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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

Pools, or ponds, are usually an integrated part of a more complex nuclear facility. In some particular cases, however, the pool may be considered as a separate nuclear facility. A number of nuclear installations utilize pools for the cooling of spent fuel or the shielding of research reactor cores or irradiator sources.

Some pools, for example newer facilities handling zircaloy cladding oxide fuels, are generally well managed and in a good condition, and the decommissioning challenges are relatively straight forward. However, this is not always the case, particularly for older facilities. Over a service lifetime that can span decades, nuclear pools may become contaminated as a result of the deposition of radioactive substances, for example aerosols or corrosion products on pool surfaces and stored components. In the longer term, this may be a serious decommissioning issue. The contamination may be difficult to remove, depending on the operating conditions and the chemical and physical environment. In addition, the physical logistics of pool decommissioning may be complex, for example the difficulty of removing sludge or handling bulky items. Relevant aspects of pool decommissioning include project planning and management, health and safety, and management and disposal of the resulting waste. Such issues are quite common in IAEA Member States, owing to the ubiquitous presence of these major facilities.

Although cases of pool decommissioning have been sporadically described in the technical literature, comprehensive treatment of decontamination and dismantling strategies and technologies does not currently exist for contaminated pools. Similarly, although many IAEA publications have been issued in the field of decommissioning, none focuses specifically on this subject. It can be often assumed that generic decontamination and dismantling technologies would also apply to nuclear pools, but such treatment disregards a number of specific physical and radiological characteristics that make pool decommissioning a unique undertaking. With growing experience in the decommissioning of nuclear installations, including the recent completion of some large scale decommissioning projects, it is timely to review and consolidate the worldwide experience available on the technical and planning aspects of pool decommissioning in a dedicated report.

The IAEA is grateful to all the contributors who reviewed, amended and finalized this publication, and to the participants of the consultants meetings. The IAEA officers responsible for this publication were M. Laraia and V. Michal of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

PREFACE

Internationally, pools have been used in the operation of nuclear reactors and other nuclear facilities, as well as in the management of spent fuels and radioactive materials. These pools have often been used long after the associated facilities have ceased operating and well past their original design life. The inherent hazards are associated with the operation of ageing facilities with significant mobile radioactive inventory. Attention needs to be given to the decommissioning of pools in nuclear facilities.

A typical timeline for pool decommissioning project activities includes a strategy and planning stage, preparatory activities, a decontamination stage and, finally, dismantling and demolition. The extensive experience summarized in this publication relates to the potential challenges and successful approaches for each of these stages.

STRATEGY AND PLANNING

Generally, pool decommissioning strategies consider three interrelated stages in the decommissioning process:

(a) Initial cleanout and retrieval of the stored inventory, which removes the main radiological hazards and risks;
(b) Major decontamination to reduce risks further and to allow improved personnel access;
(c) Demolition of the residual structures or its safe enclosure pending future site clearance or reuse.

The strategy and planning stage considers the work required for these three main interrelated stages, but may also include any necessary up front engineering work that is required. A strategy of doing nothing is not considered acceptable.

The decommissioning strategy needs to balance the ongoing hazard associated with the facility, the context within the site and end state objectives, along with economic factors. Once the strategy is defined, a specific decommissioning plan for the pool facility has to be prepared.

Past design and operational practices significantly affect the potential decommissioning challenges. A good understanding of these issues is a valuable foundation for those developing strategies and plans for pool decommissioning.

A key source of information for the generation of the decommissioning plan will be from existing and previous operating staff, if available, as well as records. It will be necessary to review thoroughly the extent of available engineering information and to assess whether this is likely to be adequate to support the anticipated projects and safety assessments.

Consideration should be given to waste management, integration with other processes on the site, regulatory requirements and risk assessment. In terms of timing, the hazards associated with any delay in decommissioning a pool need to be balanced against the increased risk during the decommissioning phase. The sequence for removing items from pools may be varied according to the nature of the pool inventory. For example, items may be removed to facilitate sludge removal or some sludge may be removed to expose items.

PREPARATORY ACTIVITIES

Preparatory activities include characterization, removal of any remaining fuel and post-operational inventory, as well as tasks to ensure safe working conditions during subsequent stages.

As part of the preparation for decommissioning pool facilities, it will be necessary to characterize wastes and the pond condition. Characterization work needs to address sediments, sludge, solid wastes, pond water, pond radiological conditions, surface contamination levels and depth of penetration into structure, non-radioactive hazardous wastes, chemical and physical properties of wastes, plant configuration and waste location. This characterization will be used to support development of waste retrieval, treatment and disposal techniques, decommissioning activities and safety assessment.

A wide variety of activities support characterization, including, but not limited to, the review of historical records, sampling and analysis, surveys and underwater video evidence. It should be recognized that it is difficult to fully characterize wastes that are dispersed over larger areas or are obscured under sludge, debris and other components. The design of retrievals and treatment techniques need to include provisions to make them robust to variations in properties. Characterization records should be updated as decommissioning progresses and more information becomes available or as conditions change.

Most pools have overhead gantry cranes for pool operations, which are likely to be required during decommissioning. The integrity and safety of the cranes need verification and proof testing to ensure safe use during decommissioning, particularly if the facility has been in a prolonged 'care and maintenance' regime prior to dismantling. To ensure safe lifting, extra consideration should be given to the structural integrity of the pond items to be removed, as lifting equipment may have been subject to corrosion or damage.

The pool active effluent treatment plant (AETP) retains a key role during decommissioning in larger facilities, and the effluent challenge may be higher or different than during the pool operating period. In some cases, owing to delayed pool dismantling, this equipment has been found to be inadequate, obsolete or degraded beyond useful operation, and a new facility need to be provided. If the pool facility has its own existing AETP, which is often the case, then attention will have to be given to decontaminating and dismantling the AETP itself and handling any ion exchange resins used during decommissioning.

According to state of the art criteria and regulations, spent fuel should be normally removed from the operations pool and shipped to a dedicated installation as soon as possible after final shutdown. In many cases, however, spent fuel is retained in pools for extended periods, resulting in enhanced decommissioning issues. Removal and management of any remaining spent fuel is a key activity during the preparatory stage.

When fuel is shipped off-site or transferred to an independent spent fuel storage installation, a considerable amount of residual radioactive material and debris is often left in the pools. A large part of this will be fuel skips and racks and sometimes activated components from the reactor. There could also be fuel fragments from failed or degraded fuel and items from research programmes.

Sludge is present in almost all wet storage facilities as a result of corrosion and, to some extent, from external sources such as airborne dust, debris, algae growth and other extraneous material. Characterization is often difficult because sludge is not homogeneous or of uniform depth. During sludge and sediment removal operations, there is a persistent risk of suspension causing loss of visibility and complicating subsequent handling problems. Technologies exist to restore water clarity and should be considered during these operations.

DECONTAMINATION

After shutdown and defuelling, it is the pools and waste silos that are often identified as the most contaminated areas of nuclear facilities. This is especially the case if pools have been used for long term or lifetime storage of spent fuel and highly activated waste. The practical and most common use of water as a medium for cooling and shielding has the drawback of promoting corrosion and degradation of even the most durable of materials. Therefore, a major decontamination stage is typically undertaken as a part of pool decommissioning and radioactive waste management activities.

It is important to ensure that decontamination objectives are clear from the outset. Generally, decontamination is required to reduce risks further, improve waste management and allow greater personnel access for subsequent activities. The objectives need to consider the overall facility end state and waste acceptance criteria for the chosen treatment and disposal routes. Decontamination of pool facilities can give rise to significant exposure to workers owing to the mobile nature of water and airborne contamination. Therefore, care should be exercised not to undertake unnecessary decontamination that provides little benefit but which incurs significant dose uptake.

Decontamination typically addresses pool equipment and pool surfaces. A variety of techniques are available, and these can be deployed underwater or as water levels are reduced. There is extensive experience reported on the success of various techniques.

DISMANTLING AND DEMOLITION

Dismantling and demolition addresses the pond itself, residual structures, overbuilding and remaining service systems. This stage may alternatively provide safe enclosure or entombment pending future site clearance if this aligns with the site strategy.

While the overall nuclear and radiological risks may be reducing after pool shutdown, there are other risks that can increase during the decommissioning period. This is particularly important during the dismantling and demolition phase. These risks could be from chemicals, asbestos removal, major dismantling work, changes in services (particularly electrical and water) and changes in management structure. Therefore, decommissioning plans also need to consider conventional and environmental hazards, and this should be carried through to the dismantling and demolition stage.

A variety of techniques and equipment has been deployed to enable dismantling and demolition. Differing techniques may be required for a typical concrete pool structure and for the associated pool building and associated structures. Consideration should be given to the design of the pool and how it was constructed when defining the method and order for dismantling and demolition. Importantly, consideration should be given to the different approaches required for above and below ground structures. Below ground, there may be additional complications related to previous leakage to the ground, contaminated soil and structural access. It is noted that early facilities may not have been designed with dismantling and demolition in mind, requiring access and stability of structures to be considered carefully.

Demolition contractors may be utilized, in which case, consideration needs to be given to ensure their awareness and understanding of the remaining radiological hazards and radiological safety practices required. In some circumstances, the reuse of pool structures for new purposes can be given priority over their demolition.

1. INTRODUCTION

1.1. BACKGROUND

Nearly all nuclear reactors and many other nuclear fuel cycle facilities (e.g. reprocessing plants) or radiological facilities (e.g. irradiators) use pools. The term pool is synonymous with pond and basin, and these terms are used interchangeably in this publication. A simple definition of a pool is an intentionally water filled structure to provide containment, shielding and cooling for radioactive materials. Pools are usually contained within a building, but some earlier types were outdoors.

The most common application of these structures is to store spent fuel during and beyond facility operational lifetimes. In addition to spent fuel pools, there are other pool type facilities (e.g. pool type research reactors) that can store many types of highly radioactive materials and become contaminated during their operational lifetime. There are also auxiliary facilities associated with a pool complex, such as loading bays and reactor to pool fuel transfer channels. Figure 1.1 shows an example of a nuclear power plant spent fuel pool. Figures 1.2–1.4 show examples of different types of pools at research reactors.

