. These projects are also useful in adjusting the cost estimates for the decommissioning projects. The challenges faced during the execution of the modification, refurbishment and modernization projects compared with the original plan, and their impact on the time and cost, would provide a more realistic estimate for the decommissioning project. When designing a new SSC as part of a modification, refurbishment or modernization project, considerations on decommissioning need to be included. Considerations on configuration management of SSCs were elaborated in Section 3.2.

Refurbishment and modernization projects involving fuel unloading provide opportunities to conduct radiation mapping of all SSCs, in particular in the region of the research reactor core [17]. This information is very useful in the transition period to decommissioning since the radiation levels are estimated on the basis of the activation of the core components, which consider the material composition including impurities and fluence levels. Measurements of gamma radiation levels can provide more realistic predictions for future decommissioning. These measurements can be complemented with radiochemical analyses in laboratories to validate the assessment.

3.5. UTILIZATION AND EXPERIMENTAL FACILITIES

Experimental and irradiation facilities usually included in the design of a research reactor are radioisotope production facilities, neutron activation analysis, beam tubes, irradiation loops for material and fuel testing and special facilities such as for hot or cold neutron source or for boron neutron capture therapy. In addition, a research reactor may be linked with auxiliary facilities located outside the reactor building but at the site, such as hot cells, laboratories, post-irradiation examination facilities, radioisotope separation plants, and to external equipment such as spectrometers. During operation of the research reactor, new experimental facilities may be added and existing facilities could be removed or not further used owing to changes in the utilization plans. Therefore, it is necessary that future decommissioning processes are considered during operation for all experimental facilities and their auxiliaries, in the same manner as for SSCs. Thus, all considerations taken for the future decommissioning of a new experiment or facility need to be included in the safety analysis report prepared for obtaining the corresponding licence.

Information regarding radiation or contamination hot spots in the experimental facilities has to be properly documented for future reference, with a clear definition of location, levels of radiation fields and radiological characterization. Such information is useful when preparing for the decommissioning of these facilities.

3.6. RADIATION PROTECTION PROGRAMME DURING OPERATION

The operational radiation protection programme has to consider that the facility will be decommissioned in the future. Therefore, the principles of operational radiation protection, such as optimizing and limiting the dose to site personnel and the public and establishing secondary dose limits for normal operating and incidental conditions, need also to be evaluated regarding the planned decommissioning activities.

Moreover, many measures to optimize the dose to workers, including selecting material to minimize activation products, radioactive waste and the spread of activated corrosion products, and measures to ease decontamination also aid in facilitating decommissioning (see IAEA Safety Standards Series No. SSG-85, Radiation Protection and Radioactive Waste Management in the Design and Operation of Research Reactors [18]). Furthermore, the operational radiation protection programme has to consider the following:

- Layout of and access to SSCs;
- Facilitating the dismantling of activated components, if necessary using remote tools;
- Installation of equipment for decontamination and dismantling;
- Equipment that will need decontamination during decommissioning and dismantling;
- Decontamination techniques for SSCs (noting that decontamination techniques for decommissioning could differ from techniques used during operation as harsher chemicals could be used);

— Equipment that could be decontaminated in-situ or that needs to be moved to a decontamination facility;
— Whether decontamination could be performed in an existing decontamination facility or if a new decontamination facility will need to be constructed for decommissioning;
— Transport routes and handling arrangements for equipment that need to be moved for decontamination, including shielding casks or other shielding arrangements;
— Type, size, material and space for temporary shielding needed during decommissioning;
— Records of the operational programme, in particular from events registering unusual radiation levels;
— Records of spills or incidents causing spread of contamination;
— Zoning and barriers with a view to minimizing cross-contamination.

3.7. RADIOACTIVE WASTE MANAGEMENT DURING OPERATION

Research reactors usually have an interim storage facility for solid and liquid radioactive waste generated within the facility. At large organizations or sites with multiple nuclear facilities, medium and long term waste management is generally conducted by separate staff. In all cases, a waste management policy needs to be in place to manage waste in all physical states and from all streams arising from the research reactor and associated facilities, such as radioisotope production and experimental facilities. Basic principles of radioactive waste management practices during operation will assist in future decommissioning. These principles include, but are not limited to, the following [19]:

— Minimization of radioactive waste;
— Use of material that does not produce radionuclides with long half-lives;
— Control of spillages to minimize both contamination and liquid waste;
— Minimization of the air space near the neutron source and dust in the air to reduce airborne and gaseous activity;
— Separation of active and non-active streams;
— Volume reduction;
— Recycling and reuse of radioactive and contaminated materials to the extent possible.

During the operating period, a number of provisions can be made to facilitate the future decommissioning of waste. These include earmarked space for the interim storage of solid waste; access routes; transportation of decommissioning waste from the research reactor to the storage area; material handling equipment; and collection, treatment and disposal of liquid waste that includes process fluids and liquid waste generated.

In the decommissioning plan, it is necessary to conduct an initial evaluation and characterization of the radioactive waste. This includes details such as its physical and chemical state, weight and volume, estimated radioactivity, and the specific radionuclides involved. This information, which is required shortly after the final shutdown, has to be periodically reviewed and updated throughout the operation of the research reactor.

Moreover, the radioactive waste estimate has to consider additional waste that will be generated as part of the decommissioning activities (e.g. contaminated tools used for dismantling, packaging material and containers used for storage). A typical radioactive waste estimate for a research reactor is likely to vary from low level to medium level and high volume waste categories and considers the transition to decommissioning.

3.8. MANAGING EXTENDED SHUTDOWN PERIODS

As defined in SSR-3 [3],

> "A research reactor in extended shutdown is one that is no longer operating, with no decision on its decommissioning, and where there is no clear decision about the future of the reactor as to whether it will be brought back into operation or decommissioned."

There are many reasons for extended shutdown, including the following [19, 20]:

(a) Lack of utilization and inability to carry out extensive repairs or major modifications or refurbishment;
(b) Lack of technical expertise and competency;
(c) Local, political, public or regulatory concerns;
(d) Lack of financial and/or human resources.

Extended shutdown periods should be minimized or avoided, as the staff becomes less motivated, retiring staff are no longer replaced, resources start shrinking and budget allocations could be curtailed. The management of the operating organization has to consider and ensure that, at a minimum, reactor SSCs important to safety are preserved and maintained until a clear decision is taken about the future of the facility.

Moreover, when an extended shutdown state is reached, management needs to review the situation, redefine the strategic and utilization targets and implement a plan to manage this period. Such a plan has to take into consideration:

- Organizational changes;
- Regulatory considerations (e.g. modifications of operational limits and conditions (OLCs) or relief from some safety requirements);
- Safety, security and safeguards of the existing fissile material;
- SSCs that need to remain operative;
- SSCs that can be removed from the facility;
- SSCs that will remain at the facility and need to be preserved;
- Implementation or revision of the ageing management programme, which covers all relevant SSCs including experimental facilities;
- Revision of the maintenance, periodic testing and inspection programme;
- Revision of the radiation protection programme;
- Solid and liquid waste management;
- Surveillance and monitoring programme, including associated instrumentation;
- Training and retraining of the staff to retain their competences;
- Knowledge management to ensure retention of design engineering information, facility documentation and O&M experience.

Examples of provisions to ensure that the status of the facility is maintained and does not deteriorate during the extended shutdown are:

- Maintaining water chemistry to control corrosion;
- Maintaining the storage environment to control external corrosion by controlling humidity, temperature, dust in air;
- Good housekeeping and periodic cleaning of the equipment;
- Continuing an appropriate maintenance programme;
- Periodic testing of key SSCs such as pumps, valves, cranes, compressors, fans, power supply, uninterrupted power supply and emergency systems.

In conclusion, after the final reactor shutdown, the management of the operating organization has to review the situation and periodically revise as necessary the plan to manage extended shutdown and make efforts to minimize it.

3.9. UPDATING THE DECOMMISSIONING PLAN

The operating organization should track and check regularly whether the decommissioning strategy is still appropriate or needs an update. During operation, the initial decommissioning plan will evolve into a more detailed plan through design completion, manufacture, construction and operation, with increasing details being incorporated in every iteration of the plan as the facility approaches its permanent shutdown and decommissioning. As stated in SSG-47 [12] and IAEA Safety Standards Series No. GSR Part 6, Decommissioning of Facilities [21], the plan "is required to be reviewed by the regulatory body periodically (typically every five years or as prescribed by the regulatory body), or when specific circumstances warrant".

Reasons that might necessitate updating the decommissioning plan during operation [12] include:

(a) Design or process modifications;
(b) Changes in financial conditions, funding assurance or funding requirements;
(c) Changes to relevant regulatory or safety requirements and criteria;
(d) A change of the selected decommissioning strategy and/or the planned end state;
(e) Commissioning of a radioactive waste disposal facility and availability of waste acceptance requirements or criteria for disposal;
(f) Feedback from operating and decommissioning experience, and technological developments;
(g) Extension of the research reactor's operating period;
(h) Changes in contractors and/or suppliers;
(i) Incidents, events or situations with relevant consequences for decommissioning, such as changes in the estimation of the radiological inventory;
(j) Modifications such as the addition of a major experimental device which would require regulatory authorization;
(k) Fuel conversion from high enriched uranium to low enriched uranium.

If the estimated volume and/or characteristics of the waste exceed the capacities of the existing waste disposal facilities, the construction of new facilities for storage or waste disposal needs to be considered. Such considerations have to take place in the framework of updating the decommissioning plan during operation.

4. CONSIDERATIONS ON ACTIVITIES DURING THE TRANSITION FROM OPERATION TO DECOMMISSIONING

4.1. GENERAL

Once the owner decides to shut down the research reactor permanently, the transition period begins. This period differs from the extended shutdown phase because the research reactor will be decommissioned and its return to service is no longer an option. The decision to decommission the facility has to be communicated to all interested stakeholders, including the government, the regulatory body (in accordance with the national regulations and legal requirements) and the public. The duration of the transition period depends on the strategy chosen for decommissioning (i.e. immediate dismantling or deferred dismantling). In some countries, the transition period is not mandatory, or its duration is minimized; following permanent shutdown, the facility 'jumps' directly from operation into decommissioning. This is possible when the operating organization schedules the final shutdown with a change of regulatory licence, from operating to decommissioning.

An advantage of a longer transition period is that the short lived isotopes decay completely, reducing the collective dose until and during the decommissioning activities. Nevertheless, experience has shown that the transition period does not need to be long, as the disadvantage of the delayed decommissioning outweighs the advantage of a moderate dose reduction.

Typically, the activities during the transition period are conducted under the operating licence. Many States with research reactors (e.g. Canada, France, Germany, Spain, Sweden and Switzerland) allow preparatory activities for decommissioning under the operating licence while waiting for approval or an amendment to it [11]. Preparatory work for decommissioning may be completed during the operation of the research reactor. The transition period to decommissioning is used for completing the objectives outlined in Section 4.2. If the decommissioning strategy is deferred dismantling, the transition period is followed by a 'safe enclosure' preparation period, followed by the 'safe enclosure' phase [22].

4.2. OBJECTIVES OF THE TRANSITION PERIOD

Appendix I indicates the time interval from operation to permanent shutdown and through the transition period to decommissioning, along with related activities to be performed. The key objectives during the transition period are the following [6, 23]:

- To update and finalize the transition and decommissioning plans, including the specification of end points[1] and establishing and defining the required conditions;
- To make an expeditious start to activities aimed at eliminating or mitigating hazards, beginning with those that clearly need to be carried out regardless of the subsequent decommissioning strategy;
- To complete the necessary activities to meet the transition end points, with priority being given to the specified end points for mitigation and removal of hazards and hazardous materials;
- To maximize the utilization and effectiveness of current operating knowledge, personnel and operating systems or programmes to reduce hazards at the facility, with emphasis on processes and systems for which the skills and knowledge required are unique;
- To establish effective relationships among all involved parties, in particular among the operating and decommissioning organization, contractors and authorities;
- To mitigate the social impacts of organizational changes;
- To reduce the cost of surveillance and maintenance and other transition activities;
- To identify the treatment, storage, transport and disposal requirements for all materials and wastes;
- To review the budget and funding for specific decommissioning projects;
- To initiate the ongoing process of culture change and implement new work methods and philosophies.

[1] ‘End points’ are the detailed specifications for the physical condition and configuration to be achieved at the end of a specific phase in the facility’s life cycle.

4.3. TYPICAL ACTIVITIES IN THE TRANSITION PERIOD

Typical activities, to be fully or partially implemented during the transition period, are the following [6, 23]:

— Sale, further use, recycling or dismantling of usable fissile/fertile materials.
— Removal of spent fuel and other fissile/fertile material from the facility.
— Removal of spent fuel and other fissile/fertile material from the site (if applicable).
— Stabilization, treatment and/or removal of potentially unstable materials or wastes.
— Reduction or elimination of the potential for fire or explosions from violent chemical reactions or nuclear criticality.
— Cleanout operations of systems, pipelines and other equipment not needed in the future that have the potential for significant radioactive and chemical material inventory.
— Neutralization and disposal of hazardous chemicals and oil in storage.
— Using the safety assessment to review changes in the configuration and status of SSCs as a result of transition to decommissioning activities (e.g. reducing redundancies in SSCs).
— Revision of OLCs as appropriate to changed conditions; this also includes the number of personnel required to maintain the licensing condition and safety standards.
— Installation and/or verification of sufficient barriers to prevent the spread of contamination.
— Verification of appropriate safeguards and security requirements.
— Checking and updating of relevant facility drawings and other documents to reflect changes that have been made during operation and/or the transition period.
— Training and awareness of facility staff for their future work and roles.

The first milestone after permanent shutdown is the ‘defuelling’ of a research reactor (i.e. the transfer of spent fuel to temporary wet storage and subsequent long term dry storage, prior to its disposal in a permanent repository, its reprocessing or its return to the country of origin, whichever applies). As spent fuel represents more than 99% of the radioactive inventory of a research reactor, its removal leads to a first significant decrease of the inventory during decommissioning. Moreover, removal of spent or partially irradiated fuel also has significant benefits from a security and safeguards viewpoint [6].

A description of typical activities that can be performed during the transition period for a physical and radiological characterization of the site can also be found in Section 4.9.

4.4. CONFIGURATION MANAGEMENT

Following the considerations on configuration management during the operating period outlined in Section 3.2, a similar activity is essential during the transition period to decommissioning to ensure that documents are sufficiently up to date and reflect the actual physical state of the SSCs. This aspect is particularly important since the transition period may last several years and during that time significant changes in SSCs are expected.

Keeping the safety and operating documentation up to date is an important aspect of configuration management. A process has to be established within the facility's management system to ensure that every change in the facility is reflected in the corresponding document, that current versions are used and that old versions are taken out of circulation. Old versions could be archived for knowledge management purposes. This process could be reviewed periodically to ensure its effectiveness and to implement continuous improvements.

If the facility has not maintained a good configuration control system, the following documents need to be reviewed and updated at the beginning of the transition and throughout the transition period:

- Safety analysis report. This is a living document and some of the chapters of this report will need updating on a regular basis. Special attention has to be paid to updating the OLCs included in the safety analysis report. Once the spent fuel is removed and safely stored elsewhere, the OLCs will change significantly. Surveillance and maintenance requirements will also be updated as the SSCs are gradually taken out of service. This is an important document for the research reactor and it therefore needs to be updated at appropriate intervals.
- Decommissioning plan. During the transition period, a decommissioning plan is fully developed with all the necessary details. IAEA Safety Standards Series No. SSG-81, Maintenance, Periodic Testing and Inspection of Research Reactors [24] and SSG-47 [12] provide guidance on the format and content of a decommissioning plan. Until decommissioning activities have started, the decommissioning plan will continue to evolve, incorporating, for example, facility configuration changes, ageing of SSCs, the availability of new and more effective decommissioning techniques and technologies, and changes in waste management infrastructure.

— Emergency plan. The changes in the emergency plan have to be reviewed in conjunction with the site characteristics that might include other nuclear and/or radiological installations in the area.

The activities planned during the transition period have to be reviewed to ensure that a safe configuration is always maintained. Moreover, the decommissioning plan has to be reviewed regularly to determine the necessary design and operational requirements at each stage of the decommissioning process. The design basis itself may change with the changes in physical state and this therefore needs to be considered during the configuration management.

The decommissioning organization may not be the same as the operating organization (see Section 4.5). The transfer of the expertise on the facility from the operating organization to the decommissioning organization is a key part of the preparations for decommissioning.

Much of the knowledge of the research reactor comes from the day to day first hand experience of the personnel that operate and maintain the facility. As such, not all knowledge is explicitly documented. Knowledge management includes ensuring that the relevant experimental data captured during the operating period are recorded, an accurate understanding of the facility is maintained and any records and information necessary for the decommissioning process can be accessed. Activities, modifications, events, incidents and other relevant details not formally recorded in documents often exist in the staff memory, which constitutes a valuable source of information.

A good practice is to review the configuration management documents when the facility enters the transition period, compare them with the actual physical state of the SSCs and update any documents found to be inaccurate. Therefore, replacements of SSCs, irregular events, removals of unnecessary SSCs, new installations, specific experiments conducted and some temporary modifications (e.g. additional shielding to cover hot spots due to radiation and contamination levels) have to be precisely recorded. A substantial effort has to be made to retrieve and document all undocumented information before experienced staff leave the facility.

4.5. ORGANIZATION DURING THE TRANSITION PERIOD

The operating organization remains responsible for the facility regardless of its status. During the transition period, the operating team will hand over tasks to the team conducting decommissioning activities. During this post-operating period, it is expected that some of the operational risks, such as criticality risks, may be removed. It is realistic to assume that there will be organizational changes and staff numbers will be gradually reduced, as schematically presented in Fig. 1 [25]. A decommissioning team has to be assigned by the organization responsible for the research reactor. Usually, the facility will have two working teams: one that is responsible for routine operating activities (i.e. safety monitoring, maintenance, surveillance, radiation monitoring, administrative activities), and another that is planning and conducting decommissioning activities. Typically, the total number of people of the operating organization will not increase in the transition period, and the management will need to motivate the staff to accept new additional tasks within the decommissioning team. The O&M group will continue its duties after the safe shutdown of the reactor and after the team devoted to the preparation of decommissioning completes its tasks. Figure 2 [6] provides a detailed graphical example of a functional organization during the transition period. As research reactors are of various types and sizes, a graded approach is suggested to define the most suitable organization configuration, as the management needs to put a process in place to control the workflow and a smooth transition.

Operating personnel may change roles to take up preparation for decommissioning and may be supported by specialists in decommissioning activities. Experience shows that planning and physical activities need to be led by a team with decommissioning knowledge and conducted as a project, since decommissioning requires a different mindset than reactor operation. However, some of the operating personnel, with good facility knowledge, would remain in the decommissioning

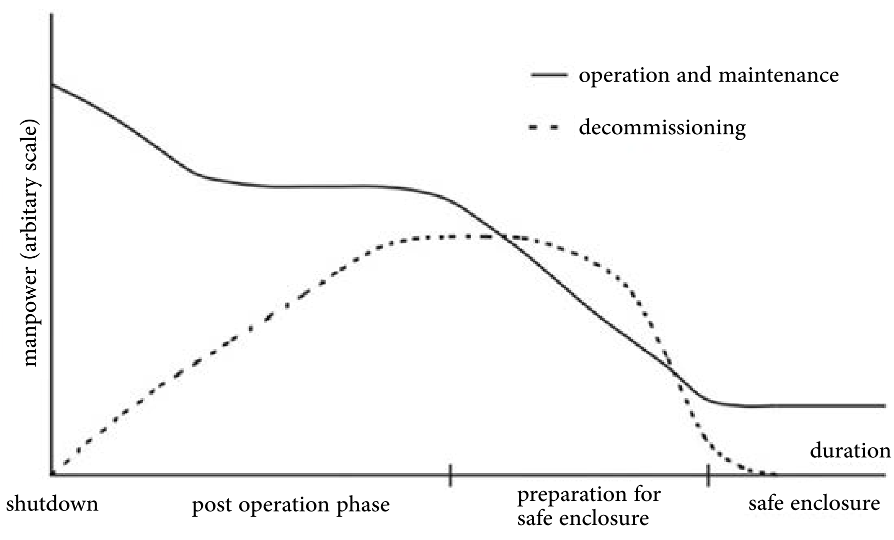

FIG. 1. Typical staff reduction profile during decommissioning (reproduced from Ref. [25]).

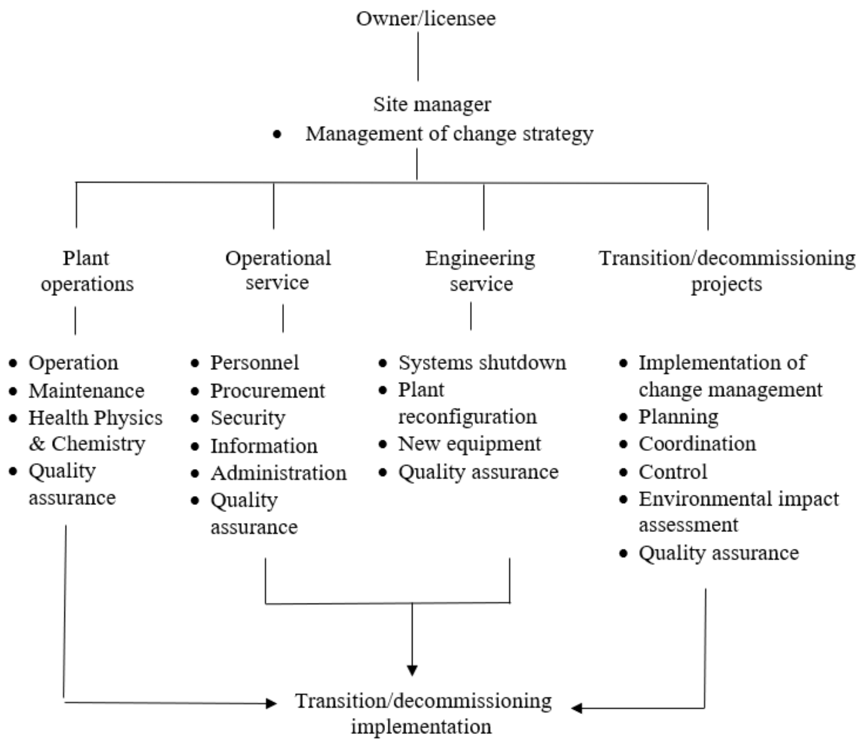

FIG. 2. Example of a functional organization during the transition period (reproduced from Ref. [6]). Note that a safety committee could be added to this organization to emphasize the importance of safety during this period.

team until the end state has been reached. Figure 3 [6] indicates a typical staffing trend during the transition period for the cases of both immediate dismantling and deferred dismantling.

Maintenance and surveillance activities are reduced during the transition period as many SSCs are taken out of service and the focus is to prevent deterioration that may hamper decommissioning and not to keep those SSCs operational. As an example, the water chemistry of the primary coolant needs to be maintained during the transition period, in order to minimize corrosion until the coolant is drained, whereas preventive maintenance and condition monitoring of primary circuit pumps might not be necessary.

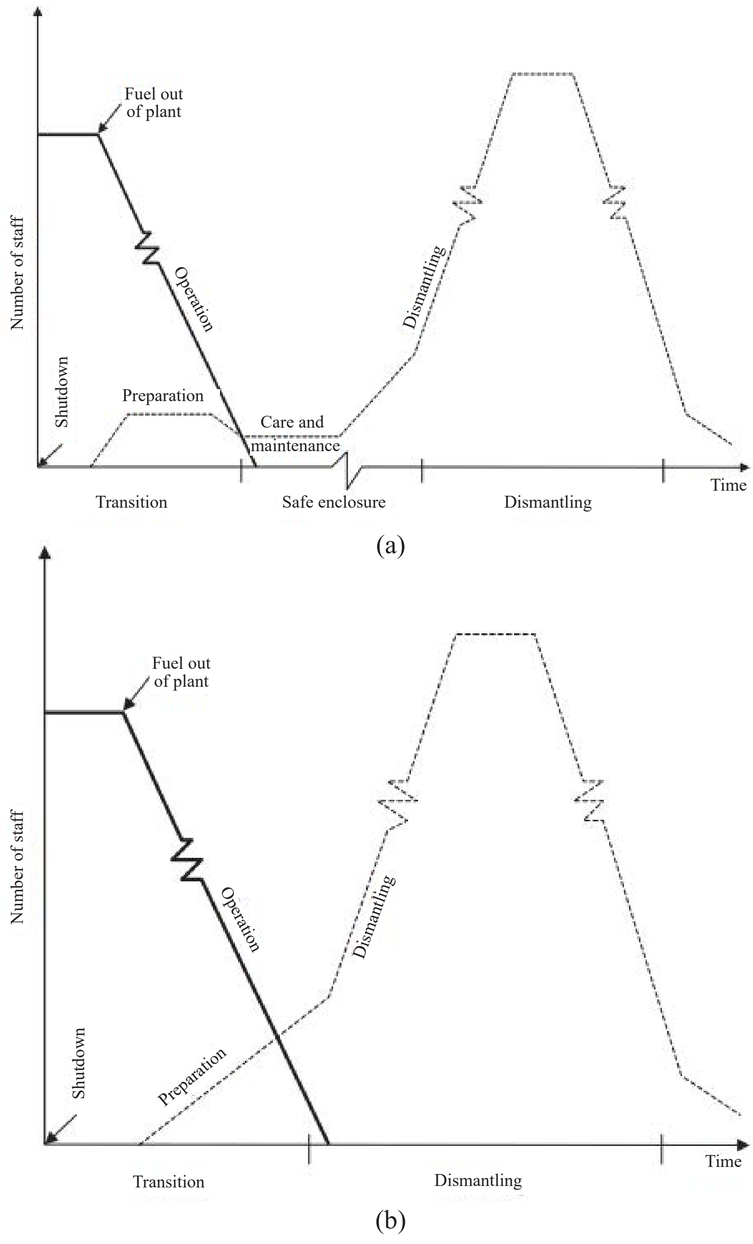

FIG. 3. Typical staffing trend following the shutdown of a research reactor: (a) during the transition period, safe enclosure and dismantling; (b) during the transition to immediate dismantling (not to scale; reproduced from Ref. [6]).

4.6. OPERATIONAL RADIOACTIVE WASTE AND SPENT FUEL MANAGEMENT

Well before the facility ceases operation, a clear strategy for the management of spent fuel has to be established. The strategy needs to cover all types of fissile material that may be present in the facility, which includes spent fuel, damaged fuel and other fissile nuclear material (e.g. in experimental facilities), as well as non-irradiated fuel (fresh fuel). The following considerations from a report by the OECD Nuclear Energy Agency [11] are discussed here regarding their specific application to research reactors.

The removal of all fissile material from the facility is a major aim during the transition period. The two main reasons for this are:

(a) Commencement of decommissioning. The removal of all fissile material from the facility is a prerequisite for starting the decommissioning. However, decommissioning may commence with nuclear fuel still on-site in a different authorized facility.
(b) Reduction of fixed costs. The costs of protecting the nuclear facility and maintaining the necessary safety and security related measures while fissile material and/or nuclear fuel is still present are significant. Once the material and/or fuel has been removed, safety and security measures can be reduced in accordance with regulatory requirements. Radiological risks are reduced significantly and the scope of the operating licence can also be reduced. This cost reduction becomes an incentive to remove the material as soon as possible.

When establishing a strategy for the retrieval, management and storage of spent fuel, damaged fuel and other fissile material, national policies and the availability of capacities, equipment and casks will be factors to consider. The options for spent fuel are as follows:

- Sending for reprocessing or recycling;
- Storing in casks in an on-site interim storage or at an off-site storage facility;
- Establishing a spent fuel pool (SFP) island;
- Returning to the country of origin;
- Disposing in a deep geological repository.

Under the SFP island approach, the spent fuel is moved to a self-contained storage area, such as an existing pool, that can be segregated for safety control purposes. The SFP island is typically much smaller than the cooling pool, owing to the lower heat load of the spent fuel; the spent fuel has had enough time to cool and new spent fuel is no longer being produced. The removal of the SFP island is also easier. If handling options for damaged fuel and other fissile nuclear material are not available, special solutions may be required.

For fresh fuel still stored at the site, as in the case of an unplanned shutdown of the research reactor, possible solutions include reusing the fuel in other research reactors or recycling in a fuel fabrication facility.

The conditioning and removal of operational waste such as decontamination wastes, liquid waste drained from the systems or solid waste as a part of pre-dismantling activities is important during transition to reduce radiation, fire and industrial hazards. This also declutters the areas for easy movement of on-site personnel and facility material, which is required for decommissioning operations and radiological and physical characterization of the facility. Early removal of operational waste also frees up space for interim storage of waste from decommissioning operations. Removal of most operational waste during the transition period is specifically recommended in SSG-47 [12]. Operational waste has to be sent to a waste storage or disposal facility. Waste that cannot be removed during the transition period (e.g. because the waste route is not available) should be stored at a location and in a form that has a minimum impact on decommissioning and that takes into consideration waste declaration requirements for final disposal.

Overall risk during dismantling activities may be reduced by removing non-radiological waste, such as asbestos, as the risks associated with conventional waste do not decrease with time. Once the waste has been removed, an assessment of the fire protection system is necessary. Some features of the system might need to be modified for the remaining risks or might not be needed any longer.

4.7. STRUCTURES, SYSTEMS OR COMPONENTS TO BE RETAINED DURING THE TRANSITION PERIOD

The transition period could be used effectively for the gradual removal of SSCs that are required neither for the transition period nor for decommissioning. Spent nuclear fuel (SNF) has to be removed from the core as early as possible to minimize the radiological risk. Removal of SNF implies that two main safety functions — reactivity control and cooling of fuel — will no longer be necessary. For pool type research reactors, the primary coolant may be retained for its shielding function.

In an early stage of the transition, an analysis could be performed to decide which SSCs are needed to maintain safety, security and implementation of dismantling and decontamination operations during decommissioning. This has to be followed by a plan to gradually remove SSCs that are no longer necessary.