In addition to spent fuel facilities and reactors, irradiators represent a category of facilities that use pools for their operation. Irradiators are employed for the sterilization of food, medical devices and municipal sludge, among other things. Currently, close to 200 industrial irradiators are in operation worldwide. Although there are some irradiators that store radiation sources dry, for the purposes of this publication, only wet storage irradiators are relevant. Overall, the estimated number of nuclear facility pools is well over 1000 worldwide.

Pool activity levels may be well managed during a facility’s operational phase. However, it is often the case that over a service lifetime (which can reach decades), pool floors, walls and auxiliary systems become contaminated as a result of surface deposition of radioactive corrosion and fission products and penetration of contamination into surfaces. Extended periods of fuel and waste storage in pools may exacerbate these problems by increasing the specific activity of pool water. In some cases where the pool is not lined, the contamination may penetrate to building foundations, underlying ground or even affect groundwater. In the longer term, this becomes a major decommissioning, soil and groundwater remediation issue.

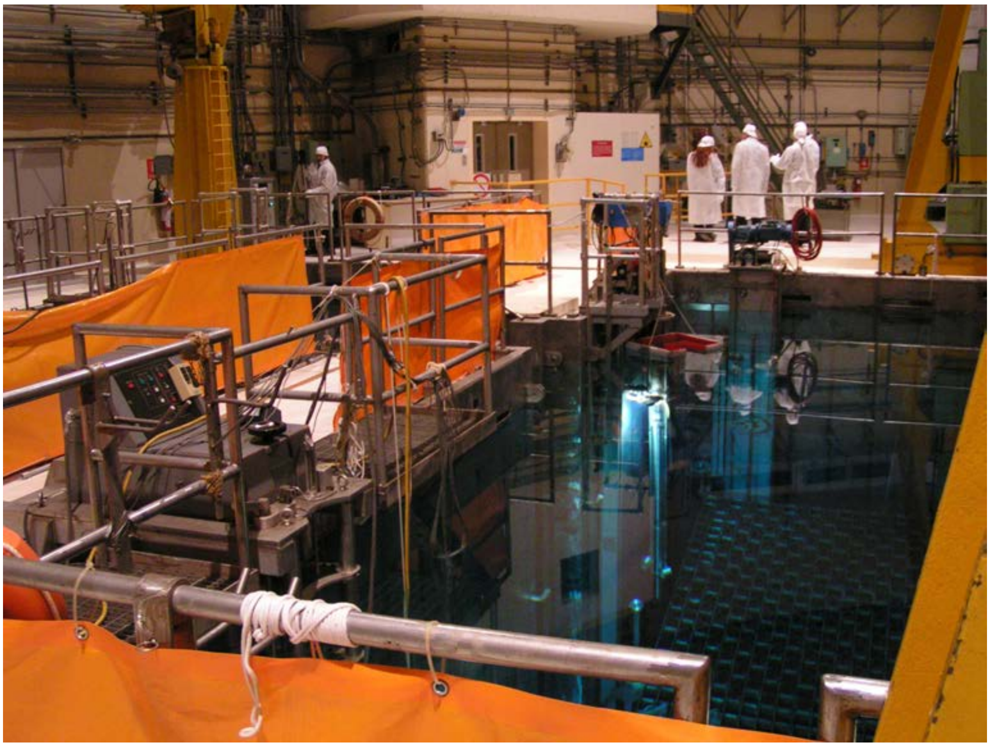

FIG. 1.1. Caorso fuel pool, boiling water reactor, Italy (courtesy of S. Ramella, Caorso nuclear power plant).

FIG. 1.2. Dounreay fast reactor pond, United Kingdom (courtesy of Dounreay Site Restoration Ltd).

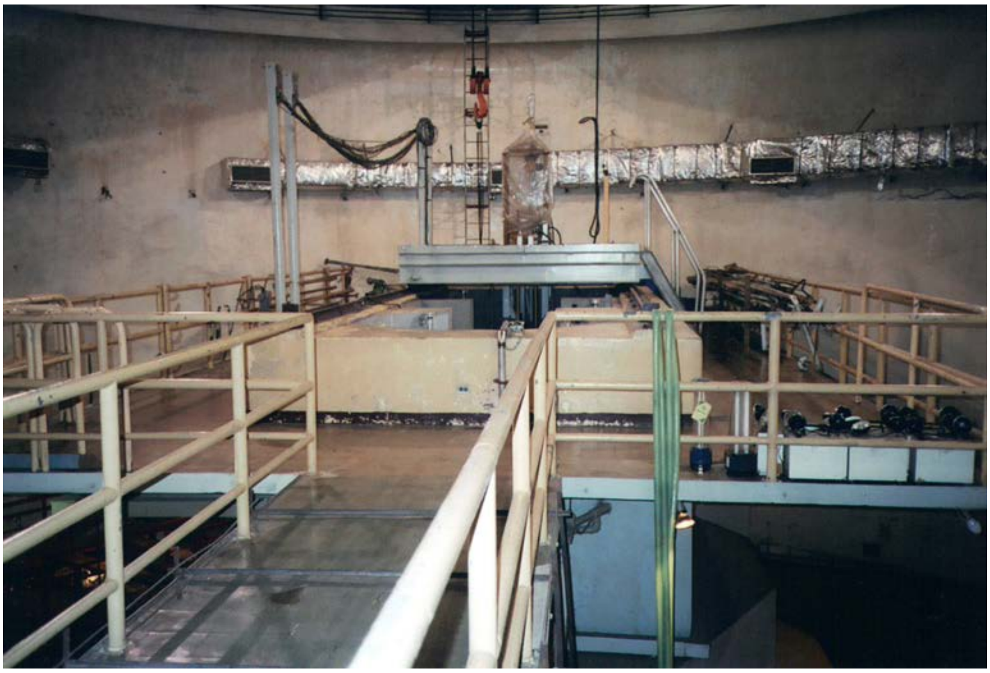

FIG. 1.3. Research reactor upper pond, Philippines (courtesy of Philippine Nuclear Research Institute).

FIG. 1.4. VR1 pool type reactor, Czech Republic (courtesy of European Nuclear Society).

The ageing, degradation and corrosion of materials is a common problem in pools and is the main source of sludge, which accumulates in many pools. In other cases, chemical dosing has been carried out to inhibit corrosion, especially of the protective fuel assembly cladding. However, in some very old pools, sludge levels can reach metres in depth. Incumbent problems are flocculation, obscuration and gas formation and the continual risk of leaks. Some facilities have been used to store a very wide range of mixed contaminated waste, some of which has created specific problems. Choice of materials and pool chemistry are specifically devised in modern plants to avoid these problems. Particulates may also arise from building ventilation or transportation casks. The challenges associated with retrieval of sludge and debris in pools have been dealt with at a number of facilities around the world. Decommissioning experience from these facilities are discussed in this publication.

This publication is part of the continuing development of IAEA decommissioning and waste management documents that present special interest to those responsible for planning and implementation of relevant activities [1.1–1.11]. In addition, the IAEA has already issued publications on practices for water quality management in research reactors and spent fuel storage facilities, which is intended to assist in good pool operations to avoid unnecessary decommissioning problems [1.12–1.15]. A report on irradiator decommissioning is at an advanced stage of preparation [1.16].

1.2. OBJECTIVE

The objective of this publication is to assemble current and historical experiences reported worldwide and to disseminate useful experiences and lessons learned. The experience has been used to provide some guidance on principles, planning and strategy for pool decommissioning. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

The IAEA has published over 70 technical reports and other documents covering the complex field of decommissioning a nuclear facility, but the specific and special subject of pool decontamination and dismantling has not been fully addressed. The main purpose of this publication is to deal specifically with pools and other pool type facilities. It is recognized that decommissioning of other storage facilities, such as silos, tanks and vaults, may involve similar techniques, and parts of this publication may be applicable to those facilities.

Advantage has been taken of past and current decommissioning experience in assimilating information on pool type facilities. In the 1980s and 1990s, a few pool facilities were decommissioned, but most have been retained in service for long periods after a nuclear power plant or fuel cycle facility has been shut down to store spent fuel and various wastes. A factor that contributed to the extensive and long term use and reuse of pools was the need to store spent fuel because of a shortage of off-site storage and reprocessing facilities and the worldwide absence of disposal routes for spent fuel. Considerable attention was given to increasing both wet and dry spent fuel storage capacity in the earlier periods of nuclear technology, but decommissioning of these facilities initially received little attention.

International attention is now being given to the proper decommissioning of pools, owing to increasing incidents and leaks to the environment and because measures have been taken to manage spent fuel, for example by provision of wet and dry storage in independent spent fuel storage installations (ISFSIs). Regulators are now requiring that the problem of degraded pools be addressed with priority. The events at the Fukushima Daiichi nuclear power plant, in Japan, have prompted concerns over the large inventory of spent fuel stored in spent fuel pools and its inherent risks. It should be noted that this publication is intended for the planned decommissioning of pools. The decommissioning of pools after a severe accident is only dealt with in the Appendix.

From published data and reported experience, it has been possible to suggest three interrelated stages in the decommissioning process. These are the initial cleanout and retrieval of the stored inventory, which removes the main radiological hazards, a major water removal and decontamination stage to reduce risks further and allow more personnel access, and then to either demolish the residual structures or establish a safe enclosure pending future site clearance. There may be a need, in some cases, to refurbish or re-establish stable pool operating conditions before decommissioning can commence, especially where pools have been dormant for many years or decades. The need to consider waste management at all stages was identified.

It was noted that most sites include several nuclear facilities such as waste treatment facilities or interim waste storages. Pools will seldom be the only facility and hardly ever the last left on a site. The strategy for pool decommissioning should be integrated with other processes, activities and operations on the site, which may include new builds, continued operation of some facilities and other ongoing decommissioning projects. The end state conditions of a pool decommissioning project need to be clearly stated with respect to possible future site remediation activities, regulatory requirements and risk assessments. The development of end state conditions and reuse opportunities are briefly discussed in this publication.

Waste management issues are not dealt with in detail in this publication, but are referred to, where appropriate, in sections where waste management is important. There are other IAEA publications which provide guidance on this subject (see Refs [1.4, 1.17]).

1.3. SCOPE

This publication covers all pool type facilities at large nuclear power plants, smaller prototype and research facilities, and large reprocessing and historical or legacy sites. Some attention has been given to spent fuel management and waste retrieval where this is directly related to pools. The decommissioning of pools associated with or included within the reactor structure and contained within the reactor containment is in the scope of this publication. These intermediate or transfer pools accept spent fuel initially for cooling before transferring to central away from reactor wet or dry storage facilities on the site. Dry storage facilities that serve the same function as interim wet storage pools are not discussed. Pool irradiators are considered in this publication.

The reported experience relates mostly to legacy facilities. However, the issues with pool decommissioning highlighted here are generally common to all pool like facilities, although issues are less acute in state of the art facilities than in older ones. In fact, it is the learning from dealing with legacy facilities that should be used for the benefit of decommissioning pools in the future.

The information in this publication is intended to give a consolidated review of experience and practical guidance to those planning, managing and implementing the dismantling of contaminated pools in nuclear facilities. The publication may also be of use to those involved in the nuclear regulatory field when reviewing plans, carrying out inspection activities and confirming satisfactory completion of decommissioning. It may also be helpful to local and other stakeholders.

There are a few large pools that are, in fact, lakes or reservoirs which have become contaminated during operation or as a result of accidents [1.18].[1] The complex challenges associated with these large pools include geological aspects and environmental remediation, which are not addressed here.

1.4. STRUCTURE

Following the introductory Section 1, this publication examines past practices in Section 2 and compares these with current pool designs. Strategy and planning is reviewed in Section 3, taking account of hazards from pools, site cleanup activities and possible future use of the site. The decommissioning process is then considered in the three phases of pre-decommissioning activities, decontamination and dismantling. These three phases are illustrated, respectively, in Sections 4–6. A summary of relevant experiences is presented in Section 7, and key conclusions are given in Section 8. The Appendix is specifically devoted to the decommissioning of pools after a severe accident. Annexes 1 and 2 record particular projects and lessons learned. To illustrate the scope of this publication, Fig. 1.5 outlines the key planning and activities associated with pool decommissioning.

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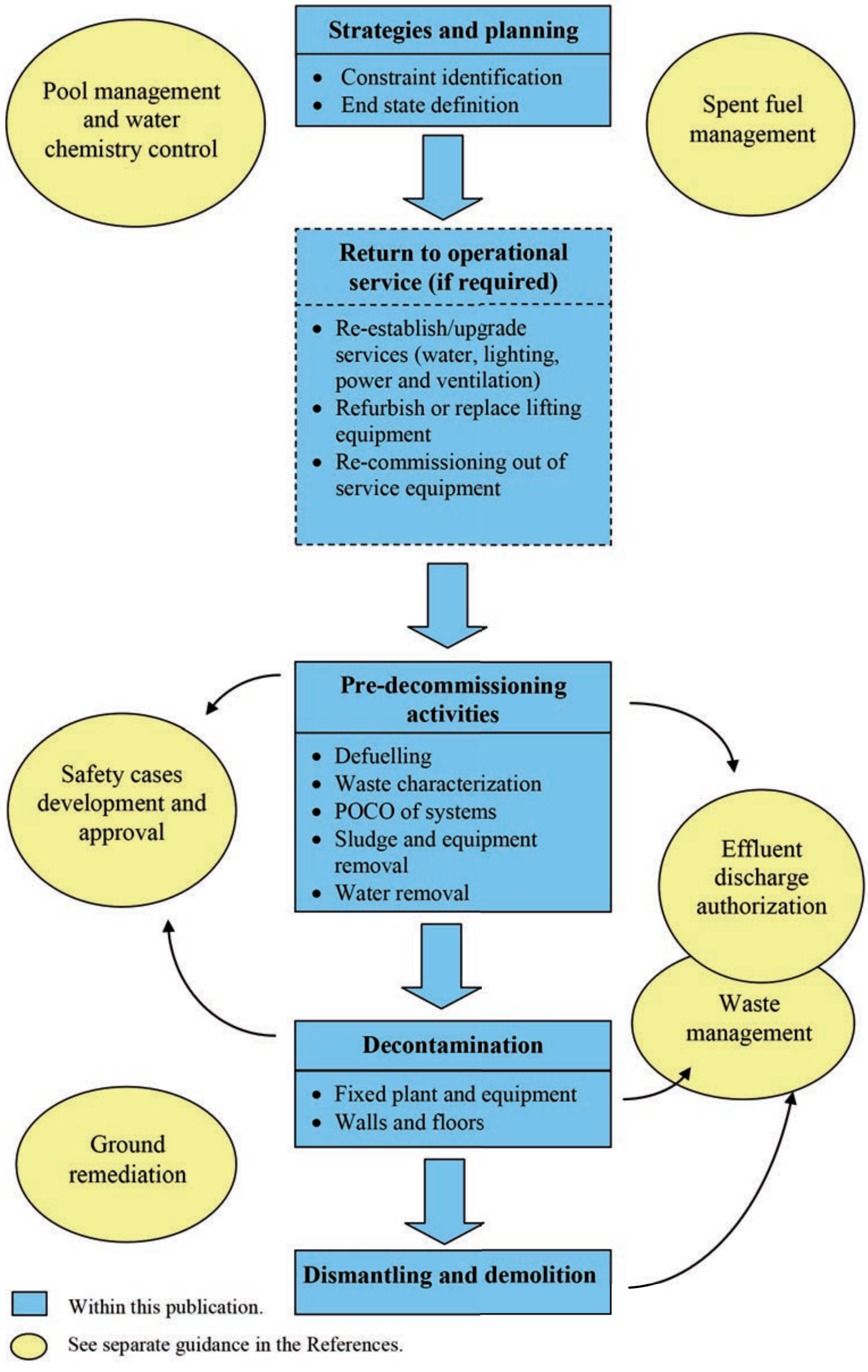
[1] See also the IAEA Workshop Results of Activity Related to Chernobyl NPP Cooling Pond Decommissioning Options, Kiev, October 2013.



Note: POCO — post-operational clean out.

FIG. 1.5. Main activities for pool decommissioning.

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2. PAST PRACTICES VERSUS CURRENT STANDARDS

2.1. CONSTRUCTION ASPECTS OF POOLS

The types of pool vary considerably in size but are commonly and mostly of mass concrete construction. There are some wet storage facilities that are in the form of metal tanks, but they will always incorporate some biological shielding, usually of concrete for radiological protection.

More than 700 research reactors have so far been constructed worldwide. Of these, approximately 250 are still in operation and approximately 25% are more than 40 years old [2.1]. Corrosion and degradation of reactor pools is a current problem.

At major fuel cycle sites such as Sellafield, in the United Kingdom, or Hanford and Idaho, in the United States of America, there are very old legacy pools that have been in operation since the 1950s or earlier (see Fig. 2.1), and are seriously degraded and contaminated. They were used for interim storage of a variety of spent fuel types and wastes. They were often operated for long periods with minimal water chemistry control and monitoring. Some were outdoor types with no containment building. Attention to decommissioning of these facilities is now in hand, with some significant decommissioning projects already completed or under way.

FIG. 2.1. Construction at Sellafield, United Kingdom, pile fuel storage pool in 1948 (courtesy of Sellafield Ltd).

Pools are almost always filled with water. There are exceptions where liquid sodium is used for initial cooling in fast reactors, but the sodium will be eventually removed, and the pool may be filled with water for decontamination. There are many research reactors where the pool may also contain the reactor core or be integral with the reactor.

Pools require a number of support services, some of which can be essential for safety reasons. Some pools will have a permanent radioactive water treatment plant to control buildup of contamination, but some may rely on portable ion exchange and filter devices inserted into the water. Forced cooling by means of a recirculating system with a heat sink will be needed for spent fuel with high heat release, but for pools with already cooled fuel, evaporative cooling alone may be sufficient. A secure water top up system will be necessary, and sometimes facilities for purging will also be necessary. A pool containment building with active ventilation is desirable, but there are a number of older legacy pools that are of an outdoor type. Many pools have multiple compartments or bays used for different functions such as fuel transport cask handling, fuel inspection, fuel element decanning and decontamination processes. Pools containing fissile material will need approved safeguards features, an administrative and operations control room and appropriate health physics instrumentation for operator dose monitoring and protection.

At many nuclear power plants, there are primary pools adjacent to the reactor to provide initial cooling during defuelling (see Fig. 2.2). Spent fuel, after a period of time, may then be transferred to an away from reactor secondary storage pool. At some nuclear power plants, secondary fuel storage may be dry in casks or vaults (ISFSIs) or may be wet pools at other locations such as reprocessing plants. Typical cooling times may be 100 days for hot fuel in a primary pool, and delays of up to 5 years in secondary pools before dry storage are permitted.

Although pools are used extensively, they have inherent safety risks owing to loss of water, either catastrophically (e.g. after an earthquake) or because of leaks, loss of cooling, corrosion and degradation of structural and stored materials, complex water chemistry to inhibit corrosion and algae formation, as well as some risk of criticality. Dry storage has distinct advantages owing to the more benign and passive nature of dry conditions, but less than 10% of world arisings of spent fuel are currently estimated to be in dry interim storage.

At reprocessing facilities and other non-reactor facilities, there are usually very large and multiple pool facilities. These provide a buffer storage function for spent fuel, some of which can come from other countries, and various wastes that await reprocessing or are in interim storage awaiting disposal.

FIG. 2.2. Hunterston cartridge cooling pond, United Kingdom (courtesy of Magnox Limited).