This will also aid in reducing the maintenance efforts and cost. Special attention has to be paid to the removal and disposal of hazardous substances, such as ion exchange regeneration chemicals, that are no longer needed in order to reduce the hazard as much as possible. Disposal of the removed SSCs could be an issue if the infrastructure for radioactive waste management is inadequate. However, SSCs that could be taken out without any restrictions, with or without decontamination, can still be removed.

Where the reactor shares SSCs with other facilities, an analysis has to be performed to determine if decommissioning activities or activities performed during the transition period will or will not adversely affect other facilities. Examples of SSCs that could be affected are the electrical power supply (including emergency power supply), water supply, compressed air system, decontamination facilities, on-site waste and spent fuel storage.

Along with the instrumentation and alarm system, SSCs that are needed during most of the decommissioning stage are the following:

- Confinement including ventilation;
- Power supply;
- Water supply;
- Lighting;
- Hoisting devices such as cranes, chain pulley blocks, material movement equipment;
- Compressed air system;
- Water purification system;
- Radiation monitoring system;
- Waste handling and interim storage system;
- Liquid waste storage and discharge system;
- Communication system;
- Access control system;
- Fire alarm and protection system;
- Decontamination facilities;
- Laboratory to monitor water chemistry, dosimetry, contamination and radioactivity;
- Machinery cooling water system.

The means of confinement including ventilation is considered necessary, as release contamination in the building may be possible. An analysis may be performed to decide whether the full ventilation system is needed during decontamination and dismantling, or if reduced capacity is sufficient. Even for the decommissioning of a research reactor with a low risk of release of radioactive material into the air during operation, an increase of ventilation power or an upgrade of the filter system might be necessary to allow for dismantling and decontamination. Many SSCs, such as the power supply, may be needed at reduced capacity. Even if the process fluid is not drained for a long time, an analysis may be performed to determine whether the water treatment system, for maintaining water chemistry, is still needed or if a smaller portable system is sufficient.

SSCs that are not needed in the decommissioning process include the reactor systems (e.g. the shutdown systems), experimental devices (e.g. spectrometers, neutron activation analysis laboratory equipment, hot cells, neutron monitoring system) and in-core removable components (e.g. reflectors). If other neutron sources (e.g. photoneutrons) are still present and certain hot cells may be retained for decommissioning activities, the neutron monitoring system becomes necessary in the decommissioning process.

Various new SSCs will be needed for decommissioning, such as dismantling tools, temporary shielding, portable ventilation system, waste storage facility, waste transfer arrangements, material handling equipment, decontamination facility, tools for radiological characterization and laboratory monitoring.

4.8. SURVEILLANCE, MAINTENANCE AND AGEING MANAGEMENT PROGRAMMES

During the operation of the reactor, the ageing management programme is closely interfaced with surveillance and maintenance (S&M) activities. The objective of S&M is to identify and implement the appropriate measures to monitor and, when necessary, to repair or replace those SSCs exposed to degradation mechanisms and/or obsolescence that may lead to an increase of failures and the consequential reduction of their reliability and availability. Similarly, during the transition from operation to decommissioning, the S&M activities are essentially a continuation of the facility maintenance programme. Nevertheless, during the transition period, the programmes for S&M need to be reviewed on the basis of the new configuration of the facility in the transition period, with the main objective of maintaining a safety envelope and allowing a smooth transition to the decommissioning stage. In general, the scope of the safety requirements in the programme can be reduced as the SSCs are taken out of service. Significant savings in energy, material and human resources can be made while still ensuring that the applicable safety requirements are met. Moreover, care has to be taken to avoid unnecessary costs, such as repairing a building scheduled to be demolished in a few years. Monitoring systems, if needed, will require periodic attention, but if such systems can be eliminated and portable systems (e.g. radiation detection instrumentation) can be used instead, the costs can be reduced. In a similar way, some SSCs may be required to operate intermittently (e.g. water purification system), reducing the maintenance effort.

If ventilation systems are required, the corresponding equipment will need to be maintained. Where possible, deactivation measures taken could result in the ability to shut down fans, filters and other ventilation system components. Similarly, by eliminating fire hazards, it may be possible to eliminate the fire protection systems and the consequent costs of maintaining them. This also eliminates or minimizes the need to enter the facility for surveillance purposes.

Maintaining the integrity of the roofs and walls of the reactor building is a prime concern during the transition period or safe enclosure phase. Risks involving facility roofs (e.g. personnel falling through or water damage to equipment) are common, but could be prevented by implementing a suitable S&M programme.

Material security and safeguards may be another consideration. Facilities that house high-value material or material under safeguards will require safeguards and security measures. Situations requiring such measures have to be reviewed with the goal of removing or otherwise eliminating the causative factors.

SSCs that are required for decommissioning activities, such as hoisting devices, transfer casks and waste handling equipment (e.g. compactors), may need increased maintenance efforts. Cranes are rarely operated at full capacity during operation, and if the facility does not have an appropriate programme, the cranes need to be refurbished and tested up to the capacity needed for decommissioning activities. Moreover, the programme has to consider how all regulatory requirements and other applicable local regulations can be met. The need and extent to which the programme has to be reviewed are influenced by the length of the transition period. In some cases, where information on the condition of the SSCs is inadequate, baseline information may have to be generated using available information, facility walk downs and/or additional inspections. This baseline information, which depicts the actual condition of SSCs, could be used to further update the ageing management programme during the transition period. Ageing management has to take into account when equipment will be needed and when adequate spare parts could be made available to overcome any possible obsolescence at the time of use.

4.9. PHYSICAL AND RADIOLOGICAL CHARACTERIZATION

Physical and radiological characterization is the key to successful and safe decommissioning, as it is the driver for decommissioning activities. Two IAEA publications, SSG-47 [12] and Ref. [26], and two reports by the OECD Nuclear

Energy Agency [27, 28] provide guidance and information on what has to be included in the physical and radiological characterization.

An accurate characterization of the facility supports the following:

- Selection of the decontamination and dismantling technique that needs to be employed for each SSC;
- Radiation protection programme during decommissioning;
- Waste management;
- The overall gain in the optimization of cost and time for decommissioning.

Site characterization involves three major steps:

(1) Developing a site characterization plan;
(2) Conducting site characterization;
(3) Preparing a site characterization report.

The characterization plan has to be developed, as a preparation for decommissioning, during the final year of operation and implemented as soon as possible after the research reactor has been permanently shut down.

Typical activities that can be performed even before shutting down the facility are as follows [27]:

- Determination of the volume and the radiological inventory of the operational waste held within the facility;
- Determination of the physical characteristics of the operational waste held within the facility;
- Physical inventory of SSCs;
- Early identification of potentially problematic wastes arising during decommissioning to allow the development of management options to minimize their impact on the decommissioning process;
- Characterization for decommissioning of remote areas not expected to be affected by the remaining operation;
- Review of historical information of radiological importance (e.g. operational records, incidents/events and abnormal operation that resulted in the breakage of safety barriers, causing release of radioactivity to surroundings or the environment).

Identification of the extent of contamination in the soil, subsurface and groundwater is essential for the decommissioning plan. Therefore, collection of the information has to be started during operation of the facility and expanded after the final shutdown.

Since radiological data are a function of time, the plan has to include information on the point in time at which the radiological data are needed for each SSC, and for which planned activity (e.g. dismantling, radiation protection, waste classification). In many cases, the timespan between the radiological characterization and its usage could be several years.

For each SSC, the characterization plan has to include at least the following information:

(a) Physical characterization:
  - Shape and size (dimensions);
  - Physical attributes such as state (solid, liquid or gaseous);
  - Weight and volume;
  - Drawings and photographs of material;
  - Material composition;
  - Condition.

(b) Radiological characterization:
  - Activation;
  - Contamination;
  - Specific activity;
  - Radioactive dose rates;
  - Type of radioactivity emitted (alpha, beta, gamma);
  - Radionuclide inventory;
  - Spatial distribution of radioactivity;
  - Depth of penetration of radioactivity;
  - Reference points.

Not only the SSCs but also the site that is earmarked for decommissioning have to be included in the plan, namely for effective dose rates, and activity measurements of soil, groundwater and vegetation. Moreover, process fluids have to be included in the characterization plan.

The characterization plan has to identify what information is already available and what needs to be generated. It also has to include the data quality objectives and quality control measures to be used and identify the number and locations of biased and random surveys. The plan has to be developed in consultation with all interested parties, namely the reactor manager, decommissioning expert, waste manager, sampling and laboratory technicians, quality assurance specialist and radiation protection personnel. Moreover, the plan has to clearly identify the various tasks, the responsible person or group for conducting each task and the associated timelines. Missing information could be obtained by conducting additional characterization. It may be necessary to take samples for radiological characterization (e.g. pipe pieces or samples from reflectors, core structures). Care has to be taken while drawing samples to prevent incidents such as fluid draining or contamination spread. While drawing samples particularly for measuring the depth of penetration of radioactivity, for example in concrete shielding, the techniques employed have to ensure that the activation products from the surface are not driven in, or that the method used in the extraction of a sample does not affect the possible radionuclides contained in the sample. For example, some research reactors use D_2O as the cooling medium, leading to tritium contamination of the SSCs. Using a method to extract a sample, which might cause heating of the sample, will drive off the tritium contamination and subsequently give misleading results.

Additional radiation and contamination surveys will be necessary to obtain the radiological characteristics of the SSCs. In some cases, owing to access limitations, only estimated values might be available. In such cases, a review is suggested to check if the estimated values could be updated when physical dismantling progresses and, if so, need to be included in the characterization plan.

Records of characterization need to be included in the characterization report with all reference documents that could be retrieved. The characterization report may be used many years later; hence, selection of a suitable storage medium (hard copy, electronic or a combination of both) is necessary. Additionally, experts will need to review the characterization report to ensure that all relevant information has been recorded. An example of the content and structure for the characterization report is presented in Ref. [26].

4.10. TRAINING AND QUALIFICATION

During operation, the operating personnel carry out routine and repetitive tasks for which they are qualified and trained. However, preparation for decommissioning is a one-of-a-kind activity, and operating personnel need to be trained and qualified for this. Skill sets and mindsets for decommissioning are different than those for the operation of a research reactor. The training and qualification programme for decommissioning has to be implemented at an early stage of the transition period, just after the permanent shutdown. The training programme is established according to the complexity of the project and the organizational structure for decommissioning, and the roles and responsibilities of the individuals concerned. Reference [29] provides information on training and human resource considerations for the decommissioning of nuclear facilities and emphasizes that the specific training programme needs to include, among others, technical, cost and schedule considerations, and has to reflect different training needs for different groups. It is expected that some of the operating personnel will continue to be associated with the facility, and that additional people including contractors will be employed at different times during the transition period. The training programme and documents need to be developed before the permanent shutdown and implemented as early as possible after the permanent shutdown. The training strategy has to ensure adequate management of employees with the following goals [11]:

— To ensure that the skills and competences necessary for the facility and its remaining lifetime are maintained until decommissioning has been completed;
— To ensure that employees are retrained by anticipating the needs of the site;
— To promote internally the transfer of skills and lessons learned from experience.

In view of diverging training needs for different groups (e.g. reactor managers, safety personnel, budgeting personnel, decontamination personnel, dismantling personnel, operating personnel), target groups have to be identified before the training programme is implemented. A syllabus for each target group needs to be developed that includes the necessary knowledge and skills so that the group can perform its work safely and efficiently. The training programme also needs to include the timing at which the training will be started and completed for different groups. Ideally, the training begins as close as possible to the start of the activity for which the training is provided. The risk of knowledge loss increases as time passes and/or people retire or leave. This has to be considered in the training programme.

An example of typical training needs for the various target groups is given below, based on Ref. [6]:

(a) Managers. Emphasis on the transition activities as a 'project' as opposed to regular production/operational activity. This involves training in technical, cost and schedule preparations. Training has to ensure that managers are familiar with the concepts needed for:
    — Determining the criteria for and conditions of regular staff reductions;
    — Complementing the operating organization (e.g. using contractors);
    — Amending the safety assessment and safety requirements;
    — Estimating decommissioning costs and budgeting;
    — Configuration management.
(b) Safety personnel. Training has to focus on safety issues, with emphasis on the typical issues linked with radiological hazards (e.g. irradiation, contamination, alpha risk) of permanently shut down facilities, where safety requirements could change over time as SSCs are taken out of service and/or new systems are added. It has also to address how the safety conditions

could be changed and how the requirements for technical specifications, surveillance and maintenance could be reduced.

(c) Operating personnel. Training of personnel responsible for the O&M of systems and equipment has to focus on:
  — Shutdown and isolation of systems;
  — The changed surveillance and maintenance requirements owing to the change in the safety case resulting from the cessation of activities or the reduction in their frequency. The system changes need to be recorded.

(d) Regulatory inspectors. Where facilities have been in extended shutdown, the training of inspectors could emphasize structural assessment (building and plant), evaluation of roof integrity and identification of radioactive, chemical, electrical and other physical hazards.

(e) Budgeting personnel. Many of the cost line items for transition are not normally considered during operation. Those responsible for budgeting have to be aware of the differences as well as the models used for estimating such costs.

(f) Waste managers. New waste characterization, waste retrieval and conditioning techniques may be developed, for which training is required.

(g) Radiological protection technicians and chemistry technicians. The technicians completing this work will generally be qualified to complete the work by virtue of their discipline competence. However, the use of new techniques and tools for radiological characterization not applicable to the operating period of the reactor, or exposure to high radiation doses and the suitable means to implement safety measures, are likely to be new areas of training. Changes in radiological risk need to be considered in the training material (e.g. where alpha or tritium contamination risks may increase and gamma exposure may decrease following shutdown).

If the facility configuration management is well developed, the necessary material for training is readily available except maybe for decommissioning techniques, which can be developed closer to the time of decommissioning. Special attention has to be paid to non-visible systems, interconnection of different SSCs, degraded characteristics of SSCs owing to ageing, use of special tools and techniques (e.g. remote tools), and work in different conditions such as working with personal protective equipment and in confined spaces.

A systematic approach for training includes the following main stages:

— Analysis of the work to be performed and the training needs;
— Design of a training programme;
— Development of training materials;

— Implementation of training;
— Evaluation of training effectiveness.

In view of the reduction in hazards after the removal of the spent fuel from the reactor core or reactor site, a graded approach is needed in training. The approach encourages the application of techniques that allow the most efficient use of personnel and resources in training activities. However, under no circumstances should health or safety concerns be compromised for cost savings or expediency.

Training material may include documents, drawings, photographs, 3-D models and videos. In some tasks, mock-ups could be very effective. The training programme can also include a possible event analysis or hazard analysis, and the actions needed to be taken if such events take place during the decommissioning activities. Examples of safety significant events may be broken SSCs, corroded bolts, unexpected dose rates, spills and contamination. Experiences from similar projects, including video footage and photographs, are very effective tools for training. These could be either completed projects or ongoing projects.

4.11. LESSONS RELEVANT TO DECOMMISSIONING ACTIVITIES LEARNED DURING OPERATION

During the operation of a research reactor or during a planned refurbishment outage, many aged SSCs are replaced. This provides opportunities for carrying out several actions applicable for the transition from operation to decommissioning. Major actions include the draining and drying of systems or a part of them for the removal of degraded or damaged components and the installation of new components. Sometimes, a complete core unloading is required for the replacement or repair of core components or primary coolant system components, which are not isolatable. Previous complete core unloading provides valuable experience for future spent fuel handling and storage, and the removal of active components provides experience on the deployment of dismantling and decontamination techniques. This may require the development of new tools or the deployment of existing tools. From a cost perspective, preference is given to the use of readily available tools rather than the development of new complex tools. Removal of active process fluids and resins from systems, active components, high efficiency particulate air (HEPA) filters, and their storage and disposal provide opportunities for the development of waste management techniques. Waste storage facilities may be developed if they are not available either on the site or away from the site as applicable according to each country regulation. An interim waste storage facility, which has to meet the required safety criteria, may also be established.

4.12. FINALIZATION OF THE DECOMMISSIONING PLAN

A final decommissioning plan needs to be completely developed during the transition period and includes, among others, the following aspects [12]:

- — Decommissioning organization;
- — Radiological characterization;
- — Decontamination techniques for various SSCs;
- — Dismantling techniques for various SSCs;
- — Identification of SSCs and infrastructure that need to be maintained for use during decommissioning;
- — Identification of new SSCs that need to be installed for decommissioning;
- — Safety assessment of decommissioning.

The final decommissioning plan needs to be submitted and approved by the regulatory body before an approval or a licence for decommissioning is granted. The regulatory body may include hold points or witness points in the schedule of activities. Reference [6] provides suggested issues and the structure and content of the final decommissioning plan, and Ref. [26] provides detailed information on the process.

The final decommissioning plan could be a standalone document or a combination of separate documents that describe the process. A graded approach can be used based on the size and complexity of the decommissioning project. The operating organization needs to develop the final decommissioning plan and subject it to an independent review (e.g. safety committee or through international or bilateral arrangements if sufficient expertise is not available locally). During the development of the plan, lessons from similar activities need to be considered.

5. REGULATORY CONSIDERATIONS

5.1. REGULATORY OVERSIGHT DURING PREPARATION FOR DECOMMISSIONING

Requirement 5 of GSR Part 6 [21] states:

“**The regulatory body shall regulate all aspects of decommissioning throughout all stages of the facility’s lifetime, from initial planning for decommissioning during the siting and design of the facility, to the completion of decommissioning actions and the termination of authorization for decommissioning.**”

The requirement applies also to experimental facilities connected to the research reactor and associated nuclear facilities. Therefore, the initial task for the regulatory body is to ensure that the regulatory supervision covers the transition to decommissioning of the facility (e.g. through a modified operating licence). It may be further converted to a decommissioning licence. Moreover, it is expected that the regulatory body will present, in the same or in a separate document, the typical activities requested to be performed during the transition to decommissioning.

Paragraph 7.4 of GSR Part 6 [21] states that “The licensee shall prepare and submit to the regulatory body an initial decommissioning plan together with the application for authorization to operate the facility.” This plan enables both the regulatory body and the operating organization to ascertain the necessary documentation and activities to be carried out during the stages prior to decommissioning, including the necessary human resources and competences. Moreover, it minimizes unanticipated situations that can lead to delays in decommissioning, overrun in costs, or presentation of unnecessary hazards, including radiological hazards (see Section 2.3 for details). Furthermore, and if applicable, the regulatory body may issue a separate permission or licence or modify the existing licence with specific safety requirements for the extended shutdown period.

During the transition from operation to decommissioning or during the extended shutdown period, an important function of the regulatory body is to conduct inspections of the facility. Both the frequency and the scope of inspections may be adapted from those established for normal operation, depending on the size and complexity of the facility. The basic purpose of such inspections is to confirm that the approved extended shutdown permission or licence is adhered to, and that specific safety requirements established for this period are met. Of these, the most important areas to inspect are as follows [20]:

— Nuclear safety (i.e. handling and storage of spent fuel to avoid nuclear criticality, whether in the reactor core or in a spent fuel storage facility);
— Operational radiation protection (i.e. protection of the operating personnel and the public against excessive exposure and measures to prevent radioactive materials from being released to the environment);
— Technical aspects such as ageing management, maintenance, surveillance (i.e. degradation of SSCs important to safety);
— Knowledge retention of the operating personnel (i.e. training, re-training and re-licensing).

It is important that the results of each inspection are well documented and that discovered issues are addressed by the operating organization.

One of the main activities for the regulatory body during the transition period is to review, assess and approve the final decommissioning plan. In many cases, a long time may elapse between the approval of the decommissioning plan and the actual start of the decommissioning activities. Many safety and operating documents at facilities will undergo revision, including the safety analysis report, OLCs, the emergency plan and operating procedures, to keep pace with the changing configuration. The regulatory body normally requires the operating organization to seek permission or approval before changes are implemented. Reference [30] provides information on model regulations for decommissioning.

5.2. PROCESS FOR OBTAINING A DECOMMISSIONING LICENCE

The licence approach to permit decommissioning activities varies greatly among States. Regardless of the approach selected by the operating organization, it is important to engage with the regulatory body as early as possible in preparation for decommissioning. Key areas of focus are as follows:

— Regulatory requirements that apply during the decommissioning process;
— Preparatory activities that are permitted to be performed as part of the operating licence;
— Submissions that are needed for approval or information prior to each authorization stage and the associated submissions schedule.

Just after the final shutdown, during the preparations for decommissioning, the usual methods of submission to the regulatory body for review and approval might not be as efficient as during operation. Therefore, the involvement of the regulatory body during the early stages of the development of the decommissioning plan is vital. It is suggested that the licensee consults the regulatory body before entering the phase of extended shutdown or as soon as the decision is made to permanently shut down the reactor.

The extended shutdown is often regulated under the operating licence. However, the regulatory process and the licensing conditions may differ compared with the normal operating period. If clear regulations are established regarding extended shutdown, the facility has to be regulated accordingly. However, if that is not the case, the regulatory body needs to review the existing regulatory framework and formulate suitable regulatory activities for the extended shutdown in consultation with the licensee.

The licensee has to apply for licence amendments from the regulatory body if certain conditions cannot be met, such as minimum staffing, certification of the operating personnel and certain mandatory surveillance activities (e.g. reactivity worth measurement of control rods and shut-off rods).

6. LEADERSHIP AND MANAGEMENT CONSIDERATIONS

6.1. MANAGEMENT RESPONSIBILITY

Requirement 7 of IAEA GSR Part 6 [21] states that “**The licensee shall ensure that its integrated management system covers all aspects of decommissioning.**” Furthermore, para. 4.1 of SSG-47 [12] recommends:

> “The licensee should implement an appropriate integrated management system before the commencement of decommissioning actions. The management system should extend to all phases of the decommissioning project, including planning for decommissioning and preparatory actions performed during normal operation.”

Certain considerations ought to be taken early, in anticipation of all of the requirements of a final decommissioning plan. In general, the goal of the management system is to provide a framework for managing, performing and assessing. By considering decommissioning during all life stages of the research reactor, the management system will be ready for a smooth transition to decommissioning.

The documentation for the management system needs to include a description of the organizational structure, functional responsibilities, level of authority and interactions between those managing, performing and assessing the adequacy of these activities, and coverage of management measures including planning, scheduling, resource allocation and human factors.

Prior to and during operation, the management system of a research reactor has to include several processes that will support the eventual decommissioning of the facility, for example:

— Processes to conduct configuration management;
— Processes to maintain the records of engineering changes;
— Processes to inspect the condition of SSCs and record the findings;
— Processes to document abnormal events, the radiological consequences and any corrective actions that were taken in response.

In accordance with SSG-10 (Rev. 1) [16], the consideration of decommissioning in all life stages of a research reactor necessitates that the ageing management programme includes the following:

(a) Planning and prioritizing work;
(b) Addressing regulatory requirements, codes and standards;
(c) Ensuring compliance with the operational limits and conditions and with the safety analysis report;
(d) Ensuring the availability of sufficient qualified personnel with suitable skills;
(e) Ensuring the availability of spare parts, special tools and equipment;
(f) Following up inspection and test results in a timely fashion;
(g) Establishing appropriate operating procedures following relevant standards, including procedures for assessing and correcting non-conforming items;
(h) Identifying, disseminating and using information on good practices from designers, manufacturers, contractors, suppliers and other operating organizations;
(i) Performing and adequately documenting the necessary inspections and tests;
(j) Performing root cause analyses of significant degradation of SSCs and incorporating lessons learned from experience.

6.2. PROCESS IMPLEMENTATION

Normally, the operating organization creates processes to include consideration of decommissioning in each life stage of the research reactor.

Significant changes in the facility configuration such as the addition or removal of SSCs, radiological characterization such as hot spots, reportable events such as radiation spills, or contamination levels that affect or impact the eventual decommissioning, have to be recorded and the data have to be analysed and trends discerned to identify the causes of these changes. The information could be used as input to improve the decommissioning plan.

Valid monitoring and measurements have to be performed to provide evidence of conformity to requirements and to ensure that considerations on decommissioning in all life stages of the research reactor are in place.

The management system has to include measures to control records essential to the performance of the relevant activities and to the verification of the results achieved. The records processes have to provide for the identification, approval, review, filing, retrieval and disposal of records.

6.3. RESOURCE MANAGEMENT

The operating organization has to provide adequate resources (both human resources and financial resources) to implement the consideration of decommissioning in all life stages of the research reactor. The management of the operating organization could participate in these activities by:

— Determining the required staff competences and providing training where appropriate;
— Preparing and issuing specifications and operational procedures that include consideration of decommissioning in each life stage of the research reactor;
— Supervising external personnel who perform considerations on decommissioning in all life stages of the research reactor, and ensuring that these personnel are adequately trained and qualified.

6.4. MEASUREMENT, ASSESSMENT AND IMPROVEMENT

Measures have to be established to ensure that considerations for decommissioning in each life stage of the research reactor are accomplished as specified in the appropriate documents. Such measures are listed in SSG-10 (Rev. 1) [16] and include:

— Reviews of procedures;
— Verification by inspection, witnessing and surveillance;
— Checks of non-conformances and implementation of corrective actions;
— Follow-up on the adequacy and timeliness of corrective actions.

Audits and independent assessments of operations have to include the consideration of decommissioning in each life stage of the research reactor. This assessment could be performed by the safety committee or by another competent body.

6.5. RECORD KEEPING

Requirement 89 of SSR-3 [3] states:

> “**The operating organization for a research reactor facility shall prepare a decommissioning plan and shall maintain it throughout the lifetime of the research reactor, unless otherwise approved by the regulatory body, to demonstrate that decommissioning can be accomplished safely and in such a way as to meet the specified end state.**”

During the life cycle of the facility, many documents are created to describe the site and ensure that the facility meets defined requirements (e.g. environmental impacts, design basis reports, safety reports) [9, 11]. It is important to keep a good record of these documents to facilitate the decommissioning and dismantling processes.

Previous experiences have shown that, in general, records for decommissioning purposes have not been well managed or managed at all. There are many reasons for this, for example [8]:

— Little understanding of the requirements of decommissioning, especially the need for accurate configuration drawings and facility data;
— A belief that, if any records of the facility are kept, this will suffice;
— Lack of well defined responsibility for decommissioning records within the organization;
— Lack of priority being given to key records, such as those needed to sustain the operating safety case and for critical maintenance;

— After shutdown, the loss of interest in all records as operating personnel are dispersed.

A clear definition of the record storage media (hard copy, electronic) and responsibilities for maintaining and managing these records have to be established. Additional relevant data are also important, for example on equipment changes, incidents or accidents that could have an impact on dismantling, the operating history of activation and contamination, and the operating waste inventory. The records that are specifically for decommissioning purposes need to be identified, reviewed for accuracy and preserved in a secure archive. Most other records, which can amount to over 90% of all facility records, are generally only of historical value after a facility has been permanently shut down. There will also be important general records such as licensing, site characterization, decommissioning financial fund statements and ownership deeds [8].

The responsibility for the management of records, including those for decommissioning, has to be identified within the organization and could be subjected to appropriate quality assurance procedures, with special emphasis on the transfer of necessary documentation — including, among others, the operating experience, configuration management, records, documents — to the new decommissioning organization. As described in Ref. [11], documents may also include, among others, policies, procedures, instructions, specifications, drawings and training materials. Throughout the facility's life cycle, numerous documents are generated to detail the site and ensure compliance with established requirements. Key documents, such as environmental impact assessments, design basis reports and safety reports, are crucial for decommissioning and dismantling phases. Effective knowledge management during this transition relies on tools like records, archives and repositories, as well as information management systems and processes. The facility adheres to the necessary protocols for controlling and retaining documentation [11].

The physical characteristics of facilities as designed, constructed, commissioned and operated are recorded and retained during the operating period. Descriptions of the as built facility and design changes are provided in specifications, manuals, drawings and photographs. These provide the foundation for configuration control. Material analysis reports are useful in defining quantities of trace elements and need to be retained for components likely to become activated [11].

Prior to permanent shutdown, it is advised that all relevant design, construction, commissioning, operating and maintenance documentation and history be collected and archived [11]. The detailed shutdown plans, a description of the permanent shutdown state achieved, and a plan for managing spent fuel and radioactive and hazardous wastes from permanent shutdown activities should be included as records of the permanent shutdown [11].

As listed in Ref. [11], information sources to assess the state of the facility after shutdown might include the operating history and knowledge of the facility, a geophysical assessment, configuration management and investigations or non-destructive examinations. Details of radiological safety incidents, such as contamination spills, may also be included.

In preparation for decommissioning, a review (e.g. self-assessment, audit) of existing records should be started as early as possible. Relevant archived records and documentation also need to be reviewed. Further investigations and characterization activities may be needed in the case of missing site records or site documentation [11].

6.6. COST ESTIMATION AND SECURE DECOMMISSIONING FUND

The need for reliable cost estimates has not been properly recognized in the past, except for the simplified assumption that a 'set-aside' fund, representing the actual decommissioning costs, needed to be established. Based on practices validated for nuclear power plants and a cost structure developed by the OECD/NEA [31], the IAEA has developed a 'simple to use' software for estimating the decommissioning costs of small nuclear facilities [32]. More details can be found in three supporting IAEA publications [33–35]. Also, Ref. [8] provides relevant lessons that can be adapted to the research reactor environment.

For example, some States have assumed an approximate cost proportional to 10% of operating revenue, but this practice has then been mostly discounted. A problem can arise if a facility shuts down prematurely for technical or other reasons and insufficient funds have been accumulated. While a generous set-aside fund may be possible for large revenue producing facilities such as nuclear power plants, it is unlikely to be possible for non-revenue producing facilities such as reactors employed for research and training purposes. Quite often, even in developed States, funds supposedly set aside for decommissioning have not been available due to the diversion of the funds to other national priorities. In some States, there has been no fund at all because of economic and political changes, or a simple lack of recognition of the need. This has resulted in extensive delays in giving the required attention to shut down facilities in many States. In some cases, there have been delays of 20 years or more during which nothing has been done and care of the facility has been minimal. This approach is highly undesirable.

Such delays and lack of attention have been the topic of significant regulatory concern and there is now a widely applied requirement for a secure, independent and inflation-resistant fund to be set up as a licence condition. This has resulted in more robust and comprehensive estimates of future decommissioning costs. Established costing models are now available to formalize the estimation of decommissioning costs [34]. Some studies have analysed the adequacy of decommissioning funds using probabilistic models [35].

The process of updating cost estimates has to extend throughout the design and construction stages, moving from preliminary estimates to more comprehensive estimates when the design is well developed. Cost estimation is an iterative process needing regular review and refinement. During the operating period, updates to the decommissioning plan and cost estimates have to be made periodically to account for changes in actual facility or initial assumptions.

Before final shutdown, it will be necessary to review the cost estimates to take account of any abnormal operating conditions, accidents and the operating history to determine the full extent of the radioactive inventory and waste volumes and also to take account of applicable developments in decommissioning technology. There will also be a need to review legislative changes that may have become more, or in some instances, less restrictive. All these factors are likely to have a significant effect on costs.

The experience available internationally from well developed decommissioning projects will be invaluable. Identified contingency allowances could be made in the estimates to allow for changes in the facility and in decommissioning technology and for uncertainties over long periods of time. In some States (e.g. the United Kingdom), decommissioning cost estimates need to be reviewed every five years. Finally, decommissioning funds need to be segregated in the financial records or, preferably, held by appropriate financial management institutions independent from the operating organization and/or owner of the research reactor facility.

Appendix I

DECOMMISSIONING RELATED ACTIVITIES, PROJECTS AND ORGANIZATIONAL ASPECTS

Figure 4 shows a possible scheme for decommissioning related activities, projects and organizational aspects covering the period from operation up to the final dismantling of a nuclear installation, as suggested in an early IAEA publication (see Ref. [6]). The figure refers to nuclear power plants, but may be well adopted as also relevant for research reactors.

Neither early design activities nor operational activities are shown in Fig. 4, although the conceptual structure of the scheme may be kept today, following the lessons learned during the past two decades. It is important to notice that decommissioning processes are expected to be simpler owing to proper early considerations in the design and operation stages of research reactors.

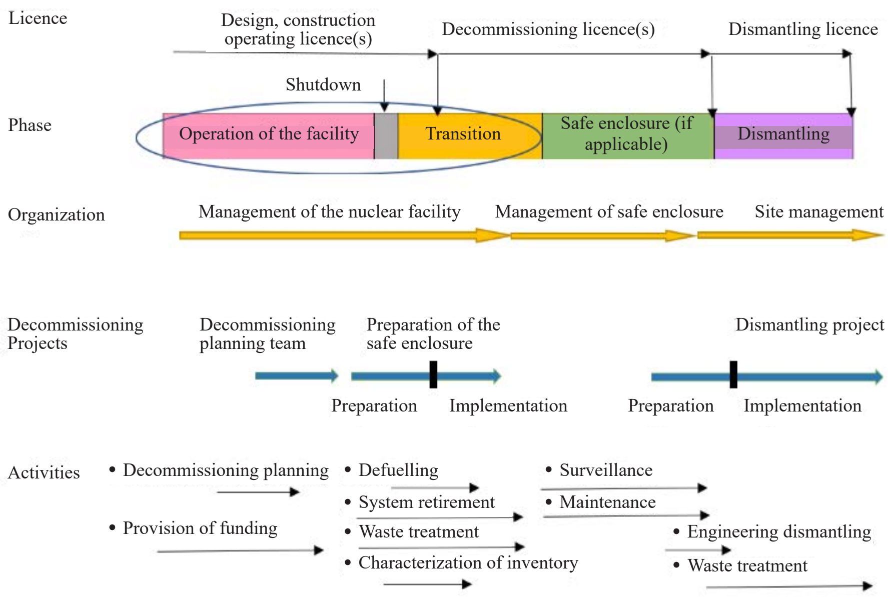

FIG. 4. Decommissioning related activities, projects and organizational aspects covering the period from operation to final dismantling of a nuclear installation (adapted from Ref. [6]).

Appendix II

LIST OF FACILITY, OPERATIONAL AND DESIGN FACTORS

Table 1, as adapted from Ref. [8], shows the range of beneficial design features together with suggested responsibilities for implementation. Features considered in Table 1 refer to facility design for the optimization of waste management and contamination control, and the design interface with decommissioning planning, with licensing and safety, and with project management.

TABLE 1. FACILITY DESIGN AND OPERATIONAL DESIGN FACTORS [8]

Feature		Description/comment	Responsibility (organizations and persons)
1.	**Facility design**		
1.1.	The facility design has to maximize the ability to use conventional dismantling techniques.	Conventional experience and practice in non-radioactive dismantling and demolition is well tried and tested.	Designers, Policy makers
1.2.	It has to be recognized that some construction features, such as modular construction, may prove beneficial for decommissioning.	Make increased use of such features and record them in the decommissioning plan. The modular construction concept can be applied to the smaller nuclear facilities as well as the large reactors.	Designers, Planners
1.3.	Provisions have to be made in the design for easy and safe access for final dismantling.	Adequate access has to be provided not only for maintenance but also for eventual dismantling.	Designers
1.4.	The design has to provide for access for the intact removal of very large items of the contaminated plant.	This refers to items like steam generators and large pumps for which access for the intact removal of equipment has to be considered.	Designers

TABLE 1. FACILITY DESIGN AND OPERATIONAL DESIGN FACTORS [8] (cont.)

Feature		Description/comment	Responsibility (organizations and persons)
1.5.	The option to segment large contaminated or activated items ‘in situ’ for easy removal needs to be retained.	Experience has revealed significant problems in the need to segment large items in confined spaces and sufficient access is needed.	Designers
1.6.	Designs have to limit embedding pipework, ducts, tanks and equipment in floors and walls.	Removal of contaminated and embedded items presents problems during dismantling. The use of sleeved pipe penetrations and removable tanks may be an alternative.	Designers
1.7.	The design and the installation of pipes and ductwork have to minimize the holdup and deposition of liquids, crude and radioactive dust.	Systems have to be designed to avoid low points, bends and pockets where radioactivity can accumulate. Sufficient access and provision for removal need to be provided.	Designers
1.8.	Where necessary, consider the use of remote handling techniques to remove active items and allow provisions in the design for this application.	There may be instances where the judicious use of remote equipment may be the best solution, and this has to be planned for in the design.	Designers, Planners, Policy makers
1.9.	Limit the use of potentially radioactive underground tunnels, ducts and drains.	These items can be a serious source of contamination accumulation and present difficulties in removal.	Designers
1.10.	Designs have to consider corrosion resistant tanks, containments and sumps with provision for early leak detection.	Tanks and sumps that hold active liquids are not to be permitted without these provisions.	Designers, Regulators

TABLE 1. FACILITY DESIGN AND OPERATIONAL DESIGN FACTORS [8] (cont.)

Feature		Description/comment	Responsibility (organizations and persons)
1.11.	Designs have to provide for ease of chemical decontamination of primary circuits and other contaminated piping systems.	For reactors and radiochemical plants, this will greatly facilitate access for dismantling and reduce dose to workers.	Designers, Operators
1.12.	Wherever possible, contaminated and non-contaminated systems have to be segregated.	It is realized that in some cases segregation may not be practicable and for these cross contaminations need to be avoided.	Designers, Regulators
1.13.	The design has to minimize the number of systems and equipment that will need to be eventually dismantled.	The reduction of equipment and systems will reduce waste volume, dismantling time and cost. (It may also improve plant availability.)	Designers
1.14.	The design has to consider, to the extent practicable, the ability to adapt the capacity and configuration of auxiliary systems that may be required during the decommissioning period.	The design has to consider the extent to which this is feasible and economical. Specifically, electrical, service-water and ventilation systems will need consideration.	Designers, Operators
1.15.	Ensure that the design and operating life of the selected plant and equipment are sufficiently long to be useful for decommissioning.	It will be beneficial to select materials and to design systems such as piping and ventilation for the whole life cycle (i.e. including safe enclosure, where applicable) and decommissioning.	Designers

TABLE 1. FACILITY DESIGN AND OPERATIONAL DESIGN FACTORS [8] (cont.)

Feature		Description/comment	Responsibility (organizations and persons)
2.	**Design for optimization of waste management and contamination control**		
2.1.	Avoid ‘ad hoc’ on-site disposal of waste.	Disposal requires a properly designed and authorized facility. Interim on-site storage has to be strategically located for decommissioning access.	Operators, Regulators, Policy makers
2.2.	Minimize waste volume and total activity.	Good working practices and controls have to be instituted using proper zones and barriers. Plant complexity has to be avoided.	Operators, Regulators, Policy makers
2.3.	Consider dismantling and structural segmentation in terms of waste generation.	The optimum size of waste components and package sizes has to be considered in design and construction.	Designers
2.4.	Seek to simplify waste management operations.	Provide easy-to-follow waste segregation procedures to facilitate waste treatment and management.	Operators, Regulators
2.5.	Provide for waste conditioning during operation and decommissioning and condition the waste for disposal, if possible.	Waste has to be conditioned for disposal or interim storage using agreed waste acceptance criteria (e.g. via early preparation of the disposal waste acceptance criteria). Suitable facilities have to be provided.	Operators, Regulators, Designers
2.6.	Provide expandable waste storage facilities based on life cycle considerations.	All necessary waste storage facilities have to be identified in the design and provided for during construction.	Designers, Policy makers, Regulators

TABLE 1. FACILITY DESIGN AND OPERATIONAL DESIGN FACTORS [8] (cont.)

Feature		Description/comment	Responsibility (organizations and persons)
2.7.	Decommissioning requirements of all waste conditioning and interim storage facilities have to be adequately considered.	The design criteria and proposals for these facilities do not always consider their future decommissioning.	Policy makers, Designers
2.8.	Provide on-site storage for spent fuel, or expandable facilities, to address the entire research reactor life.	These have to be designed for ease of decontamination and for easy dismantling and removal of such facilities.	Designers, Regulators, Policy makers
2.9.	Minimize the generation of mixed and hazardous wastes such as radioactive chemical waste.	Care has to be taken in design, construction, operation and maintenance to avoid producing mixed wastes.	Designers, Operators, Regulators
2.10.	The designs have to consider the segregation of materials to facilitate future waste management.	Barriers and separating partitions have to be considered where different materials and levels of activity are in proximity.	Designers
2.11.	Provide on-site decontamination facilities and equipment for all foreseen operations as well as decommissioning.	This will allow the good practice of dealing immediately with contamination from spills, leakage and maintenance work.	Designers, Operators
2.12.	Seal or line all porous surfaces against the ingress of activity.	Provide impervious materials and use protective covers, as appropriate. Lining of sumps and reactor pits with durable materials will avoid the spread of contaminated liquids.	Designers, Operators

TABLE 1. FACILITY DESIGN AND OPERATIONAL DESIGN FACTORS [8] (cont.)

Feature		Description/comment	Responsibility (organizations and persons)
2.13.	Seal openings created during operations and maintenance to avoid penetration of contamination.	Such openings have to be sealed as soon as possible (when not required) with durable material.	Designers, Operators
2.14.	Designs have to ensure that facilities and equipment such as evaporators for liquid waste (that create high dose areas) are not located in inaccessible or congested areas.	There are cases of serious contamination of these facilities, which are often located in very inaccessible areas.	Designers, Operators
2.15.	Plant personnel have to be trained to recognize the contamination potential at certain facilities and of equipment and avoid unnecessary contamination or cross-contamination.	Inadequate training and poor operating practices for contamination control can add to decommissioning costs and difficulties.	Operators
3.	**Design interface with decommissioning planning**		
3.1.	Facility design processes need to have an iterative interface with the development of the decommissioning plan and associated cost estimates.	There is a need to ensure that the decommissioning plan accurately records the developing design and yields reliable decommissioning costs. A dismantling process will need to be developed.	Designers, Decommissioning experts
3.2.	Estimate future decommissioning costs regularly during design and operation.	Decommissioning costs need to be reviewed and updated at regular intervals.	Policy makers, Owners, Regulators

TABLE 1. FACILITY DESIGN AND OPERATIONAL DESIGN FACTORS [8] (cont.)

Feature		Description/comment	Responsibility (organizations and persons)
3.3.	Design planning may be needed to resolve the interdependence between an operating facility and an adjacent shutdown facility.	This can apply to power plants and nuclear processing facilities that are interlinked with safety systems and services.	Designers, Regulators, Policy makers
4.	**Design interface with licensing and safety**		
4.1.	The entire facility life cycle including decommissioning planning has to be considered in the design.	It has to be recognized that regulatory requirements and facility economics will focus designs on operational safety and system efficiencies. However, decommissioning has to be an important consideration along with the other factors.	Policy makers, Owners, Regulators
4.2.	It has to be recognized that safety during the transition and dismantling period after shutdown may be different from the operating period.	Safety in decommissioning is largely achieved by good working practices.	Designers, Regulators, Operators
5.	**Design interface with radiation protection**		
5.1.	Initial characterization of construction materials is needed to minimize generation of activated and contaminated materials.	Careful selection of materials to minimize the production of activation radionuclides. The baseline inventory of trace elements will be useful in this regard. Minimize the potential for contamination from fission products.	Designers and Materials specialists, Nuclear physicists

TABLE 1. FACILITY DESIGN AND OPERATIONAL DESIGN FACTORS [8] (cont.)

Feature		Description/comment	Responsibility (organizations and persons)
5.2.	Overdesign of biological shielding has to be avoided, especially if it involves poured, reinforced concrete.	Design for average source levels. Use temporary shielding for peak levels. Design measures to reduce radiation during operation will also benefit decommissioning.	Shielding designers, Radiation physicists
5.3.	The design has to consider the use of shielding constructed with removable panels.	Consider modular, prefabricated concrete for shielding. This will facilitate the removal of these items.	Designers
5.4.	Consider modular or temporary shielding.	Design for the use of modular or temporary shielding to simplify removal (see 5.2 and 5.3 above).	Shielding designers
5.5.	Plan for regular and comprehensive site and groundwater monitoring and the rectifying of any leakage problems detected.	This has to be conducted throughout the operating period to avoid having seriously contaminated sites during the decommissioning stage. All spills have to be characterized and recorded.	Operators, Regulators
6.	**Design interface with project management**		
6.1.	The design organization has to establish a procedure for identifying, evaluating and incorporating desirable design features.	Unless a formal procedure is set up within a design organization, many beneficial features are likely to be overlooked. The principle of design for decommissioning has to be adopted. Training will be needed.	Policy makers, Design organization

TABLE 1. FACILITY DESIGN AND OPERATIONAL DESIGN FACTORS [8] (cont.)

Feature		Description/comment	Responsibility (organizations and persons)
6.2.	Maintenance and retrofit procedures and a complete record of activities are useful during decommissioning.	These procedures and their associated records have to be identified and preserved where relevant to decommissioning (see 7.1, 7.2 and 7.4 below).	Designers, Decommissioning planners
7.	**Design interface with documentation and records**		
7.1.	Records specifically needed for dismantling and decommissioning have to be identified during design and construction.	It is suggested that within the existing and permanent plant database, some procedures have to be defined to identify the records (e.g. drawings, change packages, modifications) that are necessary for decommissioning.	Designers, Operators, Policy makers
7.2.	Decommissioning related records have to be carefully preserved for the entire operating life of the facility in an appropriate storage medium.	It will be important to identify the storage medium, location and the long term responsibilities for records management.	Owners, Operators, Policy makers, Regulators
7.3.	Provision has to be made to obtain and retain representative samples of selected plant and construction materials for future analysis.	Very often there are difficulties in obtaining robust data for future safety and technical analysis during decommissioning; samples of the original materials are invaluable to perform new tests.	Designers, Regulators

TABLE 1. FACILITY DESIGN AND OPERATIONAL DESIGN FACTORS [8] (cont.)

Feature		Description/comment	Responsibility (organizations and persons)
7.4.	Provision has to be made to facilitate an accurate inventory and location of radioactive material at the end of the operational life.	Operational records of all events with radiological consequences have to be carefully preserved. Access for characterization also has to be considered.	Operators, Designers
7.5.	Appropriate quality assurance has to be applied to control and record the inclusion of beneficial features for decommissioning.	This will ensure that all features are adequately considered and that records are identified.	Designers, Policy makers

Appendix III

LIST OF POLICY, PROJECT AND REGULATORY FACTORS FOR DECOMMISSIONING

The features presented in Table 2 (adapted from Ref. [8]) consider policy and strategy, licensing and safety, project management, and management of waste and contamination control.

TABLE 2. POLICY, PROJECT AND REGULATORY FACTORS [8]

Feature		Description/Comment	Responsibility (organizations and persons)
1.	**Policy and strategy**		
1.1.	Define decommissioning strategy early.	Need to decide on immediate or deferred dismantling, or other strategies.	Policy makers, Licensees
1.2.	Consider the socioeconomic impact of final shutdown of a nuclear facility.	Policy makers need to have contingency plans available to minimize the impact of sudden or planned final shutdown of a facility. Funds for regional economic transition and incentives for companies to alter their market focus and labour force training are needed.	Policy makers, Regulators
1.3.	Consider the special case of new users of nuclear facilities.	In some countries acquiring new facilities, there may be less appreciation of future decommissioning liabilities. Training is available from many international organizations to provide assistance.	Policy makers, Future owners

TABLE 2. POLICY, PROJECT AND REGULATORY FACTORS [8] (cont.)

Feature		Description/Comment	Responsibility (organizations and persons)
1.4.	Secure decommissioning funds.	Need to establish provisions for adequate decommissioning funding with appropriate oversight.	Owners/ Licensees, Regulators, Policy makers
1.5.	Consider the future reuse of the facilities and site.	Consideration has to be given, if possible, to eventual reuse of the site.	Owners, Policy makers
1.6.	Give attention to planning for the transition period between the end of operation and the start of decommissioning.	Advance planning and training for the transition period is necessary to avoid decommissioning delays.	Policy makers, Licensees, Operators
1.7.	Ensure that lessons learned are recorded and passed on to avoid future problems.	Lessons learned from past and ongoing decommissioning projects have to be considered on a regular basis.	Policy makers, Regulators, Designers
1.8.	For ISD, consider the ability to place grout within underground structures.	A vent path is required to ensure complete filling with pumped grout. If such spaces have a roof without openings, review the ability to place a core drilling machine above the space.	Designers
1.9.	For ISD, consider the ability to place grout within large tanks, vessels and pipes.	Tanks, vessels and large pipes below grade within the structure or buried in close proximity to the facility have to be reviewed for the ability to fill with grout.	Designers
2.	**Licensing and safety**		
2.1.	Simplify licensing procedures for decommissioning.	Endeavour to simplify licensing to minimize complications, delays and costs.	Regulator, Licensee

TABLE 2. POLICY, PROJECT AND REGULATORY FACTORS [8] (cont.)

Feature		Description/Comment	Responsibility (organizations and persons)
2.2.	Consider site release and licence termination.	Recognize the difficulty of terminating the licence and achieving stages and types of site release.	Regulator, Licensee, Owner
2.3.	Perform baseline site characterization prior to construction.	Complete and comprehensive initial site characterization is needed to facilitate licence termination after operation and after decommissioning.	Owner, Designer, Environmental agencies
2.4.	Consider site reuse after decommissioning.	Consideration has to be given to safety issues, environmental issues and amenities in the potential reuse of the site or facilities.	Designers, Policy makers
3.	**Project management**		
3.1.	Justify the provisions of design features specifically needed for decommissioning.	The additional cost to the design versus the benefits of more simple and economic decommissioning need to be evaluated.	Designers, Policy makers
3.2.	The design organization needs to have decommissioning engineers on the reactor design team.	This will ensure input to design on factors that are important to eventual decontamination and decommissioning.	Policy makers, Design organizations
3.3.	It has to be recognized by operators and owners that life extension or output enhancement may increase the cost and complexity of dismantling.	Increased activation, waste volumes and additional SSCs are likely to increase the cost and extent of dismantling work. Decommissioning costs will be adjusted.	Operators, Owners, Policy makers

TABLE 2. POLICY, PROJECT AND REGULATORY FACTORS [8] (cont.)

Feature		Description/Comment	Responsibility (organizations and persons)
3.4.	Avoid tendency towards unnecessary overdesign, especially for structural and shielding concrete.	The selection of construction structures has to be based on engineering calculations according to requirements of regulators or standards. Practices in the past led to very thick concrete structures that might not have been optimized.	Designers, Constructors
3.5.	For research facilities, all contaminated equipment has to be decontaminated and removed after use.	It has to be incumbent on the research team or organization to remove all residual contaminated items.	Researchers, Operators
4.	**Management of waste and contamination control**		
4.1.	A national waste management strategy is needed that includes the decommissioning waste.	This will facilitate the conditioning of decommissioning waste to appropriate disposal criteria.	Policy makers, Regulators, Environmental agencies
4.2.	Consider recycling of material from dismantling and maintenance.	Designs have to consider the eventual recycling possibility of materials.	Designers, Policy makers
4.3.	Promote the continued development of decontamination techniques.	The development of more effective techniques has to be continually promoted.	Operator, Policy makers
4.4.	There is a need to consider the case of countries with very small quantities of radioactive waste.	There is a need to develop a suitable national waste management strategy and policy, no matter how small waste volumes are.	Policy makers, Government authorities

Note: ISD — in situ decommissioning.

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ANNEXES

The case studies presented in the following annexes reflect national experiences in Member States on considerations for decommissioning in the design and operation of research reactors.

They constitute valuable examples of the application of the concepts developed in the previous sections of this publication.

These annexes have been prepared from the original material as submitted for publication and have been edited by the editorial staff of the IAEA to the extent considered necessary for the reader's assistance. The views expressed remain, however, the responsibility of the named authors.

Annex I

INDIA — THE TRANSITION FROM OPERATION TO DECOMMISSIONING OF THE CIRUS RESEARCH REACTOR[1]

I–1. INTRODUCTION

CIRUS, a 40 MW (thermal) tank type research reactor, had been in operation since 1960. The reactor was refurbished from 1997 to 2003 following a comprehensive ageing assessment. It was restarted in 2003 and was shut down permanently on 31 December 2010. Before the reactor was shut down, a scheme for the maximum utilization of fuel had been worked out and implemented, which resulted in the saving of fresh fuel assemblies. Following permanent shutdown, the core was unloaded of all spent fuel assemblies, isotope production assemblies, experimental assemblies and shut-off rods. The spent fuel, which was under interim storage at the reactor site for cooling, was subsequently sent for reprocessing. Radioisotopes were delivered to the radiopharmaceutical division for processing and utilization. Isotope production assemblies were cut to size and sent to the waste management facility for storage and disposal. Detailed radiation mapping, to assess the radiation field inside the core, has been carried out. Moreover, a preliminary waste volume estimation and characterization of radionuclides has been carried out and a detailed radiological characterization has been started. Various reactor systems were maintained initially in wet preservation mode and the chemistry of process fluids was monitored and maintained. Subsequently, the systems were brought to dry preservation mode after draining of process fluids and drying the systems. This state has reduced surveillance requirements as well as maintenance costs. The auxiliary systems are only operated as needed at present. Radiological and industrial hazards were minimized by taking suitable measures, and systems were suitably modified to reduce surveillance. With this, the staffing of CIRUS in round-the-clock shifts ended in July 2017, after approval by the regulatory body, and the reactor is staffed in general shift hours on normal working days. A supervisor assisted by two or three technicians oversees the surveillance activities and execution of other planned jobs. A common radiological hazard control unit for the Dhruva and CIRUS research reactors provides radiological safety and health physics coverage.

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Access control to various areas in and around the reactor building is being maintained in the same manner as it was during the operating days of the reactor. All the areas with potentially high radiation fields and contamination are under access control with lock and key.

For the CIRUS reactor, a deferred dismantling (decommissioning) strategy is considered the best option. Near term, medium term and long term activities have been identified as part of the deferred decommissioning programme. Dismantling of the reactor structure and core components is envisaged after 30–35 years when the dominant radionuclide ^{60}Co will have decayed significantly, for ease of dismantling and handling of radioactive components. Peripheral systems and components will be dismantled and disposed of soon after the shutdown. The ventilation system and other auxiliary systems required for dismantling activities, radiological and industrial safety and the security of the reactor, have been kept operational. Optimum surveillance is being maintained. The resources available at the nearby Dhruva reactor, which can contribute to long term surveillance requirements, help in deciding deferred decommissioning as a preferred strategy. With the implementation of suitable steps, the reactor has been brought to a ‘safe storage’ state.

The activities carried out during the transition period have two main objectives [I–1]:

(a) The efficient operational conversion of the facility from its original mission to one in which operations, surveillance and maintenance are reduced, consistent with the lower safety risk, the systematic reduction in hazards and the need to prepare cost effectively for either safe enclosure or immediate dismantling.
(b) The preparation of a detailed decommissioning plan, which requires the most current information available regarding the condition of structures, systems and components (SSCs) and materials.

I–2. DESCRIPTION OF THE CIRUS RESEARCH REACTOR

Table I–1 shows the characteristics of the CIRUS reactor while Fig. I–1 shows a cross-section of the CIRUS reactor structure. The reactor block is located inside a steel containment, and it houses the reactor vessel, graphite reflector, cast iron thermal shields, aluminium and steel thermal shields and concrete biological shields. The reactor vessel is a cylindrical aluminium tank with a diameter of 267 cm and a height of 320 cm. It has a 7.6 cm thick cylindrical disk-shaped top sheet and bottom tube sheets. Some 199 vertical tubes of different diameters, arranged in a hexagonal lattice, are expanded, rolled in the tube sheets and passed

TABLE I–1. CHARACTERISTICS OF THE CIRUS REACTOR

Reactor type	Tank
Thermal power	40 000 kW
First criticality	10 July 1960
Reactor shutdown for refurbishment	September 1997
Reactor startup after refurbishment	October 2003
Permanent shutdown	31 December 2010
Maximum neutron flux	6.7×10^{13} n cm^{-2} s^{-1}
Fuel	Natural uranium
Coolant	Light water
Moderator	Heavy water
Reflector	Graphite
Shutdown device	B_4C rods

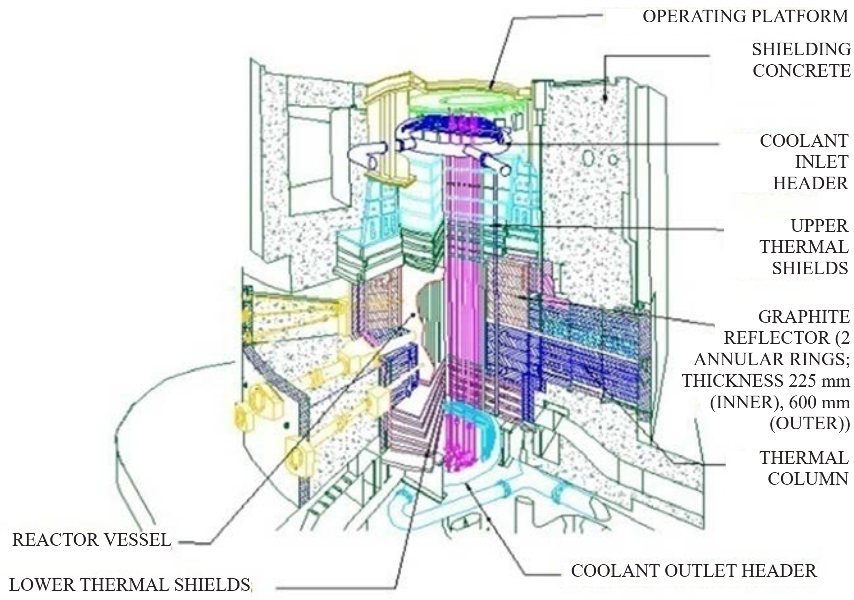

FIG. I–1. Cross-section of the CIRUS reactor structure (courtesy of R. Ranjan, BARC, India).

through the reactor vessel to permit the insertion of in-pile assemblies. The fission heat was removed by the primary coolant provided by four pumps operating in parallel. The primary coolant was in turn cooled by sea water. When the primary coolant pumps were not operating, decay heat was removed by demineralized water provided from a concrete tank (called ‘ball tank’ due to its shape) under gravity. Helium was used as cover gas above the heavy water moderator. Sea water was used to remove heat from the moderator. Primary coolant pipelines were primarily made of carbon steel while that of the moderator and cover gas system were of stainless steel.

I–3. ORGANIZATION AND MANAGEMENT DURING THE TRANSITION PERIOD

For an efficient transition from the operating state to the decommissioning state during safe enclosure, the existing organization set-up was retained. However, the roles of the operating staff changed to reflect the activities during the transition period. In addition to this, a two-tier set-up of experts with experience in reactor operation and maintenance, waste management, robotics and tool development, and radiological protection was established to prepare documents for the decommissioning of the reactor. The lower tier, headed by the decommissioning superintendent, is entrusted with the preparation of the roadmap for the transition from operations to decommissioning and the preparation of procedures, the decommissioning plan and other documents relating to decommissioning. The upper tier, headed by the director or associate director of the reactor group, reviews and approves the documents. The heads of operation, maintenance, technical services, and the waste management facility and radiation hazards control section are members of the upper tier. All plans for decommissioning are subjected to regulatory review. The decommissioning superintendent coordinates and executes the plans. Figure I–2 shows the decommissioning management structure adopted at CIRUS.