Panoramic irradiators are devices in which the primary radiation beam is not shielded during irradiator use. Typical dimensions of an irradiator pool are 5–10 m^2 in cross-section and 5–7 m in depth. A few metres of water are needed to shield the source irradiation. Figure 2.3 is a schematic diagram of a pool irradiator.

Table 2.1 provides examples of the main characteristics of pools that are part of reactor and non-reactor nuclear facilities.

2.2. PROBLEMS WITH PAST POOL DESIGN AND OPERATIONAL PRACTICES

Some of the challenges of pool decommissioning result from past design and operational practices. Many of the pool facilities discussed in this publication were constructed in many countries from 1945 to around 1960 as essential components of prototype and research facilities. These have sometimes been called legacy facilities. Much of the early development was for electricity generation and for medical, industrial and research enterprises. Many of these shut down soon after commissioning and operation owing to accidents, obsolescence or economic, political and public objections. All these prototype and experimental installations had generated some spent fuel and large quantities of waste. Many of the pools that had been constructed at the same time as these earlier facilities became the medium for long term storage of this material until solutions or initiatives were found to process the waste material or dispose of it. There was little concept of the likely storage duration at that time and little interest in preserving good storage conditions because interest in the earlier prototype and experimental installation had waned.

Many of the early designs of spent fuel cooling ponds were open to the atmosphere, although more modern ponds utilize a fully enclosed structure to minimize the deposition of airborne contaminants such as salt spray (in coastal sites) or bird droppings. Open ponds are exposed to sunlight and hence suffer greatly from algal growth (which is common, even in indoor pools), which can reduce underwater visibility to such a degree that it becomes virtually impossible to visually identify (let alone handle) submerged items.

Pools associated with earlier nuclear facilities do not have many features that would facilitate decommissioning. Many were constructed of unsealed concrete with little or no provisions for leak detection. Bare concrete absorbed radioactive contamination. Some pools did not have effective water treatment systems, and corrosion and formation of sediments were inevitable. Some fuel cladding materials and pool equipment were unsuitable for use in water for prolonged periods. The neglect of pools containing degraded spent fuel and hazardous wastes for many decades, in some cases up to 60 years, has presented many challenges. The buildup of highly radioactive sludge has been a severe problem in some cases. Sludge can contain alpha bearing and other long lived material. The opportunity is now being taken to encapsulate some waste, especially accumulated sludge,

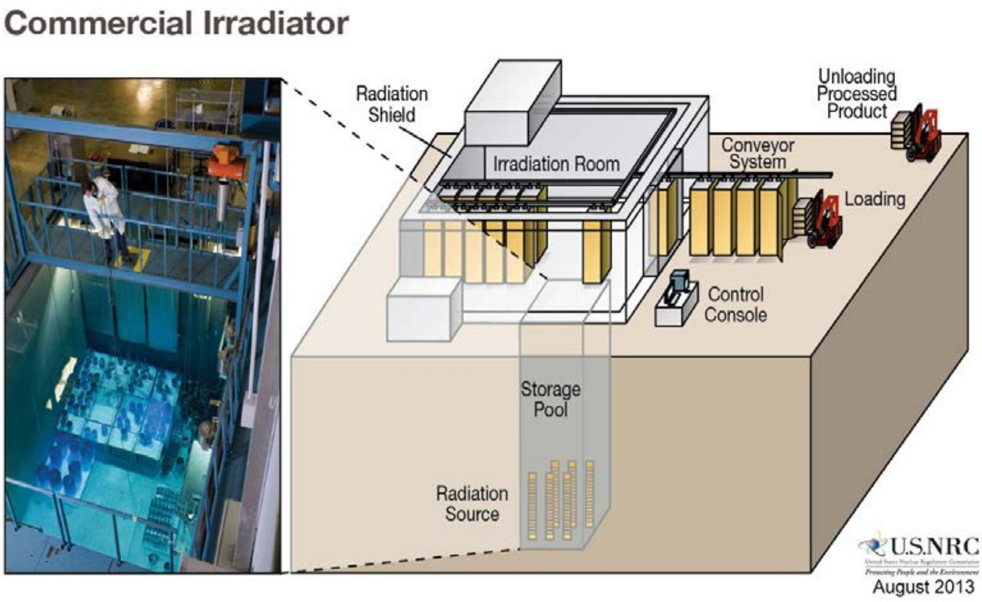

FIG. 2.3. Commercial irradiator, United States of America (courtesy of Nordion).

TABLE 2.1. EXAMPLES OF THE MAIN FEATURES OF POOLS LOCATED IN NUCLEAR FACILITIES

Name	Commission date	Shutdown date	Size, length × width × depth (m)	Capacity (m^3) × No. of pools (if any)	Floor, wall lining	Indoors/ outdoors	Status, comments
Heavy water reactors, Canada							
Bruce A (1)	1977	1997	41 × 10 × 4.3 (fuel transfer) and × 6 (fuel storage)	~9 425	Epoxy, 304 stainless steel (partial) liner	Indoors	Long term shutdown
Bruce A (2)	1977	1995	45 × 18 × 8.4 (fuel storage)			Indoors	Long term shutdown
Douglas Point	1967	1984	21 × 7.6 × 4 (fuel transfer) and × 7.3 (fuel storage)	~1 325	304 stainless steel	Indoors	Safe storage
Nuclear Power Demonstration Reactor	1962	1987	5.7 × 3 × 5 (fuel storage)	~110	304 stainless steel	Indoors	Safe storage
Pickering A (1)	1971	n.a.[a]	33.5 × 16.5 × 5.3 (fuel transfer) and × 8.4 (fuel storage)	~4 240	Epoxy, fibreglass	Indoors	In operation
Pickering A (2)	1971	1997	34 × 17 × 8 (fuel storage)			Indoors	Long term shutdown
Pressurized water reactors and water cooled water moderated power reactors (WWERs)							
Trino nuclear power plant, Italy	1965	1987	14.7 × 10.3 × 11	~1 670	Stainless steel lining	Indoors	A limited amount of spent fuel is still present in the pool
Three Mile Island Unit 1 nuclear power plant, USA	1974	n.a.[a]	64 × 9 × 9	~985	Stainless steel lining	Indoors	In operation
José Cabrera nuclear power plant, Spain	1956	2006	7 × 6.5 × 11.7	~532	Stainless steel lining (lower part); asphalt cover and phenolic painting (upper part)	Indoors	Under decommissioning
Novovoronezh nuclear power plant, WWER-1000, Russian Federation	1980	n.a.[a]	6.2 × 4.4 × 16.4	~705 × 3	Double lining	Indoors	AFR facility for Novovoronezh WWERs In operation

TABLE 2.1. EXAMPLES OF THE MAIN FEATURES OF POOLS LOCATED IN NUCLEAR FACILITIES (cont.)

Name	Commission date	Shutdown date	Size, length × width × depth (m)	Capacity (m^3) × No. of pools (if any)	Floor, wall lining	Indoors/ outdoors	Status, comments
Bohunice V1 nuclear power plant, Slovakia	1978 (1st unit), 1981 (2nd unit)	2006 (1st unit) 2008 (2nd unit)	Two spent fuel pools: 6.57 × 3 × 16.6 Mogilnik: 4.2 × 4.3 × 9	~245 × 2 ~160	Stainless steel lining	Indoors	Can be considered as standard design for WWER-440 reactors Under decommissioning
			High-power channel-type reactor (RBMK)				
Chernobyl nuclear power plant Units 1–3, Ukraine	1977–1981	1991–2000	Three spent fuel pools: 10.3 × 4.2 × 17.3 Three technological channels pools: 4.75 × 1.6 × 25	~705 × 3 ~185 × 3	Stainless steel lining	Indoors	Construction of pools on Unit 4 was the same as on Units 1–3
			Boiling water reactors				
Reference BWR, USA	n.a.[a]	n.a.[a]	12.2 × 10.7 × 11.9	1 510	Stainless steel lining	n.a.[a]	n.a.[a]
Dresden, USA	1960	1978	Distinct parts of pool with different dimensions	3 940 × 3	Stainless steel lining	Indoors	Unit 1 in safe storage, Units 2 and 3 in operation
Fukushima Daiichi 2–4, Japan	1973–1978	2011	12.2 × 9.9 × 11.8	1 425	Stainless steel lining	Indoors	Being decommissioned
Tarapur AFR facility, India	1970s	n.a.[a]	9 × 13 × 13	~1 525	Stainless steel lining	Indoors	Serves the two BWR units at Tarapur
			Gas cooled reactors				
Bradwell, UK	1962	2002	Two main bays: 30.1 × 6.7 × 4.7 Centre bay: 7.3 × 6.7 × 6.6	2 983	Painted concrete	Indoors	Safe storage

TABLE 2.1. EXAMPLES OF THE MAIN FEATURES OF POOLS LOCATED IN NUCLEAR FACILITIES (cont.)

Name	Commission date	Shutdown date	Size, length × width × depth (m)	Capacity (m^3) × No. of pools (if any)	Floor, wall lining	Indoors/ outdoors	Status, comments
Chapelcross, UK	1959	2004	32 × 11 × 6	1 825 × 2	Painted concrete	Outdoors/ indoors	Being decommissioned
Dungeness A, UK	1965	2006	Two main ponds: 14.9 × 8.7 × 6 Two transfer ducts: 23.8 × 2.25 × 5	1 056 × 2 268 × 2	Painted concrete	Indoors	Being decommissioned
Hinkley Point A, UK	1965	1999	Two ponds: 25 × 19 × 6.1	2 770 × 2	Painted concrete	Indoors	Being decommissioned
Hunterston A, UK	1964	1990	Main pond: 32 × 23 × 6.6 Handling bay A: 9 × 10 × 6.6 Handling bay B: 9 × 6 × 6.6 Crane mount bay: 6 × 7 × 6.6	6 000	Painted concrete	Outdoors/ indoors	Being decommissioned
Oldbury, UK	1968	2012	39 × 9.9 × 7	2 460	Painted concrete	Indoors	Being decommissioned
Sizewell A, UK	1966	2006	Two main bays: 13 × 12.5 × 6.8 Two deluge bays: 10 × 6 × 6.8 Dispatch bay: 11.5 × 4 × 6.8	3 300	Painted concrete	Indoors	Spent fuel, ion exchange and metal waste storage
Trawsfynydd, UK	1965	1991	Two lanes: 33 × 4.5 × 7 Two centre bays: 7.5 × 4.5 × 7 Two corridors: 10 × 4.5 × 7	5 260	Painted concrete	Indoors	Being decommissioned

TABLE 2.1. EXAMPLES OF THE MAIN FEATURES OF POOLS LOCATED IN NUCLEAR FACILITIES (cont.)

Name	Commission date	Shutdown date	Size, length × width × depth (m)	Capacity (m^3) × No. of pools (if any)	Floor, wall lining	Indoors/ outdoors	Status, comments
Vandellos I GCR, Spain	1972	1989	23 × 10 × 7.5	1 720	Stainless steel	Indoors	Decommissioned
Reprocessing plants and other nuclear fuel cycle facilities							
Eurochemic, Belgium	1959	1990	42 × 20.5 × 3.5	2 000	Stainless steel lining	Indoors	Decommissioned
EUREX, Italy	1970	1983	17 × 7 × 5.5–7.5	675	Paint only	Indoors	Spent fuel and metal waste storage
Rokkasho reprocessing plant (three pools), Japan	1998	n.a.[a]	27 × 11 × 13	~3 860	Stainless steel lining	Indoors	In operation
TAN-607, INL, USA	1955	2002	21 × 14 × 7	2 050	Painted concrete	Indoors	Fuel and core debris storage Decommissioned
Hanford K east and west, USA	1953–1955 for both	~1971	Twin basins: 46 × 24 × 6	5 000 × 2	None	Outdoors	Spent fuel, metal debris, racks, PCBs, resins
Sellafield pile fuel storage pond, UK	1952	1957	100 × 25 × 7	16 000	None	Outdoors	Spent fuel, skips, debris, metal waste, sludge
Sellafield Magnox first generation storage pond, UK	1962	1986	Three ponds up to: 65 × 17 × 6.4	14 200	None	Outdoors	Spent fuel, skips, debris, metal waste, sludge
Sellafield fuel handling plant, UK	1985	n.a.[a]	Three ponds up to: 44 × 20 × 8	18 500	Sealed with alkyd paint system	Indoors	AGR and Magnox fuel In operation
Sellafield THORP receipt and storage, UK	1988	n.a.[a]	Two ponds: 72 × 24 × 8	31 000	Sealed with alkyd paint system	Indoors	Mixed LWR and AGR fuel In operation

TABLE 2.1. EXAMPLES OF THE MAIN FEATURES OF POOLS LOCATED IN NUCLEAR FACILITIES (cont.)

Name	Commission date	Shutdown date	Size, length × width × depth (m)	Capacity (m^3) × No. of pools (if any)	Floor, wall lining	Indoors/ outdoors	Status, comments
Sellafield AGR fuel storage pond, UK	1983	n.a.[a]	50 × 17 × 8	6 500	Stainless steel lining at wind water line, painted	Outdoors	Spent fuel In operation
Sellafield LWR fuel storage pond, UK	1968	n.a.[a]	Five ponds up to: 50 × 17 × 8	16 000	None	Outdoors	Water reactor fuel In operation
Research reactors							
JEN-1 RR, Spain	1958	1987	35 m^2 × 9.0	310	Stainless steel	Indoors	Decommissioned
Ford RR, USA	1957	2003	9.0 × 3.3 × 9.0	190	Stainless steel	Indoors	Decommissioned
OSIRIS RR, France	1966	n.a.[a]	7.5 × 6.5 × 11	~540	Stainless steel	Indoors	In operation
Ohio State University RR, USA	1961	n.a.[a]	3.2 × 1.2 × 6.1	21.6	Stainless steel	Indoors	In operation
Missouri S&T RR, USA	1961	n.a.[a]	5.8 × 2.7 × 8.2–9.1	121	Stainless steel	Indoors	In operation
Pool Test Reactor, Canada	1957	1990	Diameter 2.6 × 6.1	~33	Stainless steel	Indoors	Decommissioned
SLOWPOKE RR, Canada	1971 (first commercial example)	n.a.[a]	Diameter 2.5 × 6.0	~30	Stainless steel	Indoors	Several reactors fully or partially decommissioned
Apsara RR, India	1956	2010	8.5 × 3.0 × 8.5	~220	Stainless steel	Indoors	Being decommissioned
Vinča RR, Serbia	1959	2002	40 m^2 × 6.5	230	Stainless steel	Indoors	Preparatory activities for decommissioning
Irradiators							
Reference large irradiator (reference study), PNLL, USA	n.a.[a]	n.a.[a]	3.3 × 2 × 6.6	~45	Stainless steel	Indoors	None

TABLE 2.1. EXAMPLES OF THE MAIN FEATURES OF POOLS LOCATED IN NUCLEAR FACILITIES (cont.)

Name	Commission date	Shutdown date	Size, length × width × depth (m)	Capacity (m^3) × No. of pools (if any)	Floor, wall lining	Indoors/ outdoors	Status, comments
Brookhaven National Laboratory Building 830 Gamma Irradiation Facility, USA	Late 1960s	1997	2.6 × 3.3 × 4.3	~40	Stainless steel	Indoors	Decommissioned
Genesis irradiator, USA	n.a.[a]	n.a.[a]	2.3 × 2.6 × 7.3 (1.2 above to 6.2 below ground)	~44	Stainless steel	Indoors	Commercial irradiator

Note: Pool dimensions quoted reflect the approximate overall size of the pool, which may include various bays, internal features and areas of varying depth. AFR — away from reactor; AGR — advanced gas cooled reactor; BWR — boiling water reactor; EUREX — enriched uranium extraction; GCR — gas cooled reactor; INL — Idaho National Laboratory; LWR — light water reactor; PCB — polychlorinated biphenyl; PNNL — Pacific Northwest National Laboratory; RBMK — high-power channel-type reactor (Russian Federation); RR — research reactor; TAN — Test Area North; THORP: Thermal Oxide Reprocessing Plant; WWER: water cooled water moderated power reactor.

[a] n.a.: not applicable.

in stable cement or grout matrixes [2.2]. However, in some cases, compliance with acceptance criteria for disposal may still be a problem owing to mobility and dispersion risk.

Some problems were compounded by inadequate record keeping of the pool inventory and construction details of the pools themselves. As one example of many, Section II–4 describes lessons learned related to actions taken to address inadequate design records and a lack of understanding of the structural condition and performance of an old legacy facility. It has only been in the last decade that serious attention has been given to decommissioning pool installations, although there have been notable earlier projects. Section II–9 illustrates a typical issue encountered where records related to operations and inventories were inadequate.

Pools at nuclear power plants are often in better condition than at R&D facilities because of a more routine spent fuel handling discipline under a commercial operating regime and more emphasis on safety culture. Fuel cladding is now also of much higher integrity and less susceptible to corrosion.

Implications of design on pool performance are exemplified by the Apsara reactor [2.3]. As built, Apsara pool was a reinforced concrete structure without any lining. During the initial years of operation, one of the major problems faced was leakage of pool water through the concrete. Attempts to stop the leakage by painting the inner surfaces of the pool, coating, replastering and pressure grouting all failed. Eventually, the pool was lined with stainless steel 304L plates. The stainless steel lining was installed over a carbon steel frame that was anchored to the concrete. The gap between the lining and pool wall was filled with cement mortar. Subsequent to lining of the pool, the facility has operated for over 30 years without any pool leakage.

Options such as double racking of fuel assemblies in pools alleviated the problem of storage capacity to a large extent [2.4]. However, this served to dramatically increase the pool inventory, but did not address the problem of unsatisfactory pool design. Dry ISFSIs were then being considered as more satisfactory with lower risk [2.5].

Many lessons have been recorded of the difficulties in retrieving waste from pools and in decontamination that may be more difficult because of certain aspects of pool design (see Annexes I and II). Section II–2 reports specific learning addressing pool surface finishes and decontamination.

2.3. IMPROVEMENTS TO CURRENT POOL DESIGN, CONSTRUCTION AND OPERATION

As early as 1988, the American Nuclear Society produced design criteria for pool type ISFSIs [2.6]. In addition to construction, safety and other issues, an American National Standards Institute standard for pools addressed decommissioning. The standard specified features such as design for easy decontamination, floor and wall linings, minimizing embedment of pipes, and leak detection and collection systems. It emphasized that adequate attention should also be given to interfaces with an existing facility, security and the provision of cooling and waste cleaning systems. In addition, the IAEA produced guidance at a similar time, suggesting design and operational measures to facilitate pool decontamination [2.7].

More recently, the IAEA produced a publication in 2011 illustrating suggested beneficial features for the design and construction of new nuclear installations to facilitate decommissioning [2.5]. Particular features and actions that are relevant to the design of new pool facilities are:

— Double walled containment, where possible;
— Avoiding overdesign for shielding by using removable modular components;
— Preinstalled leak detection devices;
— Avoiding the burial of structures in soil or constructing them below ground level;
— Permanently installed decontamination facilities;
— Sealed surfaces to avoid penetration of contamination;
— Provision of dedicated site waste management facilities to avoid using pools for waste storage;
— Adequate records of pool inventory, design and construction;
— Preserving archive samples of construction materials.

The OECD Nuclear Energy Agency (NEA) has also published a document relating to pool design that applies specifically to new nuclear power plants [2.8]. It identifies similar design features and addresses regulators, electricity producers and designers separately. By including these features, there is a prospect for design improvement in pool storage facilities incorporated in the new generation of nuclear power plants proposed in some countries.

In one example, specific design features to facilitate decommissioning were indicated by Westinghouse for their new nuclear power plants [2.9]:

(a) The walls of the pools were constructed using modular construction techniques and lined with welded stainless steel plates.
(b) The pools were equipped with leak chases at each weld so that the tank was effectively double walled in the area of plate joints.
(c) The pool leak detection system was zoned to allow identification of the area of the pool liner that leaked.