I–4. COST REDUCTION BY DECOMMISSIONING OF SYSTEMS OR RECONFIGURATION

During the transition period, activities were planned and carried out that led to simplified operation, reduced surveillance and maintenance requirements and lower operating costs. Systems that became redundant after permanent shutdown were identified. Similarly, systems that could be operated at reduced capacity were identified. Surveillance and testing requirements were optimized

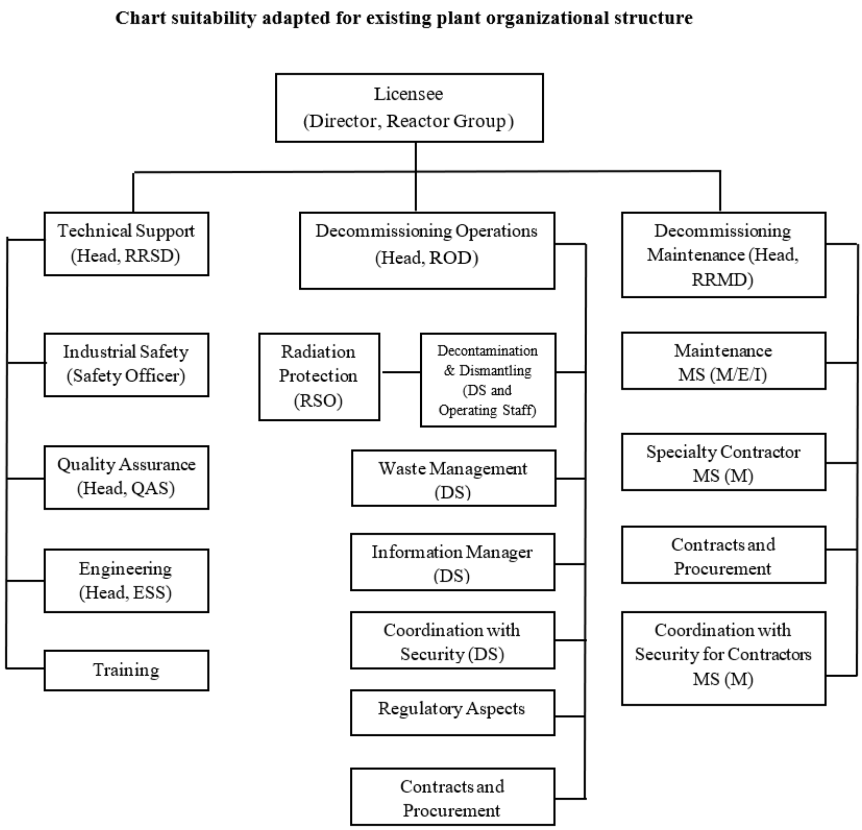

FIG. I–2. Decommissioning management structure at CIRUS (reproduced from Ref. [I–2]).

for the operating systems and suitable amendments were made in the technical specifications.

Cost savings could be achieved from reductions in the following areas [I–1]:

(a) Labour;
(b) Power and fuel consumption;
(c) Consumables;
(d) Surveillance and maintenance;
(e) Regulatory and technical requirements including inspections;
(f) Training;
(g) Recycling of material and components.

I–5. DEVELOPMENT OF TECHNIQUES AND TOOLS

After permanent shutdown of the CIRUS reactor, a cutting tool was developed (Fig. I–3) and a sample from one tube (10.2 cm outer diameter, J-07 lattice position) was cut (Fig. I–4). This tool was used for cutting samples remotely from the tube of the reactor vessel at a location about 8 m below the operating platform [I–3]. Detailed characterization of the sample was performed, and the results of this sample and similar other planned samples provide information on the radioactivity of the reactor vessel. Tools for collecting samples from other pile block components are under development. After sample characterization, the dismantling and disposal programme of pile block components will be made.

The remote reactor vessel tube cutting tool consists of a standard angle drill machine, a drill machine holder, a feeding mechanism and a sample collection mechanism. The drill machine holder is pivoted and supported at the bottommost guide pad. There are two wire ropes that are attached to the drill machine holder. The radial feed of the drill machine is controlled by pulling from them. The drill bit of the angle drill machine is replaced by an end milling cutter for piercing and side cutting. A pick lever is pivoted at the bottom of the drill machine holder

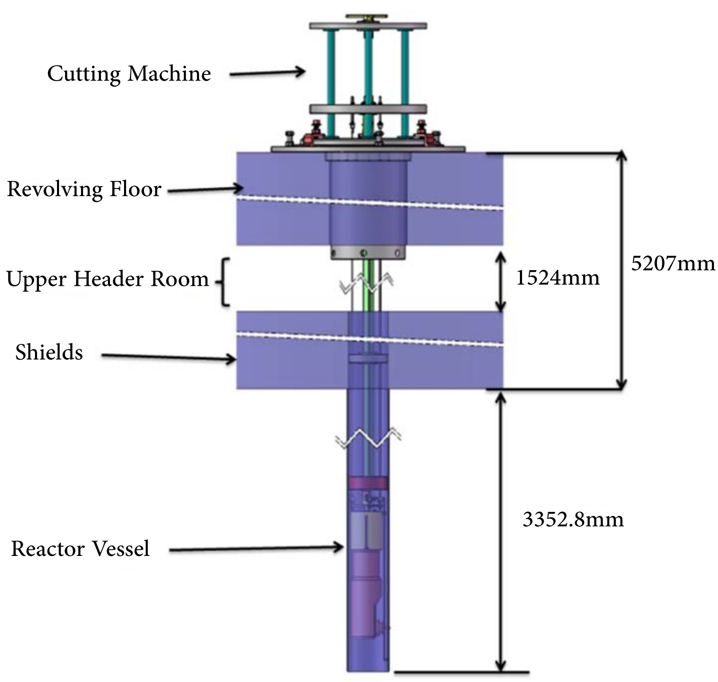

FIG. I–3. Schematic arrangement of the cutting tool (courtesy of R. Ranjan, BARC, India).

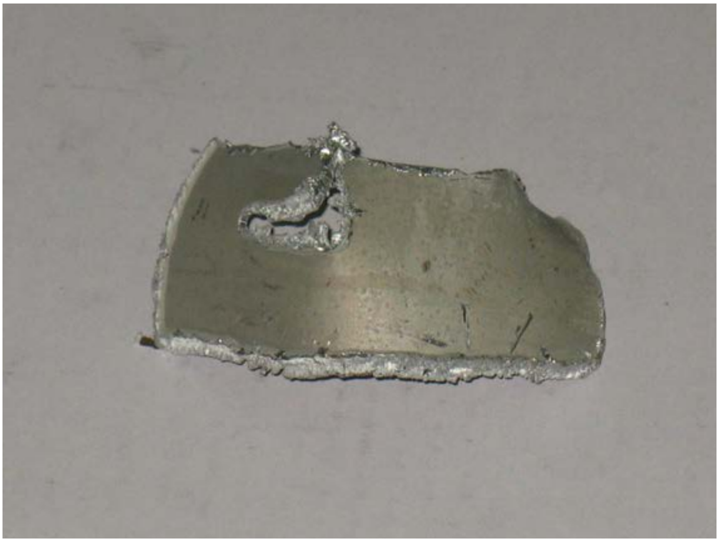

FIG. I–4. Cut from the J-07 tube of the reactor vessel (courtesy of R. Ranjan, BARC, India).

for the collection of samples. For cutting a complete sample, the following feed motions are provided:

— Axial feed motion: The mechanism consists of an axial feed nut and screw mechanism that is connected to the drill machine holder through support pipes and guide pads. The axial feed motion is transmitted to the end milling cutter through rotation of the feed screw by handles welded to the screw, whereas the nut is fixed to the structure.
— Radial feed motion: For radial feed (i.e. into the radial of the tube), two wire ropes are provided and attached to the drill machine holder. The drill machine holder is pivoted through a bracket that is bolted onto the bottommost guide pad. The end milling cutter is advanced or retracted towards/away from the wall of the tube by the relative pull of these wire ropes. The pulling of the wire ropes is provided by a nut and screw mechanism.
— Circumferential motion: The cutting tool assembly is suspended and supported from the top of the reactor revolving floor. It is free to rotate around the axis of the pipe. The circumferential feed/motion is provided to the end milling cutter by rotating the whole assembly manually around the pipe axis.

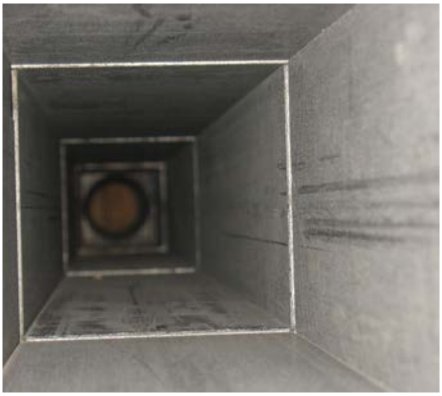

FIG. I–5. East thermal column (courtesy of R. Ranjan, BARC, India).

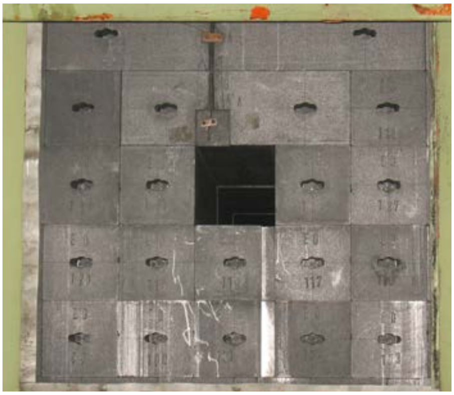

FIG. I–6. Hole after removing the plugs (courtesy of R. Ranjan, BARC, India).

— Pick lever mechanism for sample collection: This mechanism is used to pick up the sample once it has been cut out. It consists of a gravity loaded lever that is pivoted on the drill machine holder at the bottom. Once the sample has been cut, a wire rope is used to actuate the lever for latching it into the slot. The pulling of the wire rope is again achieved by a nut and screw mechanism.

Graphite plugs for sampling could be removed easily and they were found to be intact. On inspection inside the thermal column, it was found that the graphite blocks had not deformed (see Figs I–5 and I–6). This information will help in planning for dismantling of the graphite reflector during pile block decommissioning, without the need for cutting [I–4].

I–6. RADIOACTIVE WASTE MANAGEMENT

A preliminary estimate of waste volume and mass generation during decommissioning with the expected category of the waste has been worked out. A detailed estimate of radioactivity in the waste, including waste from the pile block, is available and will be included in the final decommissioning plan. Table I–2 presents a summary of solid waste generation during various phases of decommissioning.

Most of the equipment in CIRUS is inactive and uncontaminated. Measures have been taken to avoid mixing uncontaminated equipment items with contaminated items. Separate dedicated enclosures have been made for the temporary storage of the items before their final disposal.

TABLE I–2. SOLID WASTE GENERATION DURING VARIOUS PHASES OF DECOMMISSIONING

	Phase	Category	Volume (m^3)	Mass (tons)	Material	Radionuclides	Expected radioactivity (MBq)	Remarks
1	Short term or transition period	I	18.6	—[a]	Shielding sections of spent fuel assemblies	Cs-137, Co-60, Eu-152, Sb-125	17 782	
2		II	2.76	—	Spent fuel storage basin ion exchanger filled with metallic scraps; shielding sections of spent fuel assemblies	Cs-137, Co-60	102 410	
3		III	0.8	—	Sample rod outer sheath and tray section; stringer assembly	Cs-137, Co-60	151 000	
4	Safe enclosure phase	I	381.44	324.3	Primary coolant water; thermal shields recirculation system; heavy water, helium; pressurized water loop system pipes and equipment	Cs-137, Co-60		
5		II	n.a.[b]	n.a.	n.a.	n.a.	n.a.	Unexpected
6		III	n.a.	n.a.	n.a.	n.a.	n.a.	Unexpected

TABLE I–2. SOLID WASTE GENERATION DURING VARIOUS PHASES OF DECOMMISSIONING (cont.)

	Phase	Category	Volume (m^3)	Mass (tons)	Material	Radionuclides	Expected radioactivity (MBq)	Remarks
7		I	508.3	1220	Biological shield concrete			
	Core dismantling phase		911.09	2187	Storage block concrete			
8		I+II	53.31	71.8	Graphite			
9		III	86.3	316.3	Reactor vessel master, plate; thermal shields			

[a] —: data not available.
[b] n.a.: not applicable.

Decontaminated equipment is shifted promptly to its dedicated place. Access to the storage areas is under administrative control. The normal philosophy of ventilation flow from areas with lower activity to areas with higher activity is adhered to. General housekeeping activities are employed using routine monitoring surveys to identify and remove contaminated hot spots. Decontamination exercises prevent the buildup of radioactivity and alleviate contamination problems.

I–7. TRAINING TO SUPPORT THE TRANSITION PERIOD

The extent of training of personnel to support the transition period depends on the activities undertaken. If no dismantling or new activities are to be undertaken, training will be specific to the changing conditions of the facility and the differences between normal operations and permanent shutdown. However, training is required for the dismantling of a non-active plant and the introduction of novel techniques for dealing with wastes. Dismantling of non-active plants can be used to train personnel for the future dismantling of active plants. Training material for personnel is based on the following scenarios [I–1]:

— Facilities currently in operation that are going to be held in a shutdown state: much of the knowledge that was required for past outages, maintenance, refuelling, modernization and modification is needed.
— Facilities that are to be shut down in preparation for safe enclosure or dismantling: training may require the development of skills in such areas as preliminary plant cleanout, waste conditioning and dismantling activities.
— Facilities that have been out of operation for an extended period and that require inspection to determine whether additional preparatory work is needed prior to decommissioning: training in this situation will require gaining familiarization with the existing conditions.

To gain experience with decommissioning, the dismantling of some inactive systems and low active systems has been started. Typical activities during the transition period include the following [I–1, I–5]:

— Recycling or dismantling of usable fissile/fertile materials.
— Removal of spent fuel and other fissile/fertile material from the plant.
— Removal of spent fuel and other fissile/fertile material from the site (if applicable).
— Stabilization, treatment and/or removal of potentially unstable materials or wastes.

— Reduction or elimination of the potential for fire or explosions from violent chemical reactions or nuclear criticality.
— Completion of cleanout operations of systems, lines and other equipment not needed in the future that have the potential for significant radioactive and chemical material inventory.
— Neutralization and disposal of hazardous chemicals and oil in storage.
— Review, using the safety assessment, of changes in the configuration and status of systems and structures because of transition activities (e.g. reducing redundancies in systems and structures).
— Revision of operating requirements and controls as appropriate to changed conditions. This also includes the number of personnel required to maintain the appropriate safety standards.
— Installation and/or verification of sufficient barriers to prevent the spread of contamination.
— Verification of appropriate safeguards and security.
— Checking and updating of relevant facility drawings and other documents to reflect changes that have been made during operation and/or the transition period.
— Training and awareness of facility staff for their future work and roles.

I–8. REDUCTION OF HAZARDS

Following the draining of process fluids from various systems, hazards such as leakage and flooding in local areas, spread of contamination and airborne activity, and electrical shocks due to contact with liquid have to a large extent been eliminated. Fire hazards have been reduced by proper housekeeping and the disposal of inflammable materials. Chemicals such as sulphuric acid (H_2SO_4) and sodium hydroxide (NaOH), which were used earlier for regeneration of ion exchange columns, were disposed of by neutralization. Subsequently, the tanks containing these chemicals were dismantled. Dowtherm-A, which was used as a secondary coolant in the pressurizer water loop system, was sent to the Dhruva reactor for use. Redundant sections of pipelines of the operating systems, such as service water system, machinery cooling water system and compressed air system were isolated using plugs. Operational wastes were segregated and disposed of in accordance with their waste category. Many low-level active components of fuel assemblies, which were earlier recycled, were disposed of as active waste. Measures for radiation hazard control are being maintained as in normal operation conditions. All installed radiation monitors for this purpose, except the neutron monitors (for high natural background radiation areas) in the reactor hall, have been retained and are being maintained.

I–9. RADIOLOGICAL CHARACTERIZATION AT CIRUS

During the refurbishment of CIRUS, several components of the reactor — including piping, storage tanks, sumps and other equipment — were accessible and available for extensive characterization, decontamination and radiation surveying. Samples from most of the components were analysed using high resolution high purity germanium detectors and the results were recorded. This is expected to give reasonable information on the extent of radioactivity present in various components to be decommissioned. Since the data have been collected after 37 years of service, a reasonable extrapolation would be possible with further information during in-service radiation surveys. All data were generated following a reasonable decay period after reactor shutdown, which allowed the short lived radionuclides to decay. Sampling and analysis of radioactivity after permanent shutdown is available to update this data bank. Table I–3 lists typical characterization data of various components.

TABLE I–3. TYPICAL CHARACTERIZATION DATA OF VARIOUS COMPONENTS [I–6]

	Primary coolant pipes	Fuel channel isolating valves	Primary coolant heat exchanger	Primary coolant expansion tank (standpipe)	Hot spots in reactor structure cooling air ducts
Gross specific activity (Bq/g)	6.6	5.6×10^4	1×10^2	1.5×10^3	9.1×10^5
Fission products	50–90%	47%	55%	72%	—[a]
Activation products	10–50%	53%	45%	28%	>99%
Major nuclides contributing to gross activity	^{51}Cr ^{137}Cs ^{124}Sb	^{60}Co (42%) ^{137}Cs (22%)	^{60}Co (25%) ^{137}Cs (22%) ^{152}Eu (15%) ^{125}Sb (16%)	^{60}Co (26%) ^{137}Cs (32%) ^{144}Ce (22%)	^{60}Co (99%)

[a] —: data not available.

I–10. SOLID WASTE ASSAYING SYSTEM

At CIRUS, for characterization of ^{60}Co and ^{137}Cs activity in solid waste, a drum scanning system (Fig. I–7) has been developed and deployed. Solid waste is loaded in 200 L capacity drums that are examined for quantification of ^{60}Co and ^{137}Cs activity in the waste. Examination is conducted in two stages. Transmission computed tomography is used to estimate the linear attenuation coefficient as a function of spatial coordinates. Activity measurements are taken around the drum at certain locations using emission computed tomography and an equivalent source distribution is estimated using the attenuation data obtained in the first stage [I–7].

I–11. RADIOLOGICAL CHARACTERIZATION OF VARIOUS SYSTEMS

During nearly 45 years of CIRUS reactor operation, a significant amount of contaminated equipment, ranging from a very low-level contamination or radiation dose rate up to a very high contamination or radiation dose rate has been

FIG. I–7. Solid radioactive waste drum scanning system (courtesy of R. Ranjan, BARC, India).

TABLE I–4. RADIONUCLIDES IN ACTIVE SYSTEMS

System	Key radionuclides
Reactor structure	Co-60, Zn-65, Mn-54, Cd-109, Cs-137
Primary coolant water system	Eu-152, Ce-144, Sb-125, Cs-137, Ru-106, Mn-54, Co-60
Heavy water system	Traces of Co-60 and H-3 in D_2O and helium lines
Pressurized water loop	Co-60, Ag-110m, Cs-137 (trace)
Ventilation system	Co-60 and Eu-152 (in traces)
Waste disposal system	Co-60, Cs-137, Sb-125

measured and recorded. Radiation dose rates of more than 1 Gy/h exist inside the reactor structure at locations above and below tube sheets of the reactor vessel. Representative areas (and associated equipment) with significant radiation dose rates due to fixed or transferable contamination include equipment of the primary coolant water system, heavy water system, ventilation system, pressurized water loop system, waste disposal system and the spent fuel storage basin (SFSB). The key radionuclides of the above-mentioned systems are specified in Table I–4.

I–12. CHARACTERIZATION OF SOIL AROUND THE REACTOR COMPLEX

Several of the primary coolant and waste transfer pipes are laid underground but are separated from the various utility systems within the plant boundary. To detect leakage from subsoil pipelines and to check migration of radioactivity, several boreholes are provided in and around the reactor complex. Water from these boreholes is sampled quarterly to check the radiological status of the environment around the reactor. During refurbishment for inspection and repair of these pipes, soil was excavated. Several soil samples were collected in and around the plant boundary at varying depths. Most did not show any activity; however, in some places soil was seen to have radioactivity at depths of 1–5 m below surface. This was attributed to leaks from the pipelines during the initial days of operation of the reactor. These pipes have since been taken out of service. As a part of their surveillance, all subsoil pipes are pressure tested at periodic intervals to test for leaks. The soil samples collected have clearly identified the areas where activity has been trapped in soil. This information is very useful in monitoring the area through borehole samples and for eventual clean-up operation during decommissioning. It was seen that ^{137}Cs is the dominant radionuclide, with an activity ranging from 56 Bq/g to 1600 Bq/g, with traces of ^{134}Cs, ^{152}Eu and ^{154}Eu [I–6].

I–13. PREPARATION OF FACILITY ROOMS AND BUILDINGS DURING THE TRANSITION PERIOD

During the transition period, access to rooms and buildings in a radiation facility is defined in at least three ways: 'routine access', 'no access anticipated', or 'completely isolated' [I–1]:

(a) Routine access: Most of the rooms and areas of the CIRUS reactor fall under this category. In these areas, human access for surveillance and/or maintenance can be as frequent as daily or as infrequent as, for example, every three months. Industrial safety standards are provided by temporary, portable or permanent means. Ventilation, lighting and other safety measures are made available, although they need not be operated when the area is unoccupied. Walkthrough routes for periodic surveillance of unoccupied buildings are reviewed for industrial hazards and appropriate protection is put in place (e.g. guardrails, warning signs, selected electrical isolators). Contamination and radiation zones are tightly controlled and delineated to prevent the migration of contamination [I–1].

(b) No access anticipated: These are the areas containing systems and equipment that may act as sources of radiation fields and contamination. Hence, entry to these areas is restricted and permitted only with proper authorization. Examples of this category are main outside active sumps, the wet storage block, chimney access well and water bays in the SFSB.

(c) Completely isolated: Entry will not be necessary until demolition begins. Examples of this category are pile block components such as graphite reflector, steel, aluminium and cast-iron thermal shields, the ventilation duct inside the pile block, and the reactor vessel.

Decisions as to the type of access needed to specific rooms and buildings are closely tied to an evaluation of the surveillance and maintenance requirements. When the surveillance and maintenance routines have been determined and the access requirements have been decided, the results will be important inputs to creating the specifications for the end point of the transition period [I–8].

I–14. SAFETY CONSIDERATIONS DURING THE TRANSITION FROM OPERATION TO DECOMMISSIONING

During the transition period, SSCs are modified and/or decommissioned and their mode of operation may change. Plant personnel are trained for the new configuration of the systems. Operating procedures and drawings are revised accordingly and in a timely manner. Approval and authorization controls are established and documented. Scheduling and sequencing of systems to be changed, modified or decommissioned are coordinated so as to have no impact on the systems and processes required for operations during the decommissioning process. A quality control system ensures that these actions are implemented in an orderly and timely manner [I–9]. Sections I–15 to I–20 describe the major activities that are being conducted during the transition period and the associated safety considerations.

I–15. FUEL HANDLING AND STORAGE

The handling of spent fuel represents the highest radiological source term and highest heat load of any activity following the permanent cessation of power operations. Accidents involving spent fuel have a high potential to result in high occupational radiation exposure. Additionally, spent fuel accidents could cause the dispersal of radioactive contamination on and off the site, beyond the controlled area of the facility. This can complicate decommissioning and the final release of the site for subsequent use and can significantly increase the cost of decommissioning. Core defuelling has to be done carefully and as soon as possible [I–9]. In CIRUS, core defuelling operations were started one week after permanent shutdown and were completed within three weeks. Spent fuel was stored temporarily in the wet storage pool. After the necessary cooling time, the spent fuel was sent for reprocessing. During temporary storage, the water level of the storage pool, the water temperature and water activity were regularly monitored to ensure the integrity of the spent fuel.

I–16. DRAINAGE OF SYSTEMS

The drainage of systems can result in the spread of radioactive contamination to other parts of the facility and systems not intended to be drained. Draining may spread radioactive contamination to other parts of the system such as low-lying points where contamination may settle or can be drained into the drain basin or receptacle. In all cases, the drainage has to be evaluated as to its potential impact on receiving systems, on radiation monitoring procedures that need to be implemented, and on contamination control devices to be installed to monitor for local transitory radiation and contamination levels. The drainage of circuits during the transition period may also generate high volumes of radioactive fluids that need to be treated. These fluids may require filters to retain more radioactive material than during normal operation. Consequently, the filter dose rate may exceed the handling or transport limits. Engineering evaluations need to be performed to assess whether the following apply [I–9]:

— Partial drainage of systems will adversely impact the functionality or operability of the remaining system.
— The drainage process may result in changes in radiation exposures due to a loss of water (i.e. fluid) shielding.
— The liquid processing system is of sufficient capacity to handle the large volumes of liquids.
— The locations for venting siphon break and drain path are adequate.

I–17. CLEANING AND DECONTAMINATION

Based on operational and decommissioning experience, cleaning and/or decontamination efforts have typically been undertaken for the following reasons [I–9]:

— To prepare the system or component for storage or final disposal;
— To separate mixed waste (radiological from non-radiological, asbestos from non-asbestos, and oil from non-oil) to facilitate conditioning, disposal or transport;
— To reduce disposal requirements for a particular waste by reclassifying it from a higher to a lower waste category;
— To reduce occupational radiation exposure during dismantling activities;
— To reduce public exposure during the transport of radioactive material.

Cleaning and/or decontamination may spread radioactive contamination to other parts of the system, such as low-lying points where contamination may settle. Such contamination may lead to high radiation levels owing to the formation of radiation hot spots. Radioactive contamination may also be transported to drain basins or filters, purification components and support piping. This spread of radioactive contamination can be a radiological hazard because concentration levels may be higher than those experienced during reactor or facility operation. In the case of chemical cleaning, each application needs to be specifically evaluated with respect to its effects, because chemical reactivity is highly dependent on the specific material exposed to the reactant or reagent.

I–18. CONDITIONING AND REMOVAL OF OPERATIONAL WASTE

The conditioning and removal or proper storage of operational waste is important during the transition period because it has the potential to adversely affect safe decommissioning. This operational waste includes combustible materials such as rags, wood, oils, plastics, anti-contamination clothing, gloveboxes and other items used during facility operation. It also includes any liquid waste drained from the systems or solid waste generated as part of the transition process. Waste removal operations undertaken during the transition period are normally considered part of the operational activities. These operations may increase the volume and variety of the generated waste. Temporary on-site storage has to take into consideration the following aspects [I–1, I–10[2]]:

— Response to physical security threats;
— Response during radiological or non-radiological facility emergencies;
— Fire detection and suppression capabilities;
— Facility operator activities and monitoring of system performance;
— Safety system operation and availability;
— Exposure of workers;
— Containment of radioactive contamination by reducing the potential for the spread of contaminants.

I–19. EXPOSURE OF PERSONNEL

During the transition period, areas within containment and/or confinement barriers that were previously secured during facility operation may be open for access to personnel. These areas are checked for proper atmospheric controls to support human activities [I–9]. Effective radiation monitoring and personnel exposure controls are established based on the conditions prevailing during the activity. This considers transient radiation levels that could result from the modification or dismantling of SSCs, system flushes and decontamination, or

[2] Reference [I–10] refers to IAEA Safety Standards Series No. WS-G-2.4, which has been superseded by INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Nuclear Power Plants, Research Reactors and Other Nuclear Fuel Cycle Facilities, IAEA Safety Standards Series No. SSG-47, IAEA, Vienna (2018).

changes to installed or temporary radiation barriers consisting of water, metal, concrete or plastic materials. Furthermore, dismantling or changes to structures and ventilation systems may represent unanalysed changes in air pathways, which can significantly affect radiation dose modelling. Appropriate controls need to be implemented to account for changes.

I–20. OTHER ACCIDENTS POSSIBLE DURING THE TRANSITION PERIOD

Other accidents involving radiation may occur during the transition period that could result in adverse radiological conditions. These accidents could involve solid, liquid or gaseous radioactive waste and the processing, packaging and shipping of such waste. Specifically, the rupture of process piping and tanks containing radioactive material may occur. In particular, the likelihood that such accidents will occur may increase during the transition period. Also, because the structures and buildings are changing because of decommissioning, there is a high probability that new or previously unconsidered radiological effluent release pathways may be created. These pathways may not be monitored with appropriate instrumentation and alarms to warn of adverse impacts on the environment. Related accidents include, but are not limited to, the following [I–9]:

— Accidents relating to decontamination, such as leakage of the chemical reagent used for decontamination;
— Accidents relating to radioactive material handling, such as falling containers and spillage of radioactive material;
— Accidents relating to dismantling, such as drop of loads (e.g. heavy components);
— Loss of high efficiency air filtration;
— Leakages of radioactive liquids, and gaseous or solid waste processing system leaks;
— Failure of containment or enclosure;
— Accidents due to operator error;
— Unauthorized activity.

I–21. REVISED TECHNICAL SPECIFICATIONS AS APPLICABLE TO DECOMMISSIONING

In view of the change in the operational status and configuration of systems, there was a need to revise the technical specifications of CIRUS. Accordingly, a new technical specification report with the title “Technical Specifications for Permanently Shut down CIRUS” was introduced after approval by the regulatory authority. Technical specifications relating to nuclear safety issues, such as core cooling, reactivity changes, reactor protection, moderator circulation, pressurized water loop and secondary coolant systems, were no longer applicable and, hence, were not included in the technical specifications. Clauses relating to industrial and radiological safety, fire protection, the ventilation system and SFSB were relevant and, hence, were retained in the technical specifications [I–11]. Clauses relating to administrative controls were also relevant, with appropriate changes regarding staffing requirements. After about two years, due to shipment of all heavy water from the reactor site and the handover of operation of shared systems to the Dhruva reactor, the technical specification report was revised (Rev. 1) and enforced from October 2013. The items important to safety included the SFSB, irradiated graphite, irradiated reactor vessel and structural components, and radioactive components of systems such as the primary coolant and moderator systems. The staffing of CIRUS was entrusted to duly licensed shift supervisors and licensed technicians, who are responsible for the surveillance of the plant areas. The shift supervisor oversees the surveillance activities of the team. There is a common radiological hazard control unit for Dhruva and CIRUS facilities for providing health physics coverage. Any special work at CIRUS involving radiological hazard control coverage is performed only during general shift hours on working days and the dedicated health surveyor is available on such occasions. In 2017, some of the clauses of the technical specifications were deleted or further modified to facilitate the end of round-the-clock staffing of the reactor.