Another important practice for new designs is avoiding the use of wet pools for waste storage. A preferred interim storage strategy for wastes is the use of dry facilities. These minimize corrosion and degradation and benefit from lower care and maintenance requirements. Decommissioning of dry storage facilities could also be implemented with some specific challenges, although it can be assumed that they will be less of an issue.

The IAEA has produced a publication on practices for water quality control in pools [2.10], which deals with the general degradation of almost all materials used underwater in pools and pool systems. It covers water treatment technology and measuring devices for water quality control. Although this is intended for pools in operation, it gives useful background guidance on expected conditions in pools that are to be decommissioned.

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3. STRATEGIES AND PLANNING FOR DECOMMISSIONING

3.1. STRATEGY DEVELOPMENT

An effective strategy for decommissioning pool type facilities needs to balance the hazards associated with continued operation of the facility with the degree of urgency in the decommissioning programme. This will define the optimum timing for the decommissioning to take place, which needs to be underpinned with knowledge of the pool structure and the radiological inventory. The strategy also needs to be driven by a clear definition of the desired site end state for the facility and any interim states required to synchronize the decommissioning of the pool with that of other site facilities.

A typical decommissioning strategy should include an initial phase to identify and recover all removable waste. The hazards associated with the pool will be reduced once this has been achieved. The subsequent objective will be drainage of all pool water to allow the decontamination needed to support the transition to the interim or final end state. The final objective will be to deal with the residual redundant structures and systems. Four possible approaches are given in the following:

(a) Demolish the entire structure to unrestricted release level. This will require separating material below clearance levels from low level waste (LLW) bound for interim storage or disposal. Assay of the rubble will be required and criteria for bulk unrestricted release of waste will be needed. The extent of soil remediation needed will depend on the intended use of the pool site in relation to the whole nuclear facility site.
(b) Retain the pool structure and form a safe enclosure by providing a waterproof cover of concrete or other durable material to ensure dry conditions with minimal maintenance. The use of the existing pool building as a safe enclosure may be possible, but the structural integrity, security and maintenance requirements may preclude this.
(c) Reduce contamination to as low as economically possible and to backfill the enclosure with inert material such as sand or weak grout to achieve safe entombment or to seal surfaces. Environmental studies may have to be done if potential for radioactive releases still exists.
(d) Decontaminate to a safe level for limited personnel access and to reuse the cavity as a dry interim waste store or other appropriate use (e.g. to use the demolition waste as backfill material).

Above and below ground elements of the structure may be treated differently. A strategy of doing nothing is not considered acceptable, and a strategy of retrieving all removable waste but retaining the pool full of water with residual contamination is not encouraged either. The risks associated with contamination leaking to the environment will be increased in the long term, until the pool is drained.

Sections I–8 and I–9 provide examples of strategy development for a large fuel pool at the Sellafield site and the Magnox nuclear power plant pools in the United Kingdom. Section II–14 describes interim and end states considered for one specific facility. It should be emphasized that strategies need to be flexible enough to deal with changing regulations, stakeholder drivers and conditions or assumptions resulting from progressing through the decommissioning process. Section II–12 illustrates a data informed approach to strategy development.

3.1.1. Hazards of pool deferred dismantling

Experience shows that deferring the dismantling of pools, which may contain active materials, contaminated water and fuel, can last over 20 years, which is far from ideal. Increasing incidents and hazards have been reported from pools in poor condition or of unsatisfactory design and from the common practice of storing large quantities of uncharacterized and undocumented waste. A number of nuclear power plants have been shut down without a decommissioning strategy, as is often the case with their spent fuel pools. The following hazards should be considered before deciding on any deferral strategy:

— Risks from degradation (e.g. corrosion and freezing/rupture) of non-operational facilities following removal of other services (e.g. heating, ventilation and air-conditioning);
— Pool water management (pool water chemistry and risks from corrosion);

— Leaks and contamination spread from any remaining inventory within the pool;
— Cracks or deterioration of concrete structures;
— Corrosion of metallic structures, equipment and components;
— Changing chemical nature and solidification of sediments, making retrieval more difficult;
— Dose uptake and conventional safety risks during any deferral period prior to decommissioning;
— Degradation of protective coatings and pool linings;
— Continued risks from external hazards and accidents;
— Failure of associated plant and equipment affecting the pool, including degradation of overbuilding structures;
— Loss of pool water from leakage and risk of groundwater contamination;
— Secondary waste generation (e.g. from pool water filtration systems and as a result of inventory corrosion);
— Ongoing risks to the public and environment;
— Fire and criticality risks for ponds with a remaining fuel inventory;
— Degradation or contamination spread from wildlife intrusion;
— Ongoing security risks.

While there is significant evidence that deferring the decommissioning of pools will lead to increased risk, this needs to be balanced with the gains associated with allowing activity to decay over a longer period and the risks associated with the decommissioning activities. In addition, proper care and maintenance and the development of new techniques for repair of pool structures [3.1] may be used to underpin a longer deferral period.

In February 2001, the United States Nuclear Regulatory Commission (NRC) published NUREG-1738, Technical Study of Spent Fuel Accident Risk at Decommissioning Nuclear Power Plants [3.2]. It is a detailed study, using a modelling approach of a typical site, and was subjected to stakeholder and public reviews. This study has been a basis for amended licensing regulations of spent fuel pools and ISFSIs during decommissioning. Normally, decommissioning of a facility, including the pools, will be subject to all regulatory approvals that are in force in a country.

Deferral strategies coupled with lack of attention to degraded conditions have sometimes led to problems or introduced additional risks. In 1978, for example, Unit 1 at the Dresden nuclear power plant, in the United States of America, was shut down, defuelled and put into care and maintenance. In January 1994, it was reported that a 1.1 m diameter fuel transfer tube associated with the spent fuel pool in the containment building had frozen and there was the risk of substantial water loss [3.3]. It was reported that a decision had been made previously to remove heating from the reactor containment. It was estimated that approximately 200 m^3 of service water leaked into the basement of the off-gas filter building. Closer inspections revealed other unsatisfactory practices associated with the pool and systems [3.4]. In 1999, work was undertaken to characterize the fuel [3.5], which resulted in a decision to remove all fuel into dry cask storage and to close the pool as part of a safe storage period. It was necessary to determine whether the fuel was in a suitable condition for dry storage before final decontamination of the pool and removal of the pool water in 2004.

A special inspection was initiated by the NRC following a pool leak at the Indian Point nuclear power plant, in the United States of America [3.6]. The leak was because of hairline cracking in the pool wall that was discovered during excavation work for a new cask dry storage project. The radiological consequences were minimal, but the NRC nevertheless published the reportable information on its web site.

In 2004, the NRC issued an information notice on spent fuel pool leakage to on-site groundwater [3.7]. In 2006, the NRC informed all operators of nuclear facilities about recent examples of leaks from pools and underground pipes and associated facilities [3.8]. There was concern about undetected leaks and that monitoring did not necessarily provide a full understanding of potential environmental contamination. It was required that the potential for leaks from water and fuel transfer systems should be registered. Plant operators should also monitor groundwater leaks that arise from underground rooms. On-site monitoring and sampling for representative isotopes was insisted upon.

An unusual event occurred at the Zion nuclear power plant, in the United States of America, in January 2001, three years after it had been shut down [3.9]. Electrical power was lost to the spent fuel pool and cooling system and the pool water temperature rose from 32.8°C to 33.3°C in approximately one hour. The NRC reported the event was not significant, but nevertheless indicated the constant need for operator vigilance.

Società Gestione Impianti Nucleari (SOGIN) — Italy's state owned agency in charge of the national decommissioning and waste management programme — reported that leakage was found in 2004 in the spent fuel pool at the SOGIN enriched uranium extraction (EUREX) pilot fuel reprocessing plant. This was over 20 years after the plant had been shut down [3.10, 3.11]. This event prompted some pre-decommissioning activities in 2006 to remove a number of spent fuel assemblies transferred to EUREX from various reactors in Italy. A fuel transport cask still existed but had to be requalified to secure a transport licence for removal of the fuel. However, the capacity of the 27 t pool handling crane and limited access to the pool required that the cask be loaded outside the pool, and a special shielded shuttle had to be developed to allow safe transfer of the fuel into the cask [3.12].

In the late 1970s, a tank struck one of the stationary source racks at the Radiation Technology Incorporated licensed pool irradiator near Rockaway, in the United States of America, as it was being lowered into the pool, damaging one of the sealed sources. Leakage from the damaged source resulted in ^{60}Co contamination of the irradiator storage pool water. The contamination was not immediately identified, and flocculent and other cleaning agents used in cleaning the (believed uncontaminated) pool of dirt and algae were swept onto the ground south of the irradiator building. Backwash water was disposed of by pumping the water onto the ground outside the equipment room, on the south side of the irradiator building. Over several years, this method of disposal caused a significant accumulation of ^{60}Co on and near the surface of the ground immediately south of the irradiator building, and ^{60}Co contaminated soil was also identified outside the fenced site in a wooded area. In response to these findings, the management initiated a series of remedial action tasks to identify, characterize and remediate the site [3.13–3.15]. Other irradiator events that have resulted in soil contamination have been reported [3.16–3.19].

Pool operators find particular difficulty in continuing to make a safety case for the ongoing operation of fuel ponds as their condition begins to deteriorate. The team responsible for preparing Sellafield's first generation Magnox fuel storage pond (FGMFSP) for decommissioning was required to develop a novel approach to safety assessment and site regulation requiring significant interaction between the site operator and the regulator [3.16].

For natural uranium type fuel (e.g. Magnox fuel), there is also a risk of a uranium hydride fire that will ignite the magnesium alloy cladding. The hydride forms in water in anhydrous conditions if there is exposed uranium metal due to defective cladding. If the hydride is exposed to air, there is some — though low — risk of ignition. Laboratory tests have shown ignition, but there has been no recorded fire in practice.