After approval of the deferred decommissioning strategy for CIRUS, process fluids from reactor systems were drained and the system components were dried. Several other actions were carried out to bring the reactor to a safe storage status. The technical specifications were further revised, and a new technical specifications report with the title “Technical Specifications for Deferred Decommissioning (Safe Storage) of CIRUS” was prepared and, following approval by the regulatory body, enforced from January 2020.

I–22. CONCLUSION

A deferred dismantling (safe enclosure) decommissioning strategy has been adopted for CIRUS. After shutting down the reactor permanently, preparatory activities for the chosen decommissioning strategy have been started. The reactor core has been unloaded and spent fuel and heavy water have been removed from the site. Process fluids have been drained from the systems no longer required for decommissioning. The systems required for decommissioning or for the operation of new facilities under installation on the site are being maintained in operational mode. Modifications or simplifications of systems, as appropriate, have been implemented to reduce resource consumption and surveillance requirements. The detailed radiological characterization of reactor components has been started. The preliminary decommissioning plan has been prepared, as well as other documents for decommissioning. Technical specifications of the permanently shut down reactor have been replaced by technical specifications of deferred decommissioning, and a preliminary decommissioning management structure has been put in place.

The following design features of the CIRUS research reactor are conducive to the decommissioning of the reactor:

(a) Material of construction: The reactor vessel, reactor vessel tube sheets and calandria tubes are made of aluminium alloy ALCAN 6056, which facilitates a fast radioactive decay of the irradiated material. Thermal shields located just above and below the reactor vessel are also made of aluminium alloy; the thermal shields located above and below the aluminium thermal shields are made of steel. However, their activation is not significant, as neutrons escaping from the reactor vessel are absorbed by aluminium thermal shields. Removal of the shields can be performed in one piece without cutting them. The reflector, made of nuclear grade graphite blocks, is assembled in a cylindrical shape around the reactor vessel. The blocks are interlocked with each other. This feature will facilitate the removal of graphite blocks during decommissioning, without cutting them.
(b) Layout considerations: The piping layout design of the primary cooling system was such that the complete primary coolant (demineralized water) could be flushed out when needed. This feature would be of great help in case of a fuel failure.
(c) Considerations during operation, including:
    (i) Maintenance of strict chemistry control of process fluids. This helped in the control of corrosion as well as the generation of activation products.
    (ii) Strict control of the quality of the air supply to the containment building, which was used for the cooling of the graphite reflector, ensured that graphite blocks would not stick to each other, and it would be easy to remove them during pile block dismantling. The same is true for thermal shields.

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Annex II

AUSTRALIA — HIFAR DECOMMISSIONING CASE STUDY[1]

II–1. INTRODUCTION

The purpose of this case study is to describe and analyse the key issues and solutions discovered during the decommissioning of the High Flux Australian Reactor (HIFAR), with an emphasis on issues considering the initial design and the activities during the operation stage, before permanent shutdown. These lessons can be applied to the future decommissioning of research reactors.

II–2. SCOPE

The case study in this annex describes HIFAR and its operational characteristics and briefly describes some of the more significant design and operational issues found during characterization of the facility and that are predicted to present sizeable challenges during physical dismantlement. The annex then proceeds to describe the stages of final shutdown of the HIFAR facility and identifies a number of recommendations for actions that would have been beneficial to the subsequent characterization and decommissioning projects.

II–3. HIFAR RESEARCH REACTOR

II–3.1. Introduction

The HIFAR research reactor is located within the grounds of the Australian Nuclear Science and Technology Organisation (ANSTO), at 32 km southwest of the Sydney central business district. HIFAR was a 10 MW heavy water moderated and cooled reactor of the DIDO class. Initially, it used highly enriched uranium as fuel, but was later converted to use low enriched uranium. HIFAR went critical for the first time on 26 January 1958. It was a multipurpose nuclear reactor used for:

- The production of radioactive isotopes for Australian nuclear medicine and industry;
- Materials testing;

[1] Alec Kimber and Warren Imisides, Maintenance and Engineering Decommissioning Programme, ANSTO.

— Neutron beam experiments;
— Silicon doping (neutron transmutation doping);
— General research purposes.

HIFAR was permanently shut down on 30 January 2007, after 49 years of operation, when the OPAL reactor, which was commissioned in 2006, replaced it. At present, HIFAR is in the planning phase to transition from a ‘care and maintenance’ to a ‘decommissioning and dismantlement’ licence. The following section provides information about HIFAR and a description of the more important existing systems and circuits when they were operational.

II–3.2. Design and construction

HIFAR is a DIDO class reactor designed by Head Wrightson Processes (HWP). HWP designed all six DIDO class reactors operated worldwide, all of which are now permanently shut down and at various stages of decommissioning. The other five DIDO class reactors are Dounreay Materials Testing Reactor (UK), DIDO (Harwell, UK), PLUTO[2] (Harwell, UK), FRJ-2 (Jülich Research Centre, Germany), and DR-3 (Risø National Laboratory, Denmark).

II–3.2.1. Principal characteristics of HIFAR

The characteristics of HIFAR are summarized in Table II–1. The reactor containment building and its contents are shown in Fig. II–1 and a 3-D diagram of the reactor block above the D_2O plant room is provided in Fig. II–2.

TABLE II-1. SUMMARY OF HIFAR CHARACTERISTICS

Item	Detail
Reactor type	DIDO
Faces	10
Height (base to top of concrete)	5.0 m
Height (base to top of top plate)	6.0 m
Height of reactor top above ground	11 m
Diameter (face to face)	6.7 m

[2] PLUTO and DIDO reactors are essentially of the same design.

TABLE II-1. SUMMARY OF HIFAR CHARACTERISTICS (cont.)

Item	Detail
Facilities – horizontal	30
Facilities – vertical	28
Mass	974 t
Fuel element positions	25
Full thickness of biological shield	1.527 m
Fuel	Initially highly enriched uranium; by 2007 HIFAR was using a low enriched uranium (19.6% enriched) core
Moderator/coolant	10.1 t D_2O
Secondary cooling	H_2O via cooling towers, associated pumps and pipework
Coolant temperature	50°C
Full power	10 MW
Maximum thermal neutron flux	1.4×10^{14} $n \cdot cm^{-2} \cdot s^{-1}$
Control absorbers	Europium and cadmium
Applications	Materials testing, medical isotope production, silicon and other isotope irradiations
Built	1954–1958
First criticality	26 January 1958 (Australia Day)
Commenced routine operations	1960 at 10 MW
Permanent shutdown	30 January 2007
No. of major shutdowns	13
No. of operating days	13 631
Total megawatt days	136 310
Last operations programme	585

FIG. II–1. Internal image of the reactor containment building showing HIFAR and peripheral equipment (courtesy of A. Kimber, ANSTO, Australia).

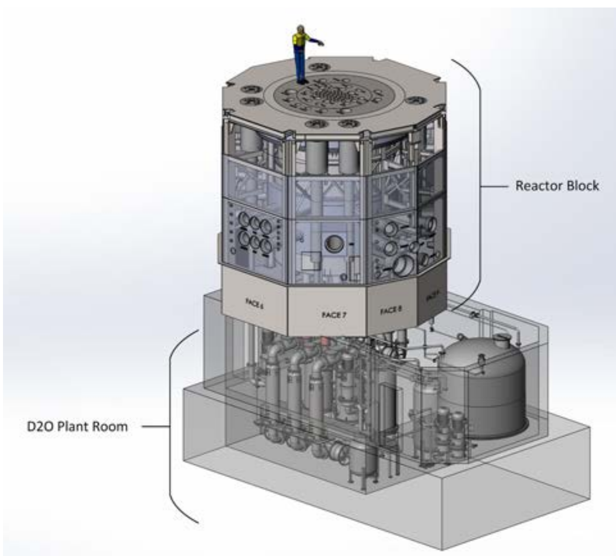

FIG. II–2. A 3-D diagram of HIFAR showing the reactor block above the D_2O plant room (courtesy of A. Kimber, ANSTO, Australia).

II–3.2.2. HIFAR licensing

HIFAR moved from an operational licence (FO0044-4A) to a 'possess or control' (PorC) licence[3] on 15 September 2008. Broadly, this licence allowed ANSTO to:

- Care and maintain the facility whereby a state of 'safe enclosure' is achieved;
- Characterize the facility to the extent approved by the chief executive officer of the Australian Radiation Protection and Nuclear Safety Agency ARPANSA[4];
- Dismantle components that meet approved exemption criteria.

II–4. DESIGN AND OPERATIONAL ISSUES AFFECTING DECOMMISSIONING

This section identifies the main design and operational issues that affected operational activities, characterization and decommissioning.

II–4.1. Design issues

II–4.1.1. Use of stainless steel thimbles

In preparation for an increase in reactor operating power to 15 MW, several of the original, horizontal aluminium thimbles in the experimental facility were replaced gradually with stainless steel thimbles integrated into experimental rigs. This design change was to mitigate damage to the aluminium from an expected neutron thermal loading in the future. The neutron activation of the stainless steel results in greater risks at the decommissioning stage, caused by the presence of radionuclides such as ^{60}Co, and presents a more complicated waste stream.

II–4.1.2. Depleted uranium shielding

The triple axis spectrometer neutron beam instrument used depleted uranium as part of its biological shield. During use of the instrument, neutron

[3] A 'possess or control' licence is a type of facility licence most commonly issued for a prolonged period of safe enclosure between periods of routine operations or leading to decommissioning of the facility.

[4] ARPANSA acts as the Australian Government's primary authority on radiation protection and nuclear safety.

scatter from experiments transformed some of the depleted uranium into plutonium. This component of the shielding is considered a nuclear controlled material, which represents a unique handling hazard during decommissioning and complicates the waste stream.

II–4.2. Operational issues

II–4.2.1. Fission products in the primary cooling circuit

In the early 1960s, there were several releases of tramp uranium contamination from the outside surface of the fuel elements into the primary cooling circuit, leading to the production of fission products that contaminated all the internal surfaces of this particular circuit. Although the fission products were burnt up in the reactor tank and the cooling circuit was flushed out several years later, a degree of contamination remains, resulting in greater risks during dismantlement and presenting additional decontamination challenges.

II–4.2.2. Damaged strainer in the primary cooling circuit

During an early life maintenance shutdown, a stainless steel bolt was left in the primary cooling circuit. The bolt moved through the circuit at reactor startup and was eventually captured by the strainer of a heat exchanger. Over an extended period, the bolt abraded itself as well as the strainer, causing stainless steel debris to be activated and circulated around the entirety of the circuit. Although the reactor tank and cooling circuit were flushed at a later stage (and at considerable expense), activated debris remains in low-lying points of the circuit, resulting in higher risks at dismantlement and presenting additional decontamination challenges.

II–4.2.3. Water leak in the shield cooling circuit

In May 1961, leakage was detected in a cooling circuit, which penetrated the concrete biological shield of the reactor. External minor leaks seeped through the biological shield and dripped onto the leak detector system of the primary cooling circuit, causing false alarms. During a major shutdown in 1970, a hole was bored into the biological shield and repairs were made to avoid this leakage. On completion of all repairs, the biological shield was restored by vibrating a dry barite concrete/polythene chip mix into the hole along with extra lead shielding. At the future dismantlement phase, this repair will further complicate both the planning and the cutting of the biological shield.

II–4.2.4. Overflow of the collimator cooling circuit

In March 1994, a spillage of contaminated cooling water from the collimator cooling circuit caused a localized contamination event in the basement of the reactor containment building and the D_2O plant room. The spillage was cleaned and the accessible area was decontaminated. The inaccessible areas that could not be cleaned up and decontaminated will present a higher risk and additional decontamination challenges at the dismantlement phase.

II–5. DECOMMISSIONING PHASES OF HIFAR AND ESTIMATED WASTE REMOVED

Several decommissioning strategies dating back to 1993 were considered for HIFAR. The strategy chosen prior to permanent shutdown of the reactor was contained in a 2005 report [II–1], which recommended decommissioning to be undertaken in three phases:

- Phase 1: Permanent shutdown;
- Phase 2: A period of possess or control, allowing for characterization work and decommissioning planning;
- Phase 3: Final decommissioning.

After HIFAR was permanently shut down in 2007, the fuel, heavy water moderator and the reactor control arms were removed. Additionally, over the next five years to 2012, some redundant systems were removed and upgrades were made to systems for radiation and stack monitoring, fire protection, supervisory control and data acquisition, heating, ventilation and air conditioning, and security. In late 2014, a project was initiated to characterize the HIFAR facility, which culminated in a two volume report describing the facility, identifying its radiological risks, quantifying the radionuclide inventory and estimating its waste types and volumes [II–2].

II–5.1. Phase 1: Permanent shutdown

During the preparation for permanent shutdown of the HIFAR facility, operations staff focused on the planning for the safe shutdown, physical shutdown and move from an operational licence to a possess or control (PorC) licence. The activities of this phase included the removal of the reactor fuel, the heavy water moderator and the reactor control arms, as well as the instigation of a care and maintenance plan. After permanent shutdown, several projects were initiated to complete upgrades in preparation for a PorC period, including the following:

- — Preparation and submission to the regulator of an application for a PorC licence;
- — Planning for the removal of the redundant plant and equipment;
- — Installation of a new radiation and stack monitoring system;
- — Upgrading of fire protection systems;
- — Improvement of the systems for heating, ventilation and air conditioning, supervisory control and data acquisition, security, and communication;
- — All other actions required to move from operations to the PorC period.

In parallel to their duties in Phase 1, operational staff were also involved in preparations for decommissioning, which included undertaking studies on dismantlement methods, collaborating with other DIDO reactor groups and reconfirming the decommissioning strategy outlined in the 2005 report [II–1]. This was supported by an engineering department project manager.

II–5.2. Phase 2: Possess or control period

The PorC period began in late 2008 with a plan to commence decommissioning and dismantlement after a ten year period to allow for radioactive decay. During this period, former operational staff removed approximately 15% of the redundant plant and equipment and completed upgrades to various systems to allow for operation as a safe enclosure. In late 2014, as the end of the ten year decay period was approaching, it was realized that the completed work on characterization had been insufficient, which would impact the commencement of decommissioning. This prompted the development and initiation of a project, resulting in funding of $A9.96 million being granted for the commencement of the HIFAR characterization project.

Once the project had begun and a team had been assembled, it was identified that collaboration and input from international expertise would be highly beneficial. To that end, a workshop was held, with engagement from enresa, the Spanish radioactive waste management agency, a private company specialized in project costing and based in the United Kingdom, DIDO reactor teams from Germany and Denmark, and ARPANSA, Australia’s nuclear regulatory body. The workshop also included subject management experts from ANSTO, including staff from waste management services. At the conclusion of the workshop, there was a clear course of action for the project team to commence detailed characterization and decommissioning planning.

The project team, over the next four years of characterization, completed the following activities:

(a) A historical site assessment of the HIFAR facility.
(b) A 3-D solid works model of the HIFAR reactor and D_2O plant room.
(c) Compilation of a searchable database of 9000 drawings and more than 730 records identifying operational radiological incidents.
(d) Frequent engagement with the regulator.
(e) Planning and submission for regulatory approval to complete characterization work.
(f) Execution of the characterization plan for:
    (i) Reactor internals and biological shield;
    (ii) Neutron beam instruments;
    (iii) Peripheral plant and equipment;
    (iv) Irradiation rig equipment;
    (v) Items stored in the No. 1 storage block.
(g) Development of a configuration management system to store and manipulate the characterization data as well as track the location of components.
(h) A neutron flux model of the reactor block and a model for determining activation.
(i) Development of specialized characterization equipment based on the theory of compressed sensing.
(j) Preparation and publishing of the final characterization report.
(k) A class IV budget estimate utilizing IAEA CERREX-D software [II–3].
(l) Finalization of the decommissioning strategy into two separate projects.

II–5.3. Phase 3: Final decommissioning

The final decommissioning of the HIFAR facility was determined to be best achieved in two separate stages, with the first stage being ‘everything except the reactor block’.

In mid-2019, and following on from the success of the characterization project, the HIFAR Phase A decommissioning project was established. The scope of the project is to prepare to move from the PorC period to a decommissioning licence to remove the following:

— Neutron beam instruments;
— Peripheral plant and equipment;
— Irradiation rig equipment;
— Items stored in the No. 1 storage block.

This first project was determined to present the most manageable radiological risks, with only minor contamination and localized activation of components requiring minimal handling.

In the second stage of this phase, dismantlement of the remainder of the facility will be conducted, during which the installed rigs, reactor internals, reactor biological shield and the main building structures will be dismantled.

The rationale behind a two stage project approach was that it would build on the knowledge gained from the characterization of HIFAR and mitigate increased decontamination and dismantling (D&D) risks associated with the loss of people with sufficient decommissioning experience and knowledge of the facility in its current state. It would also permit an agile approach to the project with feedback from various parties on the project's risk and safety management, while allowing for possible resource levelling for regulatory reviews, Q&A meetings and site inspections.

II–5.4. Estimate of waste types and volumes arising from the decommissioning of HIFAR

An estimate of HIFAR's decommissioning wastes and their classification is presented in Table II–2.

TABLE II–2. ESTIMATES OF HIFAR'S DECOMMISSIONING WASTES AND THEIR CLASSIFICATION

Structure, system and components (circuit ID)	Packaged ILW (m^3)	Packaged LLW (m^3)	Free release waste (m^3)
Cooling plant systems and circuits			
Primary cooling system (01 circuit)	0.6	3.21	48.6
Blanket gas system (02 circuit)	0.0	3.44	79.1
Graphite blanket gas system (03 circuit)	0.0	0.1	0.2
Secondary cooling system (04 circuit)	0.0	0.0	2.0
Shield cooling system (05 circuit)	0.0	0.2	1.8
Experimental rig cooling system (06 circuit)	0.2	1.7	1.0
Storage block cooling circuit (17a)	0.0	1.2	4.0

TABLE II–2. ESTIMATES OF HIFAR'S DECOMMISSIONING WASTES AND THEIR CLASSIFICATION (cont.)

Structure, system and components (circuit ID)	Packaged ILW (m^3)	Packaged LLW (m^3)	Free release waste (m^3)
Reactor utilization			
Neutron beam instruments	0.0	2.54	45.3
Irradiation rigs and equipment	0.0	1.44	10.8
Handling of radioactive materials			
Storage block contents (17)	10.8	1.3	1.4
Flasks (42)	0.2	2.0	5.3
Fuel assembly station (41)	0.0	0.2	1.0
Silicon storage blocks (58)	0.0	0.9	8.3
Other			
Control room	0.0	0.0	10.0
General equipment within the reactor containment building	0.0	0.0	25.0
D&D secondary waste	0.0	10.0	0.0
HIFAR Phase A totals	11.6	28.23	244.0

II–6. FINDINGS

The overall design of the reactor, its peripheral plant and equipment and its safe operation have contributed to achieving good characterization results and effective decommissioning planning for D&D activities. However, a number of earlier decisions made during operations and the final shutdown of HIFAR had a significant impact on this work. The apparent issues and underlying causes of these earlier decisions are presented in Table II–3.

TABLE II–3. ISSUES THAT BECAME APPARENT DURING DECOMMISSIONING AND DECOMMISSIONING PLANNING

	Issue	Underlying cause	Effect on shutdown and decommissioning
1	Early characterization data of items decommissioned during operations were not available	No dedicated role during HIFAR's operational life responsible for the collection of data that would aid characterization and eventual decommissioning	— Many items held within the facility had to be characterized and their physical details identified, which increased the work required to complete scoping surveys — Project schedule and cost were impacted negatively
2	There was no collation of operational records or radiological incidents	No dedicated decommissioning team available to provide specialist advice during the final stages of operation and shutdown	— The project team had to spend time and resources to collate the information into a database — Risk that the project team might not have discovered all the radiological incidents that could lead to higher safety risks
3	Late formation of a decommissioning team leading to gaps in knowledge and capability	A poor understanding of the complexity and challenges of decommissioning an entire nuclear facility	— Gaps in capability had to be either learned 'on the job' or through training that incurred additional expenses — Inefficiencies due to some repeated work and mistakes being made — Limited on-site support for services such as radiochemistry
4	Shortage of resources due to startup of the new OPAL reactor, the permanent shutdown of HIFAR and decommissioning planning	— Insufficient planning and resource priority for the equivalent of two reactors — Management focus to reduce cost of HIFAR operating licence and facility staffing	— Too quick to let go of staff, resulting in a loss of resources in the HIFAR facility — Limited capability to plan the PorC period, resulting in restrictive licence conditions — Difficulty retaining/engaging with key staff because of uncertainty of commitment to decommissioning strategy

TABLE II–3. ISSUES THAT BECAME APPARENT DURING DECOMMISSIONING AND DECOMMISSIONING PLANNING (cont.)

	Issue	Underlying cause	Effect on shutdown and decommissioning
5	Only 15% removal of redundant systems was completed (25% removal was planned)	Having a restrictive PorC licence hindered the post-shutdown project work	— Post-shutdown goals were not achieved (e.g. an external, contaminated system could not be removed as planned) — Characterization work was hampered owing to the non-removal of some redundant systems — Extra characterization and decommissioning planning work were required
6	Stakeholders have an expectation that the characterization is a once-only task, and that the facility would be 100% characterized	A poor understanding of the complexity, challenges and timing of characterizing an entire nuclear facility	Because characterization results are not at 100%, the risk assessments for D&D planning and activities have tended to be very conservative
7	Restrictive PorC licence hindered characterization and decommissioning planning	— Poor regulator engagement — Lack of a dedicated decommissioning team available to provide specialist advice — Insufficient planning at final shutdown stage led to a poor understanding of the requirements of the decommissioning stages	— Excessive regulatory authorizations were required for characterization work — Concerns of the regulator that the project would complete some decommissioning ‘by stealth’ during characterization — The project was unable to complete 100% characterization — Decommissioning planning was hindered owing to the inability to fully determine D&D risks

TABLE II–3. ISSUES THAT BECAME APPARENT DURING DECOMMISSIONING AND DECOMMISSIONING PLANNING (cont.)

	Issue	Underlying cause	Effect on shutdown and decommissioning
8	Projects undertaken during the immediate shutdown period required: — Multiple safety reviews and impact assessments — Duplicate documentation — Multiple sign-off for work packages	The projects were managed using the onerous HIFAR quality management system design for a fully staffed, operating reactor	— There were additional cost and schedule implications — Post-shutdown removal of redundant systems was only 50% achieved, which increased the scope of characterization and D&D activities
9	At the time of the PorC period, ANSTO had not fully committed to a single decommissioning strategy for the HIFAR facility, with varying ‘appetite’ for its decommissioning	— Multiple strategies had been put forward over many years (some with 30 year and 100 year D&D delay) — No single decision-making authority to provide a definitive project champion — Building of new facilities and new projects are given a higher priority than decommissioning a facility	— During the PorC period, the chosen decommissioning strategy had to be reconfirmed via a detailed case study — Earlier heritage decisions were ignored, leading to resistance as to what could be dismantled — Low priority for project resources
10	ANSTO systems (safety, project control, waste management) not optimized with requirements for nuclear facility decommissioning	A poor understanding of the complexity and challenges of decommissioning an entire nuclear facility	— Inefficiencies in project control, delays to safety assessments and ongoing difficulties for waste packaging and characterization — Many roles required for a redundant facility

TABLE II–3. ISSUES THAT BECAME APPARENT DURING DECOMMISSIONING AND DECOMMISSIONING PLANNING (cont.)

	Issue	Underlying cause	Effect on shutdown and decommissioning
11	$A2.2 million was taken from the budget of the characterization project	— The budget of the characterization project was used to fund the transport and refining of ex-HIFAR heavy water — The HIFAR heavy water legacy waste was given a higher priority than the characterization of HIFAR — Planning and funding for the disposal of HIFAR heavy water was not completed during the permanent shutdown phase	— Reduction in scope for characterization of the facility — Funds for training and collaboration trips overseas had to be cut — The plans to remove redundant plant and equipment were shelved

II–7. DISCUSSION

While characterization and the decommissioning planning for HIFAR have, broadly, been very successful, underlying issues have created extra work and have impacted on the overall costs of decommissioning. Most of these issues have been brought about by not fully committing to the strategy to decommission the HIFAR facility and having no dedicated role to both develop and champion the agreed strategy. Although the strategy called for a dedicated team of up to ten people to plan the decommissioning and support the permanent shutdown of the HIFAR facility, the OPAL reactor was coming on-line and its final construction and startup were very high priorities for the operating organization. This resulted in dilution of resources, which led to insufficient D&D planning, and poor engagement with the regulator, which resulted in a restrictive PorC licence. Additional complexities were caused by having a team consisting predominantly of former operational staff that had a lack of understanding of the requirements to both characterize and decommission a nuclear facility.

Additionally, the organization had limited decommissioning experience with systems, and the infrastructure was not optimized for large nuclear D&D

projects. The organization had limited capability to handle, package and store waste as well as to support characterization with radionuclide analysis. These limitations combined with the restrictive PorC licence presented challenges that manifested a loss of focus and appetite for the decommissioning of HIFAR.

II–8. LESSONS LEARNED

The following lessons were learned:

(a) During operations, have a dedicated role responsible for facilitating future decommissioning, including:
   - (i) Collation of operational records and early characterization data;
   - (ii) Recording of radiological incidents;
   - (iii) Recording characteristics of items decommissioned during operations;
   - (iv) Evolution of a decommissioning strategy;
   - (v) Early engagement with regulators, both internal (from ANSTO) and external (from ARPANSA).

(b) Approximately 2–5 years prior to permanent shutdown, assemble a dedicated team that has some degree of decommissioning expertise and sufficient operational knowledge of the facility. This team has to be independently funded, with its own reporting relationship, and is responsible for:
   - (i) Finalizing the decommissioning strategy;
   - (ii) Developing the characterization and decommissioning plans;
   - (iii) Defining the requirements for the PorC period;
   - (iv) Developing and negotiating the licence for the PorC period;
   - (v) Undertaking all necessary training;
   - (vi) Ongoing communications with regulators;
   - (vii) Performing a gap analysis of the capabilities for a large-scale nuclear decommissioning project;
   - (viii) Identifying the complexities, challenges and risks that characterization and D&D activities impose on the organization, and clearly communicate these to senior management;
   - (ix) Planning for and removing from the plant all possible low radiological risk equipment to minimize the interference with characterization work and eventual D&D activities.

(c) During the transition from operation to decommissioning, ensure the following:
   - (i) All decommissioning activities retain sufficient resources;
   - (ii) Funding is sustained and robust;
   - (iii) The decommissioning team is not distracted by external priorities.

(d) The project is provided with sufficient gravitas from an authority acting as a champion of the project.

II–9. CONCLUSIONS

Many of the discussed issues have to do with the correct allocation and timing of resources and the effect of distractions. In this case, the distraction was attempting to shut down the HIFAR facility while committing to the successful startup of the new OPAL reactor. We believe that, in general, if the items shown in Section II–8 are implemented prior to the permanent shutdown of a research reactor, the issues identified during our experience with the HIFAR facility would be negated.

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Annex III

FINLAND — DECOMMISSIONING OF THE FIR 1 TRIGA RESEARCH REACTOR[1]

III–1. INTRODUCTION

Finland's only research reactor FiR 1, a 250 kW TRIGA MkII open tank reactor, was operated from March 1962 until its permanent shutdown in June 2015 (Figs III–1 and III–2). The reactor is now defuelled and in a permanent shutdown state; the technical maintenance and security surveillance of the reactor and the premises are continuing. Preparations for decommissioning are close to completion. In accordance with the Nuclear Energy Act [III–2], in June 2021 the Government of Finland granted Finland's first nuclear decommissioning licence to the operator, VTT Technical Research Centre of Finland, for the decommissioning of FiR 1.

In this case study, we will (i) review the activities on ageing management and spent fuel management performed prior to decommissioning; (ii) describe the reactor's technical characteristics, past activities and radioactive inventories; (iii) review the organizational and management activities between shutdown and decommissioning; and (iv) review VTT's experiences and lessons learned concerning the decommissioning.

III–1.1. Ageing management

Nuclear energy legislation in Finland requires that a research reactor will have a document describing ageing management. IAEA Safety Standards Series No. SSG-10, Ageing Management for Research Reactors [III–3][2], was used in creating the ageing management system at FiR 1 prior to the licence renewal in 2011. The work included extension and improvement of inspection and service procedures, creation of an obsolescence management system for the systems, structures and components (SSCs) and identification of the SSCs important

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[1] Markus Airila, Iiro Auterinen, Jori Helin, Tommi Kekki, Perttu Kivelä, Petri Kotiluoto, Anumaija Leskinen, Antti Räty. The material in this annex has been reproduced with permission from Ref. [III–1] and edited by the editorial staff of the IAEA to the extent considered necessary for the reader's assistance.

[2] SSG-10 has been superseded by INTERNATIONAL ATOMIC ENERGY AGENCY, Ageing Management for Research Reactors, IAEA Safety Standards Series No. SSG-10 (Rev. 1), IAEA, Vienna (2023).

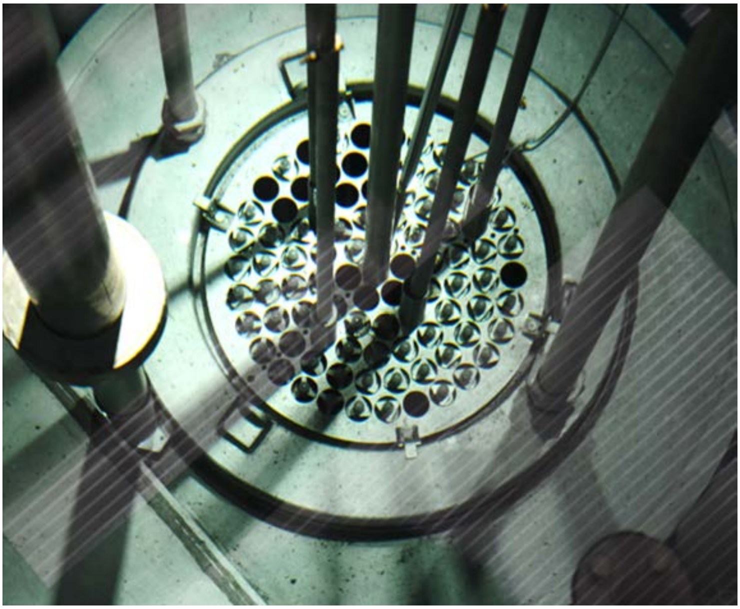

FIG. III–1. At the end of 2015, the core was made permanently subcritical by removing a sufficient number of fuel elements (courtesy of VTT, Finland).

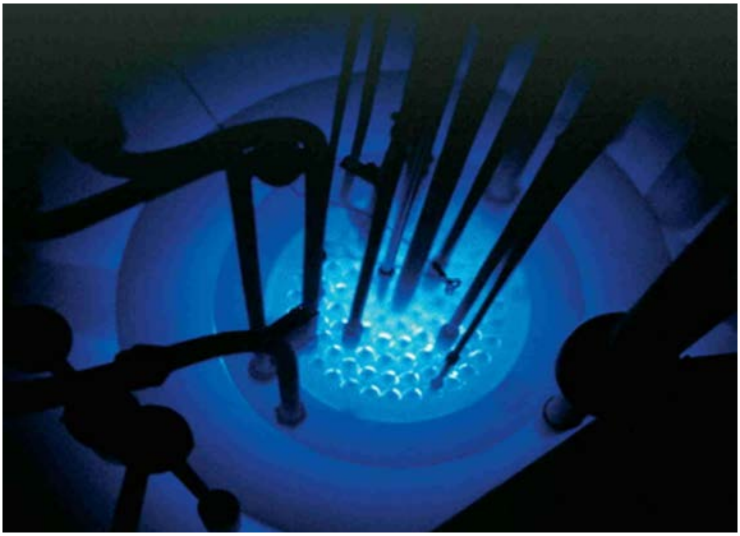

FIG. III–2. The core of FiR 1 in operation (courtesy of VTT, Finland).

to safety and the reliable operation of the reactor as well as their degradation processes that affect safety and reliability [III–4].

The ageing management system includes procedures for the detection and assessment of ageing effects as well as for the prevention and mitigation of ageing effects. To improve the ageing management, the quarterly and yearly inspections were extended to all SSCs and the data logging was improved to aid the analysis of the ageing process. The inspection of the reactor tank walls and beam tubes includes a wider selection of methods and the number of inspection points was increased.

The introduction of the ageing management programme for FiR 1 almost coincided in time with the decision to shut down the reactor, but the two events were not related. In fact, at the end of 2011, VTT was granted a new operating licence that would have been valid until the end of 2023. The shutdown decision came soon after, in July 2012, since the company responsible for boron neutron capture therapy (BNCT) treatments was declared bankrupt. Despite the sudden change of plan, VTT has continued implementing the ageing management programme also in the permanent shutdown state to maintain a good condition of all SSCs.

III–1.2. Shipping of FiR 1 irradiated fuel for re-use in the United States of America

The amount of irradiated fuel at FiR 1 after operation from 1962 to 2015 was 103 elements (about 15 kg of uranium, of which 3 kg was ^{235}U). The fuel was subject to the return programme of the United States Department of Energy, which was set to expire in May 2019 but was extended to May 2029 just before its expiry. The primary scenario for disposal of the nuclear fuel was to send it to Idaho National Laboratory (INL) in the USA where similar batches of nuclear fuel from TRIGA research reactors have previously been returned from various countries. The programme has, however, been halted since 2014. Since fuel removal from the site is such a key step in decommissioning, this blockage was a long-standing challenge for VTT in planning, licensing and contracting the following phases.

VTT considered return to the USA as the primary option for spent fuel and constantly maintained the possibility since 1981. Even the timing of the permanent shutdown of FiR 1 was decided such that it fulfilled the fuel return programme requirements (i.e. before May 2016). In parallel, VTT maintained a secondary option — final disposal in Finland — which would, however, have required proper additional licensing of the encapsulation and spent fuel disposal facilities that are now under construction by Posiva in Olkiluoto, on the western coast of Finland.

In July 2020, the US Geological Survey (USGS) in Denver, Colorado, informed VTT that USGS would need additional fuel to continue operating its reactor. As the production of suitable fuel had been suspended for several years and was not available on the market, it was of mutual benefit for both parties that the used FiR 1 fuel be transferred to the USGS for further use in its reactor. The fuel has a remarkable remaining utility value, with the maximum burnup being about 24%. At the end of operation, the United States Department of Energy would take care of the fuel.

The contract for the supply of used fuel was concluded in November 2020, and VTT arranged for the safe international transport of the fuel from Espoo, Finland, to the USGS with support from Edlow International Company. The transport of fuel by road and sea was supervised by the Finnish Radiation and Nuclear Safety Authority (STUK) and US regulatory and safety authorities. In January 2021, the USGS received all the irradiated fuel from FiR 1.

Arranging for cooperative international spent fuel management abroad is an exception permitted by the Nuclear Energy Act. Before sending the fuel abroad, Finland received a report from the US authorities on their commitment to the management of the fuel batch. It is planned that when the USGS ceases to use its reactor, all its irradiated fuel will be delivered to INL.

III–2. DESCRIPTION OF THE FIR 1 REACTOR

III–2.1. Technical characteristics

The supplier, General Atomics, has designed the TRIGA reactors for use in university environments. The name TRIGA comes from Training Research Isotopes General Atomics. Also, FiR 1 was originally in the possession of Helsinki University of Technology (which became the Aalto University in 2010), but it was transferred to VTT Technical Research Centre of Finland by government decision in 1971. In this section, we summarize the reactor design with its unique characteristics and the extensive characterization that has been done to collect reliable background data for the planning of dismantling, nuclear waste management and all related project activities. The main nuclear characteristics of the FiR 1 reactor are listed in Table III–1.

TABLE III–1. MAIN NUCLEAR CHARACTERISTICS OF THE FIR 1 REACTOR

Type	TRIGA Mk II (open tank reactor with graphite reflector)
Maximum steady-state thermal power	250 kW
Maximum pulse power (duration 30 ms)	250 MW
Maximum excess reactivity	4$
Maximum thermal neutron flux	1.0×10^{13} n/cm^{2}s
Fuel composition	Uranium-zirconium hydride (about 8% U, 91% Zr, 1% H in weight)
Uranium enrichment	19.9 %
Core loading	2.7 kg ^{235}U (13.7 kg U)
Fuel element cladding	0.76 mm aluminium or 0.5 mm stainless steel
Dimensions of the active configuration	355 mm × 436 mm (height × diameter)
Control rods	Three boron carbide rods, one boron graphite rod (pulse rod)

III–2.2. Estimate of radioactive materials and waste generation

III–2.2.1. Overview of waste characterization strategy

We present here in more detail our approach to activity characterization, since it provides the basis for waste management planning and cost estimation and has been the most valuable single set of input data for several purposes. Updating the activity inventories regularly during reactor operation is especially important for research reactors since their operating history typically contains different applications and modifications to the reactor structures. Data on, for example, operating hours in each configuration and activating impurities in the reactor structures can easily be lost if future decommissioning is not considered early enough. Figure III–3 illustrates the progress of the characterization process throughout a decommissioning project phase.

VTT's waste management is based on nuclide vectors and the scaling matrix approach. Material-wise nuclide vectors will be applied during the dismantling as presented in Fig. III–4. Characterization work in 2015–2020 focused on validating the calculated results by collecting samples from different materials.

An important limiting factor has been that since the spent fuel was still in the reactor core in 2015–2020, samples could be drilled only from the low active outer areas of the reactor, to avoid damaging the tank or core structures (Fig. III–5).

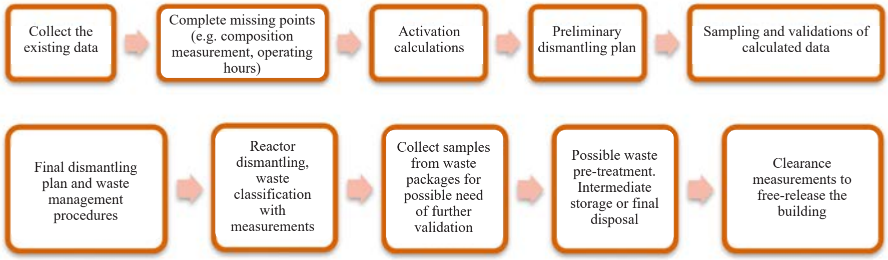

FIG. III–3. Progress of characterization throughout the decommissioning project phase (courtesy of VTT, Finland).

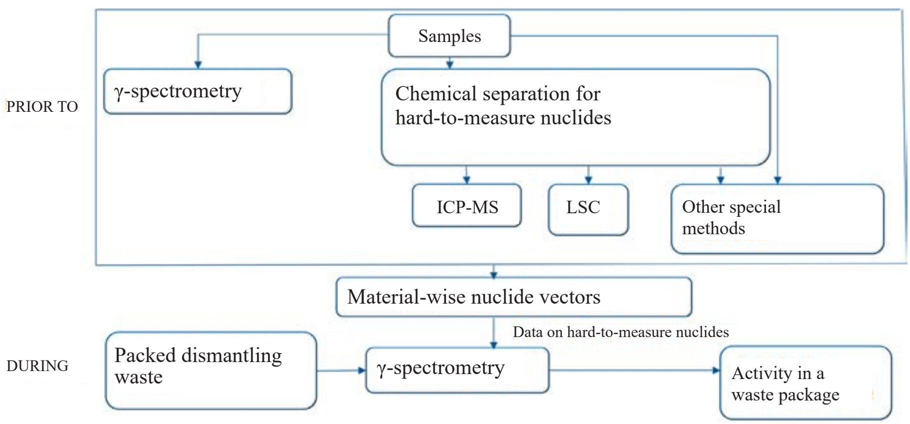

FIG. III–4. Waste classification using nuclide vectors. ICP-MS — inductively coupled plasma mass spectrometry; LSC — liquid scintillation counting (courtesy of VTT, Finland).

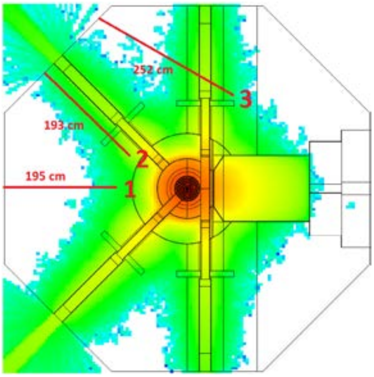

FIG. III–5. Left: drilling directions towards the activated parts of the FiR 1 biological shield concrete (red lines 1, 2 and 3), drawn on top of MCNP geometry and MCNP calculated neutron flux distribution map; right: drilling the specimens from the biological shield (courtesy of VTT, Finland).

III–2.2.2. Activity calculations and formation of nuclide vectors

In the preliminary phase, VTT conducted activity calculations using a model that combined several MCNP neutron flux models representing different reactor operation phases to ORIGEN-S point-kinetic calculations to consider the operation hours in each configuration. Since this model assumes that the target is mathematically homogeneous, the ORIGEN-S calculations were repeated for all the reactor main components and structures separately [III–5 to III–7]. These results were used in the preliminary waste estimates and dismantling plan.

The VTT–Fortum contract in 2020 (see Section III–3.4) has enabled setting Loviisa nuclear power plant waste acceptance criteria as boundary conditions to waste management planning. Therefore, the validations in the nuclide vector methodology have been done following the ISO 21238:2007 standard [III–8] and challenges relating to the final disposal of special waste packages can be discussed directly with the operator of the final repository facility.

Choosing the final waste management option and forming the nuclide vector always contain some assumptions between scientific precision and practical feasibility. Practical issues have included:

— Activity in structures is so low that the amount of difficult-to-measure (DTM, or hard-to-measure) nuclides in the vector cannot be validated by sampling. In these cases, DTM measurements are not feasible. The characterization is performed by measuring the material composition from samples, performing the activity calculations using the measured composition and finally forming the nuclide vector by gamma spectrometric measurements using scaling factors.

- The FiR 1 reactor contains several different types of steel, but the quantities are so low that it is not feasible to try to form nuclide vectors separately for each one. The best approach has been to form only one vector using conservative assumptions and checking with the waste acceptor that the list contains all the relevant nuclides.
- Relevant key nuclides have been identified as ^{60}Co, ^{137}Cs and ^{152}Eu. In addition, the FiR 1 epithermal neutron beam facility for cancer patient treatments using BNCT contains Fluental neutron moderator and lithium containing plastics, activated practically only through activation reaction $^{6}Li\ (n,\alpha)\ ^{3}H$. In the lack of gamma activity, they do not have a suitable key nuclide and have to be characterized using only sample measurements and averaging the results to larger waste masses. Calculations are still utilized to choose suitable sampling locations, maintaining conservatism. Some structures contain also hazardous waste (lead, cadmium) not allowed in the Loviisa final disposal repository. Fortunately, these contain mainly short lived nuclides, so they can be eventually free released after letting them decay in interim storage.
- How to measure the nuclides because of contamination from reactor operation (isotope production and activation analysis)? The current approach is to measure only gamma active nuclides and supplement the data with historical records of reactor operation.
- Since some of the materials are inaccessible before dismantling commences, the approach has been that VTT will form preliminary calculated nuclide vectors with conservative assumptions and these will be further refined and validated by Fortum during dismantling.

It has been estimated that altogether VTT will need 15 nuclide vectors. It is a relatively large number but illustrates the special challenges in a research reactor with various material and structural modifications throughout the facility operating history.

III–2.2.3. Experimental characterization and development of methods

Radiochemical method developments for DTM radionuclides have been a collaborative effort between modelling and experimental studies. The modelling results have provided lists of materials with DTM radionuclides with conservative activity concentration. This information has been the basis for radiochemical method developments as both DTM wastes and interfering gamma emitters could be accounted for (i.e. the effort could be efficiently targeted on the most relevant radionuclides). DTM radionuclide analyses are long processes as the radionuclides first need to be quantitatively extracted from the solid matrix. For example, the solubility of concrete [III–9] and graphite [III–10] are a major challenge in their analysis. Second, the DTM of interest requires complete separation from interfering radionuclides. For example, complete purification of ^{63}Ni from ^{60}Co is required for accurate analysis [III–11]. The DTM analyses can also suffer from radionuclide volatility, quenching in liquid scintillation counting etc. Therefore, method validation is required and in many cases, it can be carried out using reference materials. However, there are no commercially available reference materials for DTM analyses in decommissioning waste and therefore validation via intercomparison exercises has been carried out for steel [III–11, III–12] and concrete [III–13] organized in the Nordic nuclear safety research community. In total, eight laboratories have participated: three from Finland, one from Sweden, one from Denmark, two from Norway and one from France. The current intercomparison exercise focuses on DTM analysis in spent ion exchange resin. The exercises have highlighted the importance of collaboration and information exchange between laboratories.

III–2.2.4. Applications of inventory data in planning

Along with validating the nuclide vectors, characterization work in 2015–2020 has also included applying the results, especially in radiation safety planning and safety assessment of the final disposal of the waste. The VTT–Fortum agreement has also been essential to set the boundary conditions for this planning. Practical issues include the following:

— Intermediate waste storage in the research reactor facility area (a couple of months at a maximum) is a challenge since the reactor is located in a university campus area and all radiation dose to the public has to be prevented. Building an MCNP virtual model of the reactor building has enabled estimating direct doses through the building walls [III–14]. The current plan is to use dismantled free-released heavy structures from the reactor to provide extra shielding. This is illustrated in Fig. III–6.
— Choosing the waste packages is a compromise between several factors. For example, the packages have to provide enough shielding, but the reactor hall crane and doorways set limitations for package size and weight. Logistics and requirements for both public road transportation and final repository site also need to be considered. This is illustrated in Fig. III–7.
— Special material and certain long lived nuclides have to be taken into account in the safety assessment of final disposal. (Which barriers are needed? Do the packages have to provide a barrier in the final disposal of the waste?)
— Validating all the methods used in waste classification and sufficient environmental safety procedures.

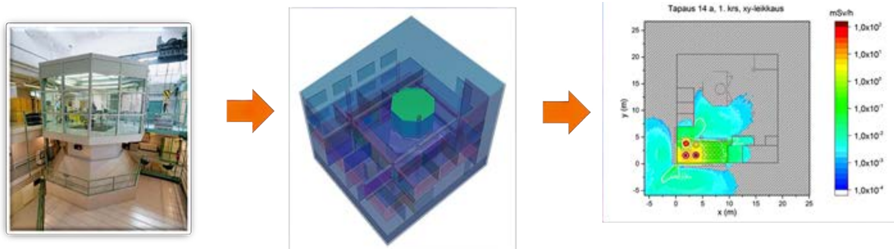

FIG. III–6. Direct radiation doses to the public are estimated using an MCNP model of the building. Some of the dismantled heavy structures of the reactor will be utilized as extra shielding close to the building outer walls (courtesy of VTT, Finland).

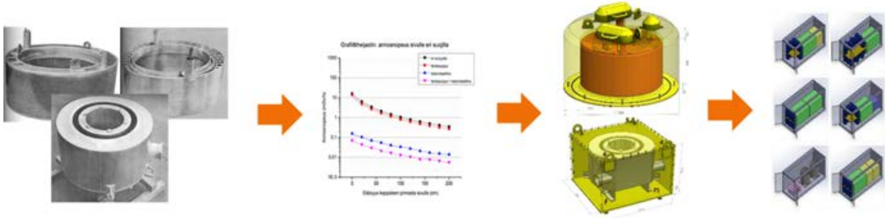

FIG. III–7. Package planning has included studying options taking into account sufficient shielding, logistics and safety of final disposal (illustrated here for the radial graphite reflector of the core; courtesy of A. Tommila and T. Seitomaa). Graph shows doses to the public according to different thicknesses of shielding material.

III–3. ORGANIZATION AND MANAGEMENT DURING THE TRANSITION PERIOD — BETWEEN SHUTDOWN AND DECOMMISSIONING

III–3.1. Safety culture in the transition to decommissioning

From a technical point of view, the risk landscape changes remarkably when a nuclear facility ceases operation and enters the decommissioning stage. The main safety goals during operation (i.e. controlling the nuclear chain reaction, ensuring cooling of the fuel, and confining the radioactive fission products) become irrelevant at the latest when the irradiated nuclear fuel is removed from the facility. While general radiation protection requirements (shielding from direct radiation and contamination control) become very prominent during specific (early) decommissioning tasks, they can eventually be gradually relaxed along with the progress in decommissioning. In addition, the phases of decommissioning (see Fig. III–8) bring significant new industrial

FIG. III–8. Simplified phases of decommissioning (courtesy of VTT, Finland).

risks relating to the demolition, involving various issues such as cutting work, heavy lifts and transports, work on scaffolding and from cranes, dust, noise, all of which require the operator and their contractors to adopt completely new safety practices on-site.

In terms of organization and attitude, during decommissioning the workplace changes from a steady state facility into an ever-changing environment. This challenges the mindset of all employees, which is also highlighted in para. 4.9 of IAEA Safety Standards Series No. SSG-47, Decommissioning of Nuclear Power Plants, Research Reactors and Other Nuclear Fuel Cycle Facilities [III–15], which states that "The licensee is required to foster a safety culture to discourage complacency at all levels in the organization. This is particularly important in decommissioning, where the facility's configuration is undergoing continual change."

Another major change is the increase of external workforce present at the facility, as stated in para. 4.11 of SSG-47 [III–15]. "Decommissioning actions may involve additional organizations, including contractors and subcontractors who might not be familiar with the facility and the management system of the licensee." This implies that the facility knowledge possessed by long term employees becomes very valuable, especially because the configuration of an old plant may not be fully documented. As stated in para. 4.13 of SSG-47 [III–15], "Although new skills might be required for decommissioning, attention should also be given to preserving the knowledge of key personnel who are familiar with the facility from its operational stage." It is essential to pay attention to motivating the remaining long term and knowledgeable employees who joined the organization in order to produce energy and may have very diverse emotions after the plant has been shut down and as the procedures and roles are adjusted towards decommissioning.

For preserving and developing the safety culture, a safety culture development plan was written in 2016 and has been maintained since then. In 2017–2018, a comprehensive FiR 1 specific safety culture assessment was conducted by VTT's own independent experts, including interviews of the major stakeholders such as the Finnish Radiation and Nuclear Safety Authority STUK and the Ministry of Economic Affairs and Employment (MEAE) [III–16]. An annual safety culture survey was introduced, to follow up and to measure the safety culture development [III-17].

III–3.2. Preserving facility knowledge and complementing expertise at FiR 1

The organization of FiR 1 maintains its safety responsibilities and continues to operate during the permanent shutdown and decommissioning phase under the supervision of the Finnish Radiation and Nuclear Safety Authority STUK. In August 2021, STUK approved the new administrative rules for FiR 1, transferring the organization to the decommissioning stage. VTT considered the requirements of the changing operating environment in the decommissioning stage when organizing radiation protection, emergency preparedness, site security and nuclear safeguards. In particular, new procedures have been created to manage safety and quality in subcontracting. In practice, the new administrative rules have been applied (e.g. in the work order procedure for safety-critical work at FiR 1).

While VTT has retained all personnel of the operating organization, a few key recruitments have been important in strengthening the competences in waste management planning, licensing framework knowledge and radionuclide measurements. The project organization is relatively small and involves all staff of the previous, still maintained part-time operating organization. As previously mentioned, in 2017–18, VTT carried out a safety culture assessment [III–16]. The assessment confirms that the organization is competent and committed, but that the systemic uncertainties (such as time and cost) can jeopardize the safety culture by creating tension between economic and safety aspects. In addition, the assessment recommends VTT to pay more attention to competence and information management. A follow-up study was conducted in 2021 [III–17] with the conclusion that in general, the safety culture in the decommissioning project was experienced to be at a fairly good level and the majority perceived that it had improved. However, some of the same worries remain as in 2018. Based on the findings, VTT has defined new concrete development actions.

III–3.3. Licensing of FiR 1 for decommissioning

III–3.3.1. Overview

FiR 1 is the first nuclear facility to be decommissioned in Finland. Although fuel, dismantling waste and activity inventories are several orders of magnitude smaller than power reactors, similar licensing procedures apply to research reactors. FiR 1 decommissioning has indeed become a pioneering project not only for VTT but also for authorities and domestic nuclear power utilities that will face decommissioning issues in the coming decades. Internationally, previous experience is available. Several reactors of a corresponding type have been decommissioned, for instance in Denmark and Germany, and experiences from those projects are utilized in the decommissioning of FiR 1.

III–3.3.2. Finnish regulatory framework for use of nuclear energy and radiation

In Finland, two Government ministries (Ministry of Economic Affairs and Employment (MEAE), and Ministry of Social Affairs and Health (MSAH)) carry a shared responsibility for nuclear and radiation related matters (see Fig. III–9). The roles are defined in the Radiation Act, while nuclear energy matters are specifically regulated by the Nuclear Energy Act. The Finnish Radiation and Nuclear Safety Authority STUK operates under the performance guidance of the MSAH and is responsible for the technical supervision of both nuclear and other radiation activities. The MEAE is the supreme authority for nuclear energy matters and has a direct supervisory role concerning societal and political aspects of the use of nuclear energy.

In the following, we summarize the main steps towards fulfilling the prerequisites for the nuclear decommissioning licence for FiR 1. Actual licensing is preceded by an environmental impact assessment (EIA) for decommissioning. The main prerequisite for the licence itself is that the safety of operations as well as the personnel and financial capacity of the applicant are proven to be sufficient. In particular, the methods available to the applicant for the decommissioning of

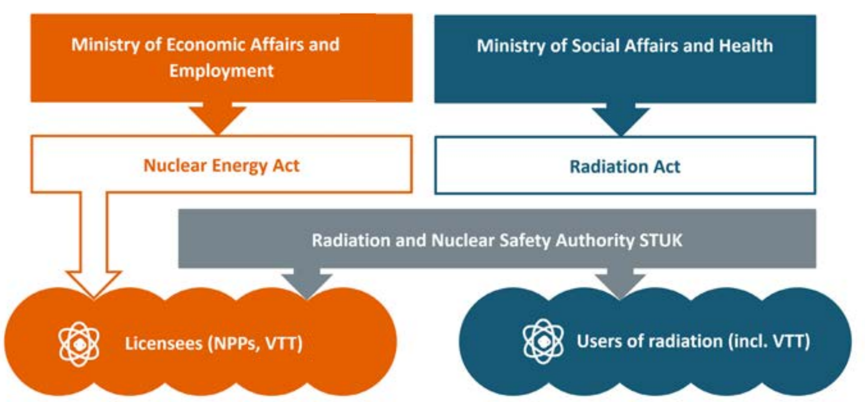

FIG. III–9. Illustration of the Finnish regulatory framework for use of nuclear energy and radiation [III–18].

the nuclear facility as well as other nuclear waste management will be adequate and appropriate [III–2].

III–3.3.3. Environmental impact assessment in 2013–2015

Soon after the shutdown decision and before applying for the decommissioning licence for FiR 1, VTT carried out an EIA for decommissioning, as required by the Act on Environmental Impact Assessment Procedure [III–19]. The EIA procedure generally aims to ensure that the environmental impact is evaluated and considered on a consistent basis in planning and decision making. Another objective is to increase the awareness of citizens and improve their opportunities to participate in and influence project planning. Decisions regarding the actual project will not be made, nor licensing matters decided, during the EIA procedure.

The EIA procedure involves programme and reporting stages. The EIA programme is a plan for the implementation of the EIA procedure and for the topical survey reports. The resulting EIA report presents the project's features and technical solutions, along with a consolidated assessment of the project's environmental impact, formed as a result of the assessment. The EIA procedure is an open process, in which individuals and other interested groups are invited to participate and present their views to the project's coordination authority, the MEAE, to VTT as the responsible party, or to the consultant. A stakeholder group was assembled to support the EIA procedure. The group assisted in the exchange of information between the parties responsible for the project, the authorities and other stakeholders. The monitoring group convened twice during the EIA execution stages.

Two main decommissioning alternatives were considered:

— ALT1: Immediate decommissioning;
— ALT2: Delayed decommissioning.

Continued operation of the research reactor, in a situation in which it is not decommissioned, was considered as the so-called zero alternative. In this case, decommissioning and other nuclear waste management measures would take place later.

As a result of the EIA procedure, it can be concluded that the VTT reactor decommissioning project will not have a significant environmental impact. The MEAE gave the final statement on the EIA report in February 2015. A few stakeholders provided the MEAE with their remarks on the report to be accounted for in the detailed decommissioning planning.

III–3.3.4. Planning phase

The Finnish licensees have to maintain their nuclear waste management plans over the whole operating lifetime of their reactors. The plans have also an economic dimension as each licensee is obliged to contribute accordingly to the Nuclear Waste Management Fund managed by the MEAE. The fund reimburses costs gradually to the licensees following the completion of their decommissioning duties.

Significant refinement of the nuclear waste management plans is required when the nuclear facility is approaching decommissioning. This planning has been further developed in the EIA for FiR 1 decommissioning that was carried out by VTT in 2013–2015 (reports only in Finnish and Swedish available at Ref. [III–20]).

In the first phase, a relatively broad range of underlying questions had to be answered, relating to specific issues of decommissioning a TRIGA type reactor. For instance, Finnish nuclear power plants do not contain irradiated graphite, aluminium or some research materials that FiR 1 will yield into the Finnish nuclear waste management system. Therefore, VTT conducted a literature survey (see Ref. [III–21]) to collect information on the chemical behaviour of irradiated aluminium and graphite under expected final repository conditions, international practices concerning the management and final disposal of irradiated aluminium and graphite, and experimental techniques for determining the chemical form (organic or inorganic) of the ^{14}C released from graphite waste. This study is represented by one of the grey boxes in Fig. III–10. In general, this and the many other studies shown in the lowest layer of the figure were completed in the EIA phase or soon thereafter, providing the fundamental basis for the second grey layer.

III–3.3.5. Licence application in 2017, licence in 2021

The second grey layer in Fig. III–10 represents more technical design documentation required for composing the preliminary decommissioning plan and for updating all other facility documentation for the decommissioning stage (“Supporting documents to STUK”, as required in the Nuclear Energy Decree [III–22] and marked in blue). STUK reviewed the technical and administrative documentation and gave its safety assessment on decommissioning in April 2019 (and updated it in April 2021). In parallel, the MEAE was reviewing the actual application and its appendices (orange; a public set of documentation available on the web pages of the MEAE [III–23]), making sure that VTT’s plans and contractual arrangements are mature enough for the decommissioning and nuclear waste management to take place in a reliable manner until the very end.

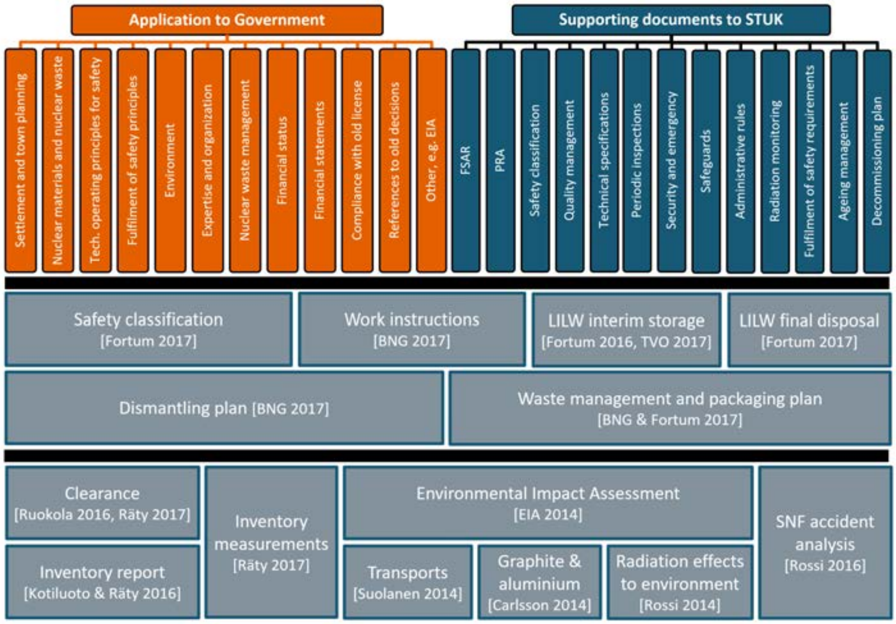

FIG. III–10. The structure of VTT's licence application, following the Nuclear Energy Decree. The actual public application and its appendices (titles shortened) are illustrated in orange. The more detailed technical documentation was reviewed by STUK and is illustrated in blue. In the environmental impact assessment phase and during the following preliminary planning phase, preceding the application, VTT and contractors carried out several studies illustrated in grey (courtesy of VTT, Finland). Original references have been retained. LILW — low and intermediate level waste; FSAR — final safety analysis report.