A particular risk of overheating and spontaneous ignition resulting in an uncontrolled fire associated with water loss from pools containing zircaloy cladding spent fuel was reported in NUREG-1738 [3.2] early in 2001. This suggested there could be catastrophic consequences from a zirconium fire in pools at decommissioning reactors. The risk of a fire had, until then, been considered to be very low based on low levels of decay heat and a negligible risk of a fire. The study considers nine events that could lead to fuel being exposed to air: severe earthquake and cask drop accidents were considered important at decommissioning sites. It was subsequently reported that the fire risk of fuel in pools at decommissioning sites is not zero but very low [3.20–3.22]. Risks associated with this type of hazard should be considered carefully for each facility.

Extended deferral periods lead to increases in the risks associated with external hazards, including earthquakes, terrorist attacks and aircraft impacts. In 2004, the US Congress mandated a study by the Board of Radioactive Waste Management of the National Academy of Sciences to be undertaken to determine whether more measures should be introduced to protect spent fuel pools at commercial reactor sites [3.23]. In August 2004, the NRC issued orders for additional security measures at ISFSIs and decommissioning reactors and for Honeywell, the materials licensee [3.24, 3.25]. Details were not given because of safeguard restrictions, but access to facilities was to be restricted.

In Japan, the Fugen nuclear power plant was shut down in 2003, and a probability risk assessment [3.26] was used to evaluate risks of storing spent fuel in the pool based on credible events mentioned in NUREG-1738 [3.2].

Finally, the Fukushima Daiichi accident on 11 March 2011 and its impacts on spent fuel ponds may prompt operators to accelerate the transfer of spent fuels from pools to dry cask storage or reprocessing facilities [3.27–3.29]. Quite recently, Hanford workers moved more than a third of the highly radioactive capsules kept underwater in central Hanford to a more secure location [3.30]. However, an updated study by the Electric Power Research Institute (EPRI) concluded that it was "unclear" whether the benefits of an accelerated transfer of used nuclear fuel from storage pools to dry storage at US nuclear power plants would outweigh the risks and costs involved in the transfer [3.31, 3.32].

3.1.2. Interim states

Pool decommissioning cannot be seen in isolation from nuclear power plants or other large fuel cycle facilities on the site. Similarly, consideration needs to be given to the future use of the whole site. Many pools continue in operation after shutdown of the main facility for many decades and often beyond their initial design life. The primary role of a pool is to provide interim spent fuel and waste storage until processing or disposal facilities are available. It is only the transfer of these waste materials to other storage facilities that allows pools to be considered for decommissioning. However, it is possible that the pool or its structure may provide alternate functionality for the site and may be reused. The IAEA has published guidelines on post-decommissioning reuse and redevelopment of nuclear facilities and sites [3.33]. To illustrate the application of this, Section II–14 describes interim and end states considered for one specific facility.

An example of reuse is described in the literature for the Pool Test Reactor in Canada. Following decommissioning, the former pool of the reactor will be covered and returned to operation for reuse. The facility will be converted into a high bay laboratory utilizing the former pool for additional height to install loop systems or test sections for future R&D work [3.33].

Many ponds are split into main pond areas and separate bays or compartments that may be isolated. This allows strategies to be developed that address the parts separately or at different times. Benefits may be achieved by decommissioning certain areas early to provide learning that can be applied to the remaining parts of the facility (see Section II–12). Similarly, such an approach may allow reuse of part of the facility (e.g. as a buffer store for contaminated items) as an interim state.

There are numerous situations where pools are now ready for total dismantling, and many such projects have been completed. However, the sites remain licensed areas if adjacent reactor safe enclosure structures or long term interim dry waste storage facilities are not dismantled and remain under care and maintenance. In such instances, immediate demolition of the pool may not represent the best strategy for the site.

Clearance of the local pool site to unrestricted release levels is desirable because it removes the need for monitoring and surveillance. In some cases, it may be possible to reduce the overall radiologically controlled area of the site. If funding is available for clearance of the pool site and for management of the waste, then it is sometimes prudent to take advantage of this. However, consideration should be given to whether the hazard reduction benefits merit the financial and dose investments associated with performing the work promptly.

There are instances where, even after substantial decontamination, it is not economic or as low as reasonably achievable (ALARA) to dismantle a residual pool structure to an unrestricted release level, and an entombment, sealing or passive safety strategy may be adopted. In these instances, the pool could be capped or filled with sand or weak grout. Alternatively, surfaces could be sealed or surfaces left untreated.

Where full decontamination of a pond is not considered economically viable, consideration may be given to partial decontamination and sealing of the inner surfaces when the pool is drained. Selection of a 'drain and seal' strategy needs to be consistent with the strategy for the overall site and will require that the pool remains under a care and maintenance regime, along with the rest of the site until full site clearance. Section I–2 is a relevant case in question.

The economics of this approach will be influenced by a number of factors, including:

— Degree of land contamination around the pool;
— Extent of contamination penetration into the structure, particularly into construction joints and any cracks in the lining;
— Proximity or connection to other significant structures on the site that will remain under care and maintenance;
— Ability to control or limit the spread of contamination from the structure during care and maintenance.

This approach enables advantage to be taken of radioactive decay, and enables pool demolition to be undertaken when the final conditions for acceptance of the whole site are known. This method also has the advantage of avoiding contamination of infill material, a potential by-product of taking an entombment approach.

It will be necessary to demonstrate to regulators that the pool may be kept safe during the storage period and that potential contamination spread from water ingress will be minimized. Therefore, it is likely that a cap or weatherproof cover over the structure will be required to protect the pool during the care and maintenance phase.

The installation and maintenance of such a structure and the periodic inspection and maintenance of the pool seal need to be considered from an economic viewpoint.

There are a large number of sealants that could be considered, and selection will depend on the residual contamination to be sealed. The presence of actinides may necessitate a robust sealant (see Section I–9), whereas lightly contaminated surfaces may enable a light duty sealant or paint to be used as a dust control measure. R&D on new coating processes is an active commercial field. Such an example is the advanced underwater coating system, a unique coating process that can be utilized underwater [3.34]. The process for application of coatings has been “supported by various testing programmes involving pressure, temperature, adhesion, and radiation exposure” [3.34]. Developments at Idaho National Laboratory (INL) and Dresden, both in the United States of America, are provided in Refs [3.35–3.37]. Robotically deployed polymer based repair techniques have been reported that can be used to repair leaks in spent fuel pool liners [3.1]. Although mainly intended for pool operation, these could be applicable to circumstances during pool decommissioning.

Entombment strategies are cases where an emptied and substantially decontaminated pool has been backfilled with sand or weak grout. These are appropriate where it is considered uneconomic or not in accordance with ALARA to remove any more lightly contaminated material or to deal with any possible contamination of soil beneath the structure. If the residual material is classified as LLW or below, then to expend effort in removing it and for it then only to be disposed of elsewhere may not be sensible. The overall strategy for the site needs to be taken into consideration. For example, significantly contaminated sites (e.g. reprocessing sites) may never be fully decontaminated and would remain as a radiological controlled site for the foreseeable future. In this context, to backfill a lightly contaminated and partially demolished pool structure may be the sensible option.

A specific entombment project at the Idaho site (INL) is described in Refs [3.38, 3.39]. Water will be allowed to passively evaporate to reduce the spread of contamination from the walls of the basin. The basins will be filled with grout, underwater, because the water evaporates to maintain the basin water at a safe level.

In 2011, the Savannah River National Laboratory (SRNL) completed entombment on the P and R reactor buildings. Specialty grout was pumped at high rates into massive dry rooms and underwater fuel storage basins to stabilize contamination [3.40]. Serrato et al. [3.41] provides recommendations for grout formulations. The grout formulation stabilizes the waste but allows possible removal and retrieval in the future. More recently, a similar strategy was employed at the SRNL C reactor [3.42].

A comprehensive description of an entombment strategy is given in Ref. [3.43], which highlights the key steps in an entombment strategy and offers two possible scenarios for managing the entombment of the pool. There are even cases where lightly contaminated pools containing miscellaneous wastes have been filled with sand or grout [3.38].

3.1.3. Site cleanup criteria and end state specifications

The criteria for site cleanup and end state definition are complex and depend on many factors that are governed by national laws and regulations. If a site is a valuable asset for construction of a new nuclear generating plant, then criteria may be relaxed because the site will remain a controlled area for the foreseeable future.

There are smaller facilities where site contamination has been low and there is a desire for unrestricted release. University sites within commercial or residential areas are good examples where unrestricted release has been achieved. Where the strategy is to return a whole site to unrestricted release status, then complete decontamination and removal of residual activity above an agreed threshold need to be considered.

Where a facility may be part of a contaminated research laboratory site that also has a long term interim waste store (e.g. as in Georgia and elsewhere) then entombment of the reactor and its associated pool may be an option [3.44].

For very large complex sites such as Hanford and Sellafield, the prospects of unrestricted release may not exist. The decommissioning of redundant pools, however, should proceed to achieve a dormant and safe state with minimum environmental risk and low cost of surveillance and monitoring (see Section II–14). These sites, including redundant pool structures, are likely to remain long term centres for interim waste storage. The reuse of the pools may be considered within the overall decommissioning strategy for the site, although this may introduce additional regulatory requirements and/or physical preparations that negate the benefits of the opportunity.

The difficulty in disposing of residual radioactive concrete waste from the demolition of contaminated pools has sometimes prompted a strategy of in situ burial or entombment. This is not always satisfactory if unrestricted release is contemplated for expected future use. Guidance for general clearance practices has been published by the IAEA and the European Commission [3.45, 3.46]. A recent IAEA publication gives radiological guidance on site clearance and end state specifications [3.47].

3.2. DETAILED PLANNING AND ENGINEERING

This section deals with planning and key engineering issues of a project to decommission a pool facility. Many of the aspects will be the same as for any nuclear decommissioning project, and the pool decommissioning activities may be included in the main project.