The review time of VTT's application for FiR 1 decommissioning was relatively long, about four years. The main reason is that VTT's nuclear waste management solutions are based on commercial contracts, which were not yet in place upon submission of the licence application. An essential complement of the original application was VTT's letter to the MEAE in the first quarter of 2020. In the letter, VTT reported that a comprehensive contract on decommissioning services had been signed in March 2020 between VTT and Fortum Power and Heat Oy (Fortum), covering dismantling of FiR 1 and all necessary nuclear waste management services. We describe the contract in more detail in Section III–3.4. The contract eliminates the longstanding uncertainties, which were mitigated by VTT by pursuing alternative waste management solutions in parallel (e.g. preparing for interim storage for spent nuclear fuel (SNF) at a Finnish nuclear power plant in case the USA would not have been able to receive it in the near future). A consolidated schedule, taking also into account the removal of the spent fuel at the end of 2020, is presented in Fig. III–11.

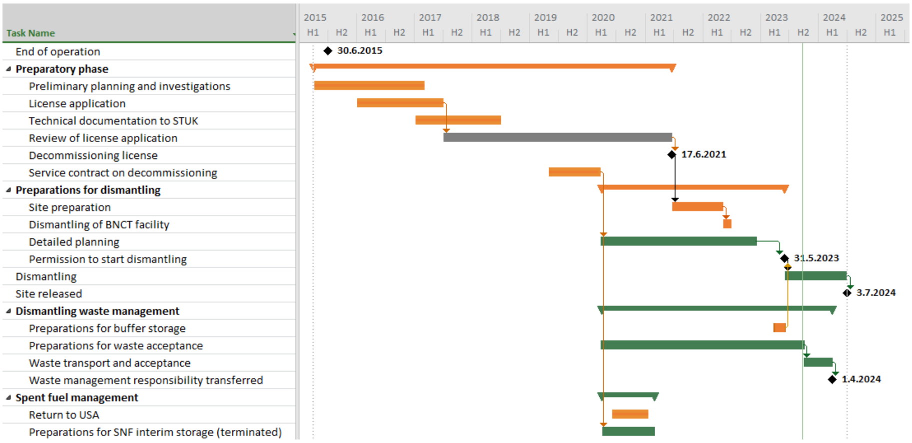

FIG. III–11. Schedule for FiR 1 decommissioning after shipping of the spent fuel and terminating interim storage preparations for the fuel as obsolete. Green bars represent tasks that are mostly covered by the service contract for decommissioning (courtesy of VTT, Finland).

III–3.4. Contracting

Essential for the FiR 1 decommissioning project, and for fulfilling the prerequisites for the decommissioning licence, is the comprehensive contract on decommissioning services, signed in March 2020 between VTT and Fortum. The contract covers the dismantling of FiR 1 and all necessary nuclear waste management services as well as the radioactive waste management for the decommissioning of the adjacent radioactive materials research laboratory (called OK3). An industrial partner taking responsibility for the waste management is absolutely necessary for a research organization like VTT, which does not have its own nuclear waste management facilities. Presently, there is also no national option for such mid-scale nuclear and radioactive waste streams (tens or hundreds of m^3) in Finland, only for small radioactive waste streams from industry, medicine and research.

Because of the complex scope, the service contract was concluded using a negotiated procedure, according to the Act on Public Procurement and Concession Contracts, as VTT is considered to be a public procurement unit. In the first phase of the negotiated procedure, tenderers give preliminary (completely non-binding) tenders, based on which the procurement unit (buyer) and the tenderers undergo negotiations in order to specify the scope, schedule, contract terms, pricing models and other aspects accurately enough so that the buyer can publish a high-quality final call for tenders. In this case, the procedure was particularly useful for specifying an accurate division of responsibilities, use of VTT's staff and the facility's existing equipment, limiting the scope concerning the clearance of the site as well as defining nuclear liability issues and the transfer of waste management obligations between licensees.

The technical base for the dismantling work tendering was a detailed plan of the dismantling work and interim storage of the dismantling waste prepared in 2016 with Babcock Noell GmbH (BNG). BNG had previous experience in dismantling research reactors, including TRIGA type reactors.

The whole negotiated procedure took about 11 months and included five rounds of negotiations, individually between VTT and each of the tenderers. Prior to this formal procedure, VTT held more informal discussions on industrial support for decommissioning waste management already during the operation of FiR 1, but the formal procedure and a competitive setting proved to be invaluable in reaching agreement on all matters, even the most challenging ones, within a finite timeframe.

In general, 2020 was a year of important contracts, since also the SNF transport and transfer contracts were concluded in the third quarter of 2020. Some of the projects' contracts have been concluded using direct procurement, because of limited availability of service providers in the market (e.g. for technical or ownership related reasons) or for security reasons. We also used a public (open or restricted) procedure in selecting the EIA and dismantling planning consultants in 2013 and 2016.

III–4. ANTICIPATING DECOMMISSIONING IN RESEARCH REACTOR DESIGN, CONSTRUCTION, OPERATION AND MAINTENANCE

As the FiR 1 research reactor was built already in the 1960s, the international and domestic requirements and regulations were much different compared with the current situation (i.e. much lighter). For instance, the current IAEA general and specific requirements take decommissioning very much into account already in the early stage of the life cycle of a nuclear installation (e.g. by requiring a preliminary decommissioning plan).

As far as FiR 1 is concerned, the TRIGA reactor design itself does not pose any specific problems for dismantling of the SSCs. However, lack of detailed knowledge on the used materials and their specifications has been noted. This concerns, for instance, the material specifications of the graphite, aluminium and steel. The mechanical construction specifications of the concrete of the biological shield were exceptionally well documented by the Finnish experts at the time of construction [III–24, III–25] but still it turned out later that for activation evaluation, some additional composition data were needed. In particular, europium isotopes ^{152}Eu and ^{154}Eu were identified as the radionuclides producing the highest contribution to total activity in concrete, although the europium concentration is only about 2 ppm [III–26] but the neutron capture cross-sections are large.

Following the current requirements, the materials would have been documented in much more detail, and material samples from each production batch would have been stored. The current international requirements pay much more attention also to knowledge and data management. For instance, the detailed use and operating history of the FiR 1 TRIGA beam tubes has not been very well documented or the data management has failed to preserve these data, including the details of the used equipment inside the beam tube, especially in the early history of FiR 1.

Paying attention to detailed documentation of the reactor design and construction, as well as operating history and plant modifications, cannot be emphasized too much. Today all planning work and most of the communication takes place in the digital world. Therefore, thousands of paper documents have been scanned to digital format, mainly PDF. More than five hundred of these have been listed in the FiR 1 dismantling document system, which has been shared with the planning and execution phase contractors.

Early and comprehensive computational characterization of radionuclide inventories has been highly valuable for all later planning. We strongly encourage decommissioning operators to invest sufficiently in that important phase early on. Also, we have seen that the demand for characterization remains high for a long time, to which VTT has responded with continued competence building in both activation modelling and measurements.

Reflecting on new build projects, collecting inactive reference materials of the reactor structures is essential so that activation calculations can be performed with reliable input data. Validating the calculated estimates with measurements also requires systematic development of the measurement methods. International intercalibration exercises are an example of valuable method development. This also provides an opportunity to systematically document the best methods.

III–5. LESSONS LEARNED

The licensing phase of the project has tested both VTT's capability to fulfil the requirements and liabilities and also the Finnish nuclear legislation, regulations and authorities' guidelines. Exchange of experiences between VTT and authorities has led to improvements in the Nuclear Energy Act and the regulatory guides on nuclear safety and security (YVL guides) issued by the Radiation and Nuclear Safety Authority STUK. Different waste streams are now better considered in the national waste management activities, especially via improvements in licence conditions of the nuclear power plant waste facilities. The lessons learned during the decommissioning of FiR 1 can be applied to the preparations for the decommissioning of nuclear power reactors.

Looking back, it is easy to see that having binding contracts for waste management in place already at the moment of the shutdown decision would have simplified planning and licensing for decommissioning, saving time and expenses. In Finland, operators of nuclear power plants are currently obliged to arrange their own waste management. This approach is incomplete in the sense that it might leave out minor waste streams from research institutes (like VTT), universities, hospitals and industry. However, a task force led by the MEAE has elaborated recommendations for further development of the national radioactive waste management [III–27], which has led to improvements for instance in the licence conditions of the nuclear power plant facilities, allowing more flexible acceptance of waste streams from other operators.

Open communication and transparency are important success factors in project work in general, and this applies also to nuclear projects with the exception that there are obvious limitations for full transparency owing to security reasons. For VTT, the Government (represented by the MEAE) is a key stakeholder, and we pay high attention to keeping the MEAE well informed about the project through regular progress meetings. This dialogue concerns especially licensing requirements but also funding (see below).

In parallel, effective technical communication with other stakeholders (waste acceptor, regulator, dismantling contractor) is also important to set the boundary conditions for activity characterization. For example, if the waste endpoint is known, documentation and data management should be developed to be compatible with the waste acceptor organization.

In the early preparations for decommissioning, VTT had underestimated the detail required for design and planning work to meet all regulatory requirements, and consequently the time and budget of the project. Because of this and the reasons detailed above, VTT faced a funding gap for decommissioning and applied in 2018 for additional funds from the Government to be paid into the Nuclear Waste Management Fund. On the other hand, the spent fuel solution in 2021 turned out to be efficient and enabled a significant reduction of future risk provisions. The fund target for VTT in 2022 is €8.3 million (i.e. the amount earmarked for remaining FiR 1 decommissioning and nuclear waste management), which already exists in the fund and is considered sufficient, with all main plans and contracts being now in place. The estimated total cost for decommissioning is €23.6 million, of which €15.3 million is already accumulated cost in 2012–2021.

III–6. SUMMARY

FiR 1 served as a central place of training and research for over 50 years, educating an early generation of nuclear energy professionals who were needed to start four power reactors in 1977–1980, with all reactors still operating with very high capacity utilization rates. Now it serves as a 'pilot' in the decommissioning stage also.

It is obvious that there is significant potential to optimize the economy of decommissioning of standard type nuclear facilities, like TRIGA research reactors or common types of nuclear power plants, by using a specialized decommissioning organization, which can multiply the know-how by concentrating the knowledge in a single organization. Still, as a research organization with a single nuclear facility, VTT has decided to build its own relevant competence and capitalize on the accumulating experiences. To this end, VTT has launched a decommissioning business ecosystem dECOmm to develop new services for the international decommissioning market together with several Finnish companies.[3]

The dECOmm ecosystem's research project supports companies' own projects and includes building information models, virtual and augmented reality, radiation transport and dose modelling, artificial intelligence, human factors, operating and licensing framework as well as innovation ecosystems and ecosystemic business. Conversely, experiences from the company projects will be exploited as valuable input for research. FiR 1, while being a nuclear facility, can provide a small scale, easy-to-access test bed for the developed technologies. By involving a spectrum of companies with different backgrounds, all partners learn about the specifics of the nuclear domain, like regulations and quality requirements. Important in decommissioning is to understand where and when requirements can be relaxed.

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[3] dECOmm — Ecosystem for New International Decommissioning Services, http://www.decomm.fi

Kaupo Viitanen, Pekka Viitanen, Christina Vähävaara, Marja Ylönen, and many others. The authors want to acknowledge the Finnish authorities MEAE and STUK for their solution-oriented attitude and willingness to exchange constructive feedback and are grateful for the various ways of support that the project has received from other domestic and international stakeholders.

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Annex IV

GERMANY — DECOMMISSIONING OF THE FRM, A 4 MW OPEN POOL RESEARCH REACTOR[1]

IV–1. INTRODUCTION

Decommissioning is the last stage in the lifetime of a research reactor. Prior to this, the research reactor is designed, constructed, commissioned, operated and maintained. Typically, a manufacturer designs the research reactor and is involved in its construction. The main concerns when designing a research reactor are nuclear safety and good utilization possibilities. This case study is referring to the FRM, a 4 MW open pool research reactor built in 1957 as the first nuclear reactor in Western Germany and located in Garching, near Munich. Currently, it is necessary to present an initial decommissioning plan in the design and licensing of a new research reactor. This was not the case when the reactor was built, although the initial decisions on the matter, made in the past, are acknowledged.

Consideration of decommissioning in all stages of the lifetime of a research reactor will greatly facilitate its later decommissioning. While certain tasks, such as the management of radioactive waste, might be obvious, there are other tasks, such as keeping a good configuration management of the research reactor's structures, systems and components (SSCs), that are worth looking into.

This case study describes the numerous activities during the reactor's lifetime where considerations on decommissioning were implemented or should have been implemented (see also Ref. [IV–1]).

IV–2. DESCRIPTION OF THE RESEARCH REACTOR

Operation of the FRM, owned by the Technical University of Munich (TUM), started in 1957 and continued until it was permanently shut down on 28 June 2000. In around 1989, scientists and the Bavarian government initiated plans to build a new, more powerful research reactor on the same site. In 1996, the new reactor (FRM II) received the first partial construction licence. It became clear that, with a new reactor being built, operation at the old research reactor would soon be terminating. Table IV–1 indicates the milestones from the start of FRM operation up to the beginning of the decommissioning and dismantling upon the issuance of the decommissioning licence. Table IV–2 presents the technical data of the FRM.

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[1] Ulrich Lichnovsky, Technical University of Munich, FRM II, Germany.

TABLE IV–1. TIMELINE TOWARDS DECOMMISSIONING OF THE FRM

Year	Activity towards licence for decommissioning
1957	Start of reactor operation
1998	Application for a decommissioning licence (one page document, no appendices)
2000	Final reactor shutdown
2002	Disposal of the last spent nuclear fuel
2008	Gathering of information and documentation regarding the decommissioning scope; procurement preparation: contractor for the final decommissioning plan
2010	Start of the preparation of the final decommissioning plan
2014	Licence for decommissioning granted by the regulatory authority

TABLE IV–2. TECHNICAL DATA OF THE FRM

Type	Open pool light water moderated (MTR type fuel)
Primary cooling and moderator	270 m^3 H_2O (light water, desalinated) inside the reactor concrete pool
Secondary cooling	H_2O
Reactor power (thermal)	Until 1966: 1.0 MW Until 1968: 2.5 MW Until 2000: 4.0 MW
Thermal neutron flux	6.6×10^{12} $n \cdot s^{-1} \cdot cm^{-2}$
Total thermal power over 42 years of operation	544 GWh
Grid plate for fuel and reflector elements	Aluminium 6 × 9 grid; 54 positions

TABLE IV–2. TECHNICAL DATA OF THE FRM (cont.)

Fuel elements (MTR type)	Until 1960: maximum enrichment of 20% U-235 After 1960: maximum enrichment of 90% U-235 c. 4 kg fissile U-235 counting all fuel elements in the core
Reflector elements (MTR type)	Beryllium and graphite reflector/moderator elements
Control and safety rods	Boron carbide safety rods and stainless steel control rods
Beam tubes connecting the reactor and the experimental facilities (neutron activation analysis, diffraction/ scattering)	6 horizontal 152 mm diameter beam tubes 1 square (300 mm × 300 mm) horizontal beam tube 1 horizontal 100 mm diameter beam tube 2 diagonal 152 mm diameter beam tubes
Other experimental facilities	Thermal column size: 120 cm × 120 cm Cold neutron source (moderated with hydrogen gas) Irradiation experiments close to the core at cryogenic temperatures (cooled with liquid helium) Therapeutic neutron irradiation of patients in a separate treatment room (boron neutron capture therapy (BNCT))

IV–2.1. FRM and connected buildings

The egg-shaped reactor hall shown in Figs IV–1 and IV–2, including the circular building around it, is an industrial monument today. The wall of the reactor hall was made of a 10 cm thick concrete wall covered by an aluminium liner. The egg-shaped building contained the reactor hall and the experimental facilities. The circular peripheral building contained the ventilation system, the wastewater system, the ‘hot workshop’ and various media supply rooms. The following buildings, shown in Fig. IV–1, were also part of the research reactor:

— Reactor building with circular low-rise buildings around it;
— Laboratories and offices in low-rise buildings next to the reactor building;
— Off-site waste storage building close to the site;
— On-site waste storage building with shielded spaces for beam tubes and irradiated material/samples;
— Building with supply infrastructure (e.g. electricity, hot water);
— Office building.

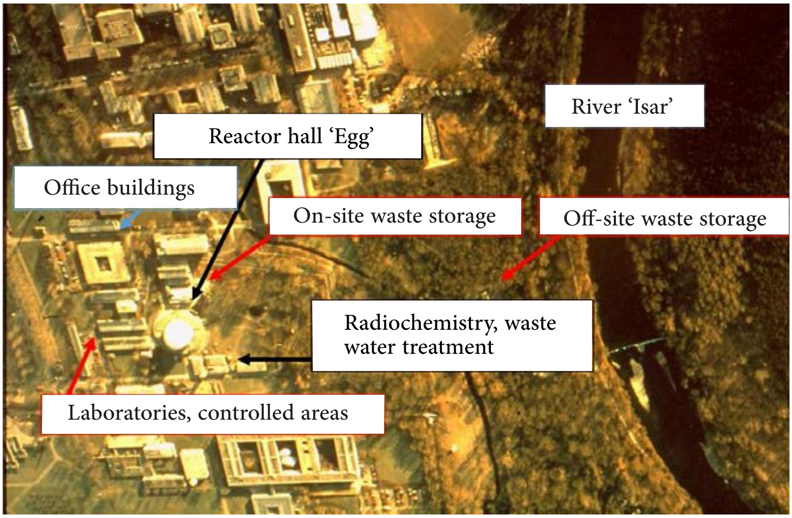


FIG. IV–1. Site overview, 1970s (courtesy of U. Lichnovsky, FRM II, Germany).

FIG. IV–2. Reactor hall (centre) and low-rise laboratories (left and right) (courtesy of U. Lichnovsky, FRM II, Germany).

IV–3. UTILIZATION

The FRM was used as a neutron source for neutron experiments and for irradiation experiments. Over the decades, the experimental facilities were changed according to scientific needs and the reactor power was increased up to 4 MW. The in-situ irradiation utilizations of the FRM were positioned inside the pool near the reactor core (see IV–3.1), while experiments, utilizing neutron beams, took place in the reactor hall. Additionally, some experiments were conducted in small cabins approximately 100 m from the reactor hall.

IV–3.1. Experimental facilities close to the reactor core

Figure IV–3 indicates the most relevant parts for the utilization of the FRM. Close to the core experimental facilities were:

- The cold neutron source (helium cooled liquid hydrogen as moderator);
- The irradiation facility with pneumatic tube (‘rabbit’) system;
- The cryogenic low temperature irradiation facility (cooled by liquid helium);
- The thermal column (1.2 × 1.2 m space in the concrete pool without a metal liner).

IV–3.2. Experimental facilities inside and outside of the reactor hall

Various neutron irradiation experiments, for example ultra-cold neutrons, spectrometry and radiography, were performed with the FRM.

The reactor had a treatment room for irradiating patients with fission neutrons. The operation of the patient irradiation needed a separate licence for operating the fission neutron converter.

IV–4. RADIOACTIVE WASTE

The types and estimated amounts of radioactive waste arising from the FRM operation (excluding some additional slightly activated parts from the neutron beam lines and the area around the experiments) are listed in Table IV–3.

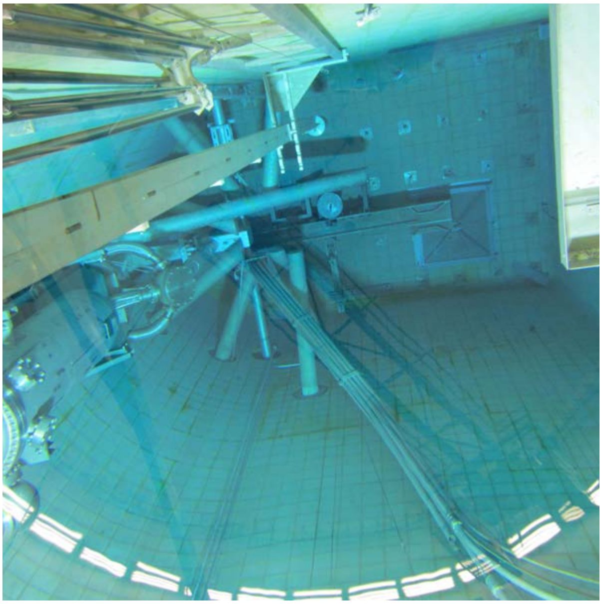


FIG. IV–3. Beam tubes with rectangular space between them for the reactor core; top of the picture: heat exchanger for the He/H heat exchange (courtesy of U. Lichnovsky, FRM II, Germany).

TABLE IV–3. OVERVIEW OF THE MAIN SOURCES OF RADIOACTIVE WASTE ARISING FROM FRM OPERATION

Type of radioactive waste	Estimated amount
Spent nuclear fuel	— Spent nuclear fuel (ca. 60 kg U-235) from 250 MTR type fuel elements (ca. 1.1 t) with enrichment ranging from 20% to 90% — Small quantities (ca. 200 g) of irradiated fuel samples
Graphite reactor core elements	100 kg of graphite in the form of MTR type graphite elements
Beryllium reflector elements	168 kg of beryllium in the form of MTR type beryllium reflector elements [IV–2]
Control rods, core instrumentation, grid-plate and tower structure	c. 300 kg aluminium, 50 kg stainless steel, 30 kg boron carbide

TABLE IV–3. OVERVIEW OF THE MAIN SOURCES OF RADIOACTIVE WASTE ARISING FROM FRM OPERATION (cont.)

Type of radioactive waste	Estimated amount
Aluminium tubes connecting the core and the experimental area	c. 300 kg aluminium
Ion exchange resins from the primary cooling circuit	900 kg
Concrete structure of the pool	15 t of neutron activated concrete rubble and iron reinforcement
Irradiated samples	300 kg of irradiated samples and other activated parts
Cooling reactor systems	Primary cooling circuit: 4 t heat exchanger, 1 t piping
Experimental facilities	— Pneumatic tube system: 4 t — Cold neutron source: 2 t hydrogen/helium heat exchanger, 50 kg hydrogen pipes — Cryogenic irradiation facility: 200 kg

IV–5. ORGANIZATION AND MANAGEMENT DURING THE TRANSITION PERIOD

IV–5.1. General

This section enables insights into the organization and management of the operator during the transition period, namely the time between the permanent shutdown in the year 2000 and the beginning of the decommissioning and dismantling process in 2014. During the transition period, the central TUM administration carried out many important processes for the research reactor organization, such as hiring new personnel, financing remaining operations, general workplace safety and procurement.

The regulatory oversight in the transition period consisted of activities similar to those conducted during operation [IV–3]:

— Conduct of scheduled site inspections, by the regulatory authority staff and its independent technical support organization, on various topics (e.g. worker dosimetry, radiation protection of the environment, radioactive waste storage, wastewater management, fire protection);

- Supervision of recurring tests on safety related systems (e.g. ventilation system, dosimetry equipment) by the technical support organization;
- Receipt of notifications on obligations of the operator, with respect to safety or in case of safety related events;
- Periodic reporting to the regulator (e.g. monthly dosimetry reports, yearly technical report, yearly radiation safety report, quarterly report on radioactive discharges);
- Regular formal meetings with the regulator, operator and technical support organization.

IV–5.2. Organization of the research reactor before permanent shutdown

The organizational structure at the beginning of the transition was similar to that established during operation, prior to permanent shutdown, in accordance with the operating manual. Following the Safety Standards of the German Nuclear Safety Standards Commission (KTA), specifically KTA 1201 [IV–4], the operating manual describes the organization of personnel, naming responsible persons and describing the processes required for the safe operation of the research reactor.

According to the operating manual, the responsible person for the reactor operation, with special emphasis on safety, is the site manager. The licensee (TUM) appoints the site manager; the appointment needs to be approved by the regulatory authority. The site manager is responsible for all the departments required by the operating licence, namely:

- Operations;
- Radiation protection;
- Projects;
- Irradiation including cold neutron source;
- Technical/mechanical services;
- Technical/electrical services, including instrumentation and control.

In total, the organization had a staff of about thirty people on the date of permanent shutdown. The head count does not include six security personnel.

IV–5.3. Changes in the organization of the reactor in the transition period

The construction of a new research reactor on the same site determined the organization of the FRM during the transition period. Although the organization of the research reactor did not formally differ from the operating period, the interest in and the know-how regarding the shutdown research reactor decayed over time. Most of the staff in the different departments received new responsibilities at the new reactor and the real workforce allocation to the old research reactor was drastically reduced. Except for two persons who were required to perform technical/mechanical services and continued their work for the shutdown research reactor on top of their new workload, the entire operations team started working and operated FRM II on the same site. Therefore, although most of the former personnel were formally available during the transition period, the entire operators group moved physically from the FRM reactor hall to the new control room of FRM II, and most of the team never set foot in the old research reactor again.

As experimental utilization ceased after the permanent shutdown of the FRM, the work for the radiation protection group also changed from working in the reactor hall to the required reporting. To minimize risk and keep the reactor hall clean, all activated or contaminated parts were stored in an off-site storage space or in the former shielded bunker previously used for neutron irradiation of patients (BNCT). Practically, after the removal of the last spent nuclear fuel (SNF) in 2002, the main interest of the whole research reactor organization was keeping the FRM in a safe shutdown state and complying with all regulatory requirements while keeping investments to a minimum; the upcoming decommissioning process did not appear to be a high priority.

IV–5.4. Managing the transition period and activities throughout decommissioning

As mentioned in Section IV–5.3, after the permanent shutdown, the reactor manager reduced drastically the workforce for the FRM. However, at the same time, all aims relevant for the organization were accomplished in the transition period:

— Removal of the SNF from the reactor core;
— Compliance with the operating licence.

Compliance with the operating licence meant that periodic tests and mandatory reports were performed according to schedule, and the safety related SSCs were maintained and repaired. Sections IV–5.4.1 to IV–5.4.8 present examples of the management of relevant activities during the transition period.

IV–5.4.1. Configuration management

The reactor operating manual for the FRM required the operator to apply a configuration control system for all safety related SSCs in the reactor.

Accordingly, all the relevant systems were in a well defined state of configuration control in the transition period. In order to reduce the risk of losing relevant know-how, at least two employees worked on those systems for relatively long periods of time (at least six months), and a training process was planned before the people working on those systems changed jobs or retired. Nevertheless, there were several SSCs (e.g. hot water and cold water supply, wastewater canals) that were needed specifically for the transition period and for the decommissioning stage. However, insufficient documentation meant that the knowledge and information for those systems was available to just one person, affiliated to the owner (TUM) or another state institution.

The list of changes (performed activities) during the transition period, as communicated to the regulatory authority for approval, is shown in Table IV–4. In order to identify the reported changes, each change in the facility received a unique number (column 1). The number, which incorporated both the year and the sequence of the intended operation, was communicated to the regulatory body starting from the final shutdown, throughout the transition period, and up until decommissioning. The activities listed (column 2) are only those connected to the decommissioning in a broader sense. The time from communicating the activity to the regulator until its approval lasted from several months to several years, depending on the complexity and the importance of the activity. In column 3 of Table IV-4, each activity is classified in one of four categories as follows: repair (R), decommissioning and dismantling (DD), maintenance (M), and planning for decommissioning (PD). Most of the activities categorized as 'PD' refer to the decommissioning process without prior dismantling. The 'connecting activities' increased the complexity of considerations for decommissioning planning. The disconnection from a possible water treatment facility made the handling of contaminated wastewater more difficult.

The introduction of a proper labelling system (e.g. 2007/18, 2008/01) for all SSCs and buildings was an important step towards a structured decommissioning approach and a proper configuration management. Prior to this, most valves and important parts were labelled but not in an unambiguous way (e.g. valve V1, valve V2 for different systems).

IV–5.4.2. Spent nuclear fuel management

The removal of the last SNF from the reactor core was a milestone for the operator. Directly after the removal of the SNF, the security requirements could be drastically reduced (see Table IV–4, 2002/05). Furthermore, plans were communicated to the regulatory authority to decommission safety systems and to reduce recurring tests and inspections (see Table IV–4, 2002/09 to 2002/15). To make the last SNF shipment possible, preparatory work was necessary. Until

TABLE IV-4. CHANGES IN THE MANAGEMENT SYSTEM APPROVED BY THE REGULATORY AUTHORITY

Number	Activity	Activity type*
2001/04	Repairing the loudspeaker system	R
2002/01	Dismantling of the retention system of the secondary cooling circuit	DD
2002/02	Changes to the site fire hydrants	M
2002/05	Simplification of security and access control after removal of SNF	PD
2002/09	Removal of high dose rate and noble gas instrumentation	PD
2002/10	Removal of instrumentation for severe accidents	PD
2002/11	Removal of 24 V DC supply	PD
2002/12	Removal of the diesel generator set	PD
2002/13	Removal of sirens and siren control unit	PD
2002/14	Removal of most level measurements in the reactor pool	PD
2002/15	Termination of recurring tests and removal of required equipment (see also Section IV–3)	PD
2002/16	Increase of tunnelled road load capacity around the reactor building to 30 t and for this change of fire compartments	PD
2002/33	Changes to the wastewater system	M/PD
2003/01	Changing the connections of the pre-demineralization system to supply the neighbouring new build FRM II	M
2004/01	Strengthening of the shielding of the on-site waste storage building	M/PD
2006/01	Removing a building part from the licensed area and integrating it into the neighbouring nuclear facility	DD
2006/02	Static inventory for various building foundations	PD

TABLE IV-4. CHANGES IN THE MANAGEMENT SYSTEM APPROVED BY THE REGULATORY AUTHORITY (cont.)