3.2.1. Project planning

A specific decommissioning plan for the pool facility is needed unless this exists in a suitable form in the overall facility decommissioning plan. Even if one for the whole site existed at shutdown, it will be essential to review it in the light of the current condition of the pool and its structure and the inventory of waste. Very often, regulatory pressure is imposed on the owners to accelerate the drafting and execution of the decommissioning plan as a result of incidents or changes in the wider environment. Again, in this instance, it is essential that it is reviewed in the light of these changes.

It is important that the plans developed are suitably informed, and it may be necessary to establish a rolling plan with appropriate decision points. Indeed, the specific challenges associated with pool decommissioning will often be informed through survey, characterization and progress of the decommissioning process, which is itself part of the plan. This may, in turn, influence the selection of technology or methodology for pool decommissioning (Section II–12 illustrates how data gained in decommissioning are used to inform the forward plan). For example, it may be that prevailing regulatory requirements necessitate significant levels of remote operation. In all cases, a safety assessment will be required for any planned activities, and regulatory approval may be needed.

It should be recognized that there is a clear link between specific pool requirements, the decommissioning approach that will be taken and the resultant schedule and costs. Examples of issues that may influence schedule and costs are given in Section 3.2.3.

A typical list of actions necessary to implement during decommissioning planning should include consideration of the following. However, specific situations may require further detailed consideration:

(a) Establish all relevant records of the pool facility;
(b) Review lessons learned from similar facilities;
(c) Undertake a through survey of the pool structure and associated services to establish the condition and need for any refurbishment of essential equipment (an example of this work from Sellafield is given in Section II–4);
(d) Undertake a detailed chemical, physical and radiological characterization of the waste and sludge inventory and the pool structure, particularly indicating where information is not obtainable (Sections II–5 and II–6 describe lessons learned related to establishing sludge and solid waste characterization data);
(e) Undertake a chemical and physical survey to determine the extent of corrosion and degradation of the inventory and the pool structure and lining, if any;
(f) Agree a target end state;
(g) Establish a decommissioning strategy to determine the extent of decontamination and dismantling that will be accomplished;
(h) Investigate options for retrieval of solid materials and sludge;
(i) Identify pool plant and equipment that may be needed for retrieval;
(j) Estimate the material quantities in volume and weight, including the waste inventory and decommissioning waste if the structure is to be demolished;
(k) Establish a definition of the likely waste streams;
(l) Establish a waste management strategy, including conditioning, packaging and interim storage facilities, recycling, reuse or disposal routes;

(m) Compile a safety case for the decommissioning activities and seek regulatory approval;
(n) Produce an environmental impact assessment for regulatory approval;
(o) At an appropriate stage, engage specialist expertise to advise on implementation and to estimate costs and duration;
(p) Secure the necessary funding for the decommissioning project and for the management of any remaining interim waste storage facilities in the long term;
(q) Establish the project delivery organization;
(r) Establish a project and contract implementation strategy (e.g. a competitive contract or single tender action);
(s) Place and manage the implementation contract or contracts;
(t) At the conclusion of the project, ensure that a final report is produced and approved;
(u) Engage with the regulatory bodies and other stakeholders at appropriate stages.

A key source of information for the generation of the decommissioning plan will be from existing and previous operating staff, if available, and from records. Some of the information will become available or change as the projects develop and the decommissioning plan will need to be amended as appropriate. It will be important to retain and preserve all records produced during a decommissioning project. The NRC has published a brief guidance document on the criteria for decommissioning ISFSI facilities (see section 72.130 of 10 CFR 72 [3.48]).

3.2.2. Key engineering issues and implementation aspects

When developing the decommissioning plan, the engineering issues facing the project need to be considered. Typical challenges faced by pool decommissioning projects include:

— Existing infrastructure is no longer serviceable or suitable for use;
— Lack of infrastructure for decommissioning;
— Inventory and inventory condition are uncertain;
— Radiological and chemical hazards;
— Pool water visibility difficulties;
— Remote operations;
— Deploying equipment in an underwater environment;
— Congested working environment and lack of space for new equipment;
— Waste acceptance criteria or dealing with wastes with no obvious treatment or disposal routes;
— Mixed wastes;
— Contamination control;
— Demonstration of compliance with clearance levels;
— Proximity to other structures and hazards;
— Building structures of uncertain condition;
— Sludge behaviour and inventory characterization;
— Access and conventional hazards associated with working over and in water;
— Challenge of an outside environment;
— Bulk material remediation and disposal;
— Groundwater and contaminated land management;
— Ensuring dose minimization and control in line with ALARA principles.

While pools at nuclear power plants and research reactors were initially intended for spent fuel, it appears that many have been used to store other highly active items that were taken out of service when reactors were shut down. The sizes and dimensions of these often required special handling equipment that may no longer exist or that has become obsolete. Devising suitable retrieval equipment was often a challenge. Much of the waste was from fuel handling equipment and fuel debris from cladding, among other things.

Most pools have overhead gantry cranes for pool loading and often handled very heavy and specialized devices (e.g. transport casks). The integrity and safety of the cranes would need verification and proof testing to ensure safe use during decommissioning. Some of the lifting equipment, along with their load bearing structures, would be 40–60 years old, and their functionality, including compliance with current regulations, needs to be proven. Examples are given in Refs [3.49, 3.50] and in Section I–8. Similarly, the current condition of building structures may not be well understood. This may be exacerbated by poorly maintained records and drawings. Section II–4 describes lessons learned related to actions taken to address these issues.

Some pools contain large quantities of sludge and sediment that are often in colloidal form, which arises from corrosion of metal components, fuel cladding and sometimes fuel. The most troublesome cladding material has been magnesium alloy, aluminium and, to a lesser extent, stainless steel. Aluminium and stainless steel may corrode in the wrong chemistry, but the corrosion product results are minor to negligible. At R&D establishments, other materials may be present. The serious problems encountered with sludge were solidification due to settlement and obscuration of pool water when disturbed, which usually hampered retrieval efforts.

Water treatment plants for decontamination processes and for final discharge of pool water are often obsolete or inadequate after long dormant periods and will have to be re-established to modern standards.

Fragments of spent fuel pellets and pins on the pool floor may also be a problem for recovery and for separation into waste streams that can be managed. Safeguard issues associated with fuel fragments often complicate the plan.

The condition of handling of spent fuel in steel skips and baskets, which are of indeterminate structural integrity after long periods of storage, require special precautions for lifting during decommissioning activities.

The permanent fixing of fuel racks, supports and other pool furniture (equipment) onto pool floors causes difficulties for removal and decontamination. Embedded contaminated pipes in many installations have caused difficulties and prompted many lessons to be learned, together with a special workshop on the decontamination of embedded pipes [3.51].

Access above the pond and deployment of tooling for underwater operations is often a problem; in some, cases divers with special suits have had to be used to undertake underwater cutting [3.52].

The indeterminate extent of pool leakage and penetration into concrete has caused problems in decontamination and demolition and final site clearance. Almost no pools designed for earlier nuclear power plants and at fuel cycle facilities have had double walls, which is an effective means of monitoring or preventing leaks into the subsoil beneath pool foundations. Pool linings, where provided, often leaked and contaminated the underlying concrete, and characterizing any material trapped between the lining and the pool is always difficult.

At some fuel cycle facilities (e.g. Hanford and Sellafield) the pools are very large and are of the outdoor type. Decontaminating these facilities without spreading contamination to the environment will require special precautions.

The characterization of underwater sludge has presented challenges, and a number of special techniques and devices have been developed. These are discussed in more detail in Section 4.3.2.

There has been some very successful pool decommissioning projects, in spite of the challenges, difficulties and costs. Many of these have been at research reactor facilities where contamination was not severe, but some projects associated with seriously contaminated facilities have been successfully completed under contracts lasting only a few years. Examples are at Hanford, INL and some Magnox nuclear power plants in the United Kingdom.

There is extensive evidence of a wide range of techniques and procedures that have been developed and are now proven and safe in use, which include:

(a) The use of divers to undertake special underwater tasks (see Refs [3.52–3.54]);
(b) The development of special underwater remotely operated robotic devices for surveying, cutting, dismantling, retrieving sludge and taking samples for characterization (see Sections I–8 and I–9);
(c) The ability to scabble and remove concrete from the pool wall and floor surfaces by techniques such as hydrolasing and using rotary scabbling heads (see Section I–9);
(d) The ability to suspend, retrieve and encapsulate sludge and debris from pool floors (see Sections I–8 and I–9);
(e) The successful re-establishment of site infrastructure and management organization for projects on dormant sites;
(f) The adaptation of existing systems to appropriate standards.

There is continuing development of new and appropriate techniques for dismantling pools, which should be reviewed and assessed when planning projects. Typical examples are highlighted in Refs [3.55–3.58].

The varying stages of decommissioning are likely to require the provision of new equipment and new operating practices. Decisions need to be made regarding whether to design equipment for specific tasks or whether to use commercially available equipment. Similarly, consideration needs to be given to the degree of effort to be spent developing and testing equipment prior to deployment. Section II–7 describes an approach that minimizes time and expenditure on equipment development. Section II–11 describes operational practices that enable decommissioning team productivity to be optimized.

3.2.3. Cost estimating

Because of the diversity of the types of pools discussed in this publication and the different stages of decommissioning progress and approaches taken for different projects, it is difficult to make cost comparisons or derive parametric norms. Some historic costs have been given in project reports, but the relevance for comparison with new projects is questionable. Issues that will undermine direct cost comparisons include:

- Physical size, surface area and configuration of the pool structure;
- Degree of contamination of the pool structure and the required decontamination targets;
- Current and potential radiation levels;
- Quantity of materials in the pool that needs to be removed;
- Proportions of the pool above and below ground;
- Access constraints;
- Condition and serviceability of existing systems and handling equipment;
- Containment and ventilation requirements;
- Connection with, and proximity to, other significant site structures;
- Regulatory requirements;
- Stakeholder expectations.

Whereas there is undoubtedly some learning that can be taken