Number	Activity	Activity type*
2006/04	Ground investigation for various building foundations	PD
2006/05	Removing an underground building part from the licensed area and integrating it into the neighbouring nuclear facility	DD
2006/07	Strengthening the fire protection properties of floor areas within the reactor hall to comply with fire protection requirements	M
2006/10	Changes to the door alarms	M
2006/11	Integration of the alarm system into a permanently staffed station	PD
2007/01	Changes to the cooling water and rainwater discharge system	PD
2007/02	Decommissioning of the hot workshop	DD
2007/04	Changes to the door alarms	M
2007/05	Changes to the electricity supply system	DD/PD
2007/06	Renewal of the fire alarm system	M
2007/10	Decommissioning of high and medium dose rate instruments; changes to dose rate instruments in and outside of the reactor hall	M/PD
2007/13	Changes to the lock system	M/PD
2007/14	Removing a building part from the licensed area and integrating it into the neighbouring nuclear facility	DD
2007/16	Changes to the safety lights	M/PD
2007/18	Introduction of a structured labelling system for components and buildings	PD

TABLE IV-4. CHANGES IN THE MANAGEMENT SYSTEM APPROVED BY THE REGULATORY AUTHORITY (cont.)

Number	Activity	Activity type*
2008/01	Structured labelling of additional systems	PD
2008/02	Changes to the pre-demineralization system	M
2008/07	Installation of a release measurement facility (for 200L barrels and lattice boxes)	PD
2008/09	Installation of a release measurement instrument for smaller components	PD
2009/03	Integration of the discharge pipe (formerly going into the neighbouring river) into the neighbouring nuclear facility	M/PD
2009/04	Changes to the site wide flight and alarm concept	M/PD
2009/07	Decommissioning and dismantling of a cooling water system of the deep temperature irradiation facility	PD
2010/02	Due to water laws: decommissioning of internal pipes/ drains and a pipe to a neighbouring wastewater treatment facility	M/PD
2010/05	Dismantling of the pipes from 2010/02 above	DD
2010/06	Decommissioning of the pneumatic tube system outside of the reactor building that was partially connected to the neighbouring facilities	PD
2010/08	Disconnecting the reactor hall fire hydrants from the buffer tanks	PD
2010/14	Decommissioning of a fresh water pipe connected to the neighbouring wastewater treatment facility	PD
2011/02	Decommissioning and dismantling of the off-site waste storage building and bringing the radioactive waste back on the site	DD/PD
2011/04	Removal of the alarms for the building from 2011/02 above	DD

TABLE IV-4. CHANGES IN THE MANAGEMENT SYSTEM APPROVED BY THE REGULATORY AUTHORITY (cont.)

Number	Activity	Activity type*
2011/06	Commissioning of an electronic dosimetry system	M/PD
2012/03	Changes to the fresh water supply of the reactor hall	M
2012/05	Removal of a neighbouring building from the licensed area	DD
2013/02	Changes to the fresh water supply connected to the neighbouring wastewater treatment facility	M
2014/01	Changing the hot workshop and other formerly controlled areas around the reactor hall into monitored areas in order to reuse them as showers, changing rooms and break room	PD

* R — repair; DD — decommissioning and dismantling; M — maintenance; PD — planning for decommissioning.

the year 2000, the packing of SNF into transport and storage casks took place outdoors in an open transfer basin (see Fig. IV–4).

In preparation for the removal of the last SNF, the refurbishment plan of this basin was prepared and submitted for authorization by the regulator, but owing to changes in legislation, the application was rejected, and instead, the outdoor transfer basin was decommissioned in 1999 and dismantled shortly afterwards. Therefore, the last SNF loading to the transport and storage cask took place in the reactor pool, inside the reactor hall and the process was considered a big success during the transition period.

IV–5.4.3. Updating of operating activities

During the transition period to decommissioning, the FRM organization aimed to reduce the extent of recurring tests and inspections to minimize costs. For this purpose, the operator prepared a list of tests that would be no longer necessary after the permanent shutdown and the removal of SNF.

FIG. IV–4. Outdoor handling of SNF: shielded on-site transport unit attached to a crane, with grey open SNF loading basin containing the transport and storage cask (courtesy of U. Lichnovsky, FRM II, Germany).

The list that was suggested to the regulator included the following:

- All tests of the reactor controls;
- Inspection and test of the control rods with hafnium absorber and of the control rods with stainless steel absorber;
- Test of the reactor emergency cooling system;
- All tests of the controls considering the emergency cooling;

— All tests using the irradiation facility with the ‘rabbit’ system (e.g. leaktightness, instrumentation and control);
— All tests on controls of the converter facility (beam tube with converter for fission neutron production);
— Inspections and tests of reflector and absorber (MTR type elements) handling tools;
— All tests for the cold neutron source, after the hydrogen was removed and the pipes were flushed with nitrogen.

Moreover, the regulatory body authorized the termination of tests of the following systems under a separate regulatory procedure:

— Secondary cooling circuit;
— Main heat exchanger.

Furthermore, the extent of the following tests was drastically reduced:

— Tests on the reactor bridge carrying the core;
— Tests on the reactor pool;
— Structural tests for the primary cooling room (containing primary pump, primary coolant cleaning system, main heat exchanger, and secondary cooling circuit pump);
— Wastewater collecting and transfer system;
— Emergency water supply with well supply and buffer basin;
— Radiation safety instruments for exhaust air monitoring;
— Fire detection system;
— Beam tubes, vacuum system, scientific instruments and experiments;
— Backup power supply unit;
— Visual test/inspection of primary and secondary cooling circuit;
— Automatically closing fire protection doors;
— Inspection and test of a beam tube containing fissile material including its emergency cooling system;
— Lightning protection system.

Owing to the changed utilization of the FRM reactor hall (now mainly for storage of radioactive material), a new test was introduced:

— Inspection of the emergency escape routes.

Additionally, the operator suggested limiting the following tests:

- Test of the ventilation system, to perform the test without expert supervision;
- Test of recorders needed under severe accident conditions;
- Test of some radiation safety instruments in order to perform the tests without expert supervision.

The regulatory authority did not accept these last proposals for change.

IV–5.4.4. Structures, systems and components to be retained in service

The following systems were retained in service, as they were necessary for the transition period or because it was clear that they would be necessary for the decommissioning stage:

- Ventilation system;
- Primary cooling circuit;
- Main demineralization system for the primary circuit;
- Pre-demineralization system;
- Radioactive wastewater system;
- Water supply (cold and hot);
- Heating water supply (80°C);
- Power supply;
- Normal lighting and emergency lighting;
- Instrumentation and control;
- Telephone and network;
- Radiation measuring devices of aerosols, neutrons, contamination, dose rate, noble gases, ^{14}C and ^{3}H;
- Vacuum system for beam tube vacuum;
- Reactor hall crane;
- Fire protection systems;
- Alarm system;
- Speaker system.

The operating licence required the operator to maintain, test and inspect all these systems on a recurring basis during the transition period.

IV–5.4.5. Maintenance changes

During the transition period, the FRM operating organization moved from preventive/planned maintenance to reactive maintenance. For example, an improvised piping arrangement was installed to repair the primary cooling water cleaning system and for fresh water supply. The maintenance policy concept was changed from "what is best for us in the future" to "what solves the problem now with least effort".

IV–5.4.6. Physical and radiological characterization

During the transition period, only one person performed the physical inventory of the facility. This person provided a handwritten document of all parts inside the reactor hall. The extensive document included every tool, spare valve and even the structural materials of experimental facilities. The handwritten document was lost for some years and then retrieved.

A contractor was hired to perform the radiological characterization of the reactor hall facilities, except experimental facilities, as the operator thought he would remove all of them in the transition period from operation to decommissioning. Although the radiological characterization was supervised with minimum involvement from the operator, the outcome was technically on a good level, considering also that the above-mentioned physical inventory of the facility was not yet available.

IV–5.4.7. Handling of operational waste

Following the final shutdown of the FRM, the reactor hall was cleaned up in order to achieve a dose rate state as low as reasonably achievable (ALARA). For this purpose, all loose activated parts were stored in a shielded room inside the reactor hall (former patient treatment room for BNCT). Large contaminated parts were packed into plastic foil and stored in places that were difficult to access (e.g. on top of experimental facilities or on top of the reactor bridge). Moreover, burnable waste was packed into 200 L drums and stored inside the reactor hall. Furthermore, in 2010, the burnable waste was sent to an incineration facility. These activities resulted in an easy-to-maintain state inside the reactor hall.

With the decommissioning stage on the horizon, preparatory work started for handling waste and material from operation. In 2008 (see Table IV–4, 2008/07 and 2008/08), planning started for the commissioning of a measurement system for clearance and release. The operator decided to remove as much clean material as possible from the reactor hall during the transition period, prior to preparing the final decommissioning plan (FDP). The following activities were within the scope of releasing material from regulatory control prior to the FDP: cleaning up the off-site waste storage buildings, bringing back the radioactive waste on the site and releasing these buildings from regulatory control (see Table IV–4, 2011/02).

IV–5.4.8. Finalization of the decommissioning plan

The decommissioning process was initiated in 1998, when the operator applied for the decommissioning licence with a short one-page letter. The intent of the application was mainly to comply with the political demand to permanently shut down the old FRM prior to the commissioning of the new, already built FRM II. The timeline of the activities is presented in Table IV–1. The preparation of the decommissioning plan was initiated in 2008 with the appointment of an external contractor to prepare the FDP.

In 2010, the contractor started his work, supported by the operator in every respect, including by making available all relevant documentation. In addition, the contractor received all written documentation and information on the already decommissioned facilities and on the still operating systems from an experienced operator technician, who provided also overviews of the material to be dismantled.

Nevertheless, it was concluded that the documentation of the radiological inventory and radioactive waste, especially the inventory in the waste storage areas available within the operating organization, was incomplete. The radioactive material stored on-site in the radioactive waste storage building was not further characterized. The management of legacy waste in this building was not described in the FDP.

The main work performed by the contractor was the radiological mapping of the FRM hall, including the reactor core structures. The focus of the activities was to map the radioactive material inside the reactor pool and inside contaminated systems (e.g. rabbit system, primary circuit).

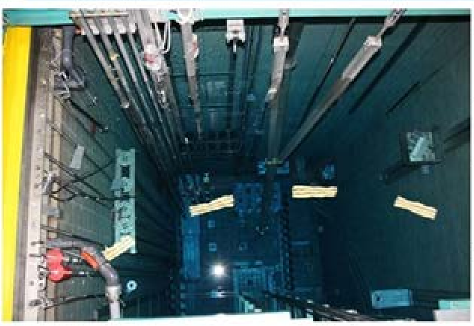
For the FDP, the contractor had to assume that all scientific experiments inside the reactor hall and inside the reactor pool (except for cold neutron source, deep temperature irradiation facility and rabbit system) would be dismantled within the scope of the operating licence. This assumption turned out to be wrong: most of the experimental facilities could not be dismantled before the licence for decommissioning was granted. From a safety perspective, this was not a problem. From an organizational perspective, this implies that the decommissioning and dismantling outlined in the FDP can only be implemented with certain technical modifications. The main results of the radiological characterization of components are shown in Figs IV–5 and IV–6, respectively.

The radioactive inventory did not include the beryllium waste in the storage building, the graphite elements in the reactor pool, a highly activated beam tube (see Fig. IV–6, on the left side of the pool floor), and other loose waste from various storage locations inside and outside the reactor hall (see Section IV–4). This led to a discrepancy between the inventory described in the FDP and the

System	Relevant isotopes
Contaminated Systems in general 	Co-60, Ag-108m, Cs-137, Eu-152, Eu-154
Pneumatic Tube System 	Co-60, Ag-108m, Cs-137, Eu-152, Eu-154, *Pu-238, Am-241*

FIG. IV–5. Results of the radiological characterization (1/2) (courtesy of U. Lichnovsky, FRM II, Germany).

System	Relevant isotopes
Activated Components close to the Core	Mn-54, Fe-55, **Co-60**, Ni-59, Ni-63
Concrete Structure (neutron activation)	Co-60, Ba-133, Eu-152



Total Activity in the reactor hall

< 2 E12 Bq (today)

- ~ **98.5 %** is **activation of components close to the core**
- ~ 1.0 % contamination of systems such as the primary cooling circuit
- ~ 0.5 % contamination of other surfaces

FIG. IV-6. Results of the radiological characterization (2/2) (courtesy of U. Lichnovsky, FRM II, Germany).

real inventory. This discrepancy can be explained taking into consideration the following points that affected the contractor's work:

— Support and supervision by the operator's radioactive waste and radiation protection team was less than required.
— The work scope was unquestionably not clear. Therefore, the separation between scientific experiments that had to be dismantled prior to decommissioning and the scope of the decommissioning stage was not well defined.
— The contractor received high quality input from the operator (especially from the experienced technician mentioned above). However, the quality of the data received regarding the radioactive inventory was not of the same high level.
— Within the scope of the FDP, the contractor had to present a fire protection plan for the decommissioning phase. This created a challenge for the contractor and subcontractor to extend the licence owing to the changes made at the facility (see Table IV–4, 2012/05 and 2014/01). Those changes, made during the preparation of the FDP, led to a discrepancy between the fire protection plan and the actual situation after the licence for decommissioning was granted.

Finally, as previously mentioned, the scope of the decommissioning plan excluded most of the experimental facilities within the reactor hall because the operator expected to decommission those facilities before the decommissioning licence would be granted. Explicitly within the scope were the experimental facilities that were commissioned with their own licensing process. Those were the cold neutron source, the cryogenic low temperature irradiation facility and the patient treatment room for neutron irradiation.

IV–6. CONSIDERATIONS ON DECOMMISSIONING IN THE RESEARCH REACTOR DESIGN

When the FRM was designed in the mid-1950s, the decommissioning process was of no concern for the designer nor for the operator. Lessons learned from long term operating reactors, which needed to be permanently shut down and decommissioned, indicated that the initial design of the facility has a great impact on the decommissioning process. The main design features having a possible impact on decommissioning are described in Sections IV–6.1 to IV–6.3.

IV–6.1. Reactor design considerations

Several reactor design features may be considered when referring to decommissioning:

- The FRM and its main components were designed by General Atomics, USA, in 1957 as the very first among a few open pool research reactors with low thermal power sold all over the western world. To minimize thermal neutron absorption and fast neutron activation, most of the structural materials in the core zone (close to the fuel elements) were made of aluminium alloys. A major exception was the use of a few stainless steel screws, which became highly activated at the end of the reactor lifetime.
- Ion exchange resins continuously cleaned the demineralized cooling water during reactor operation. Therefore, the contamination of the systems designed to be in contact with the cooling water was not expected to be high.
- The ceramics tile coated concrete basin was built according to the designer's plan and an as-built documentation was prepared. The material composition of the tiles and the barite concrete was documented by the designer and handed to the operator. This documentation was the basis for the later neutron activation calculations. Unfortunately, the information on the material of the metal reinforcement rods inside the concrete was not available.
- The primary circuit pump, the heat exchanger and the ion exchange resins for the primary circuit clean-up are in a basement room within the reactor hall. This ensures that, in the case of a leak in the primary circuit, all cooling water flows into the basement room and can be pumped back to the core for emergency cooling. At the same time, this ensures that no radioactive cooling water will find its way out into the environment.

IV–6.2. Building design considerations

The following design considerations for decommissioning were made by the owner:

- The design of the reactor hall and the other buildings relating to the research reactor facility were decided by the owner of the research reactor (TUM). When the research reactor was sited 30 km north of the city of Munich, an abundant empty space was available in the surroundings. Therefore, it would have been possible to extend the facility campus border and/or add buildings required for activities such as waste handling, but this was not done. Over time, the university campus was built around the research reactor and available open areas outside the reactor building became scarce.

Although this fact may not be considered as a design problem, it became an obstacle for the decommissioning process.

— The decision to build an egg-shaped reactor hall had only an aesthetic justification. Owing to the egg-shaped form, the circular crane in the top area of the reactor hall could not access the entire ground area in the reactor hall, limiting and complicating activities during operation, in the transition period from operation to decommissioning, and during decommissioning.
— The reactor hall was built of 10 cm thick concrete walls, limiting the storage capacity of waste and high activity radiation sources and the weight load hung on the wall.

IV–6.3. Operator's design considerations

The following design considerations were made by the operator:

— The FRM reactor hall had four access doors, one of which was big enough for a motorized truck to drive into the reactor hall. This fact facilitated the activities during operation, in the transition period from operation to decommissioning, and during decommissioning.
— To ensure a sufficient air exchange rate (one room volume per hour), a ventilator was used to ventilate the reactor hall into the unfiltered exhaust air stack. In the case of an accident involving the release of a large quantity of radioactive aerosols into the reactor hall, a detector in the exhaust chimney would have detected the event. In this case, a much smaller ventilator would have been used to ventilate the contaminated reactor hall atmosphere over the filters. In normal operation prior to the permanent shutdown, no significant amounts of radioactive aerosols in the reactor hall were expected, but in the transition period to decommissioning and during decommissioning, normal operating conditions had changed and a process of filtration needed to be implemented.

IV–7. CONSIDERATIONS FOR DECOMMISSIONING DURING OPERATION AND MAINTENANCE ACTIVITIES

IV–7.1. Configuration management

During the operation and maintenance (O&M) period of the reactor, the configuration management for safety related SSCs and for systems directly connected to the research reactor operation (i.e. grid-plate, primary cooling circuit and primary heat exchanger) was done thoroughly. In particular, changes to existing systems were documented by updating plans and documenting installed materials. Planned changes in operation, such as the increase in power and changes to the enrichment of the nuclear fuel, were precisely documented as well. For every application for a new operating licence or changes to an existing licence, extensive documentation on the design basis and the actual physical state of SSCs was prepared and submitted for approval to the regulatory body and checked by the technical support organization of the regulatory body.

Other than the configuration management documentation of the safety related SSCs of the reactor during operation, the documentation prepared to authorize the experiments inside the reactor hall focused only on the aspects of radiation safety, by checking possible negative feedback effects on nuclear safety. Therefore, as expected in a scientific and experimental environment, the needed configuration management of the FRM experiments for the decommissioning planning was not too rigorous.

IV–7.2. Record keeping

The as-built plans for the reactor hall, the concrete pool and other building structures and large steel constructions from the commissioning stage were not available to the operator for most of the operation stage, as it was kept by the state government organization that had been responsible for the construction work of the reactor building structures, including the reactor pool. Only after an effort from a concerned person from the operating organization could the as-built plans be retrieved and made available before the permanent shutdown of the FRM. Those plans were mainly necessary for answering questions regarding the load-bearing capacity of the floor of the reactor hall, after the SNF packing and transport preparation — and with it the transport and storage cask — had to be moved from outside to the reactor hall (see Section IV–5.4).

All other records of the facility were kept in various on-site archives. There were three kinds of record: personal records, operational records and records required by law or regulation. The concept of record-keeping was ‘keep everything’. When a responsible group leader or manager left, all hard copy documents were stored in the archive. The same routine applied to operational documentation. When a notebook for handwritten documentation (e.g. operators shift documentation, documentation of radiation safety relevant events such as contaminations) was completed, it was stored in an archive. The typewritten reports required by regulation (e.g. radiation protection report, technical report) were kept in the official site archive.

IV–7.3. Decommissioning experience gained during operation

IV–7.3.1. Replacement of unneeded systems

Owing to several changes in the utilization of the reactor, there was a continuous process of decommissioning old systems and commissioning new ones. Two typical examples of such activities are the following:

- — Decommissioning of the neutron beam hall. An experimental facility was located in a small building outside the area of the reactor, and a neutron guide tube was connected between the experiment location and the reactor. Once the experiment had finished, it was decided to completely decommission the facility, prior to the permanent shutdown of the reactor. Therefore, the dismantling and release from regulatory control of the outdoor building took place briefly afterwards, to make space for building activities on the site. The activated neutron guide tubes were brought into the reactor hall. During this process, much relevant experience on the decommissioning process was gained, as the operator had to clear the outdoor site from regulatory control, handle the activated components as radioactive waste and achieve clearance for other material.
- — Decommissioning of the cold neutron source. Owing to the handling of hydrogen and the expected deterioration of parts of the cold neutron source close to the reactor core owing to high neutron flux, the regulatory requirements for the operation of the cold neutron source were always high. In order to reduce the regulatory requirements, the decommissioning process of the cold neutron source was initiated in 1999, prior to the permanent shutdown of the reactor. The decommissioning was completed in 2002 by venting the remaining hydrogen and flooding the hydrogen system with an inert gas. The dismantling of the cold neutron source was left as a task to be performed within the scope of a decommissioning licence in the future. A pressure monitored water barrier filled with helium inside the beam tube and connected to the cold neutron source had to be kept operational to monitor and ensure the tightness of the vacuum part of the cold neutron source (see Fig. IV–7).

IV–7.3.2. Experience acquired from performing maintenance

Maintenance during operation included various tasks performed by the operating organization. For many systems, there was a correlation between performing maintenance work easily and comfortably performing decommissioning and dismantling. For example, most of the systems inside

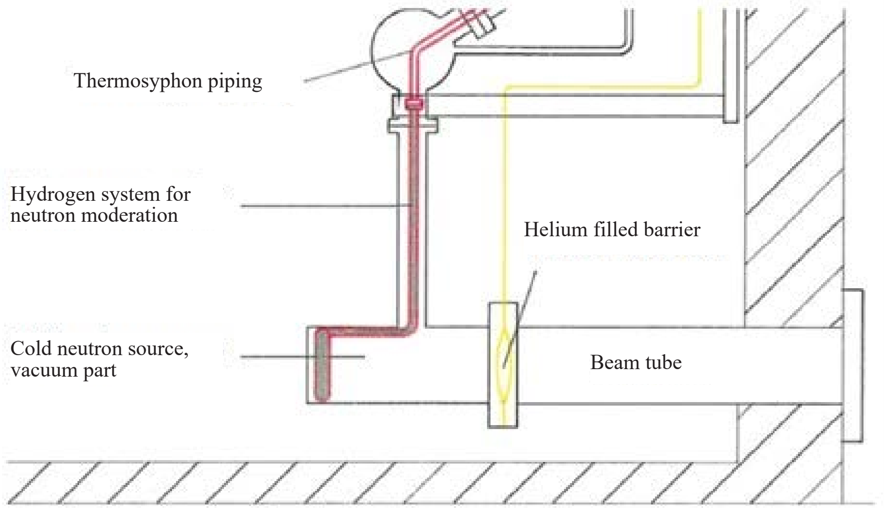


FIG. IV–7. Schematic diagram of the cold neutron source parts close to the reactor core (courtesy of U. Lichnovsky, FRM II, Germany).

and outside the reactor hall (e.g. fresh water supply, pre-demineralization system) were accessible and could therefore be decommissioned and dismantled relatively easily.

Two working areas were identified as problematic already during operation: (a) the wastewater storage and treatment area, and (b) the basement room, containing the primary circuit heat exchanger, the primary pump and the primary circuit water purification systems with five different ion exchange resin tanks. The wastewater area was packed tightly, with two 40 m^3 concrete basins, various stainless steel tanks, candle filters and a filter press. The primary circuit basement room was not only packed tightly, but also had low level contamination. In addition to the contamination, it also had a significant radioactive dose rate originating from the heat exchanger and the ion exchange resins.

IV–7.3.3. Experience acquired from the utilization and operation of experimental facilities

The ways of utilizing the FRM changed during its operating lifetime. Valuable experience in handling highly activated parts was gained when exchanging the in-core nozzle of the cryogenic temperature irradiation facility and the highly activated beam tube connecting the cold neutron source and the reactor hall. The experience gained when changing the beam tube from the cold neutron source prepared the operating organization for work that needs thorough planning to ensure radiation safety for the personnel tasked with the job and for the surroundings.

IV–7.4. Operational radiation protection programme

The operational radiation protection programme ensured a good knowledge of the radiological situation in the reactor hall. Surface contaminations and dose rates at various points were checked and documented daily. If necessary, decontamination was carried out by trained workers. Main areas of special concern regarding contamination were the handling areas of irradiated samples (i.e. the cryogenic deep temperature facility sample area and the pneumatic tube sample transfer area). Prior to operating new experimental facilities, the gamma and neutron dose rates around the experiment were checked by the radiation protection group. From those measurements, a good overview of regions with high neutron flux and possible neutron induced activation of material outside the reactor core area was available.

Some beam tubes in the reactor hall were shielded against neutron radiation by a water filled concrete basin, and it was clear that the material inside the basin would be activated above clearance levels. Radiation protection included the clearance of material from the reactor hall in accordance with clear written procedures to achieve acceptable contamination levels.

IV–7.5. Operational radioactive waste

During the operation of the FRM, the operating organization did not have the required staffing to manage the processing of all the operational waste. Hence, the primary activity of the radiation protection team was to ensure comprehensive documentation of the operational waste. This activity included the documentation of the material waste stored, the measured dose rate and the calculated radionuclides in the waste. During operation, there was enough on-site and off-site storage capacity (see Fig. IV–1) available for this approach on radioactive waste.

IV–8. LESSONS LEARNED AND CLOSURE

IV–8.1. Lessons learned from managing the transition period

Many lessons were identified during the decommissioning of the FRM, and the most important ones were the following:

- For a small 4 MW research reactor, it is possible to pass through the transition period with minimal personnel resources, as described in Section IV–5.3. This is especially the case after the removal of SNF from the site, shortly after the permanent shutdown of the reactor. To achieve a reduction of the personnel required for the transition period, it is also necessary to identify the systems required to operate during the entire decommissioning process and reduce their testing and maintenance to the minimum required. Nevertheless, it is necessary to point out that it will be very difficult even for skilled staff to remember technical or radiological details of facilities and systems after ten years or more. This proved to be true, regardless of the effort dedicated to document the know-how of the relevant staff.
- The configuration management presented in Table IV–4 indicates a formal approach to the changes in the process of systems management during the transition period. The approach required that prior to initiating actual changes, proper documentation would be available and that changes would not adversely affect safety. Unfortunately, the process did not ensure that with the technical closure of a change, the complete required documentation would be available. Therefore, at the end of the transition period, the incomplete documentation of systems changes (e.g. absence of documentation on water supply and on radiation protection instrumentation) often led to conflicting descriptions of systems in the licensing documents for decommissioning and the actual state of the systems.
- The FDP had to be prepared in the most comprehensive way soon after the permanent shutdown of the reactor. With a minimized workforce, it was challenging to support and supervise the contractor working on the FDP. Moreover, after a long transition period, it was difficult for the operator to transfer know-how effectively to the contractor. This included information on radioactive waste, physical material and procedures required for certain dismantling tasks. The lack of an established policy on radioactive waste disposal and of a clear definition of the scope in the FDP (e.g. unclear distinction between experimental facilities and the research reactor) led to minor inconsistencies in the FDP and caused uncertainties during the implementation process.

IV–8.2. Lessons learned regarding design and operation and maintenance

IV–8.2.1. Considering the reactor design

Most of the design features targeted at the O&M of the research reactor were also practical for the decommissioning process. Examples included the big-truck sized large access door, the good documentation on the construction materials and the very low contamination of systems owing to the initial design and the quality assurance during the manufacturing of the MTR fuel elements. Nevertheless, two systems reflected technical design weakness:

— The circular crane. As previously mentioned, owing to the egg shape of the reactor hall, the sealing crane was not able to cover the entire outer rim area of the hall.
— The ventilation system. As the unfiltered ventilation system in the reactor buildings was designed and built very compactly, it was a difficult task to add the required filters into the exhaust air system during the decommissioning process.

Through decades of FRM operation, the space inside the reactor hall became scarce because of the location of various experimental facilities. Moreover, limited working space was a common problem all over the reactor site, as future expansion was not initially considered. Although this is not a technical design problem, it is important to bear in mind that the decommissioning process requires predesigned spaces and dedicated rooms.

IV–8.2.2. Considering operation and maintenance

For the activities performed in the O&M period, prior to the final shutdown, to be valuable for the decommissioning stage of the reactor, the know-how from this period needs to be preserved and written documentation needs to be stored and easily accessed.

Decommissioning activities performed during the O&M period for specific facilities demonstrate that the process will be relevant to the complete decommissioning stage. Those earlier activities indicated that the organization is able to perform tasks required for decommissioning and able to learn and correct activities during the limited process. Nevertheless, it was concluded that the decommissioning and dismantling of a complete research reactor is a much more complicated task than the decommissioning of an isolated device or an experimental system. The complexity of planning and executing many and various decommissioning tasks, including the management of waste within the scope of a larger project, is considerably higher than an isolated task during operation.

Activities not prioritized during the O&M period, such as the immediate or timely predisposal management (i.e. processing and storage) of radioactive waste, will become much more complicated, time consuming and costly during the decommissioning process. Therefore, it is suggested, as a good practice, to establish already during the O&M period appropriate pathways for the processing of radioactive waste, even if the available storage space can accommodate the generated quantities of waste.

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LIST OF ABBREVIATIONS

BNCT	boron neutron capture therapy
D&D	decontamination and dismantling
DTM	difficult to measure
EIA	environmental impact assessment
FDP	final decommissioning plan
I&C	instrumentation and control
O&M	operation and maintenance
OLC	operational limits and conditions
S&M	surveillance and maintenance
SFP	spent fuel pool
SFSB	spent fuel storage basin
SNF	spent nuclear fuel
SSCs	structures, systems and components

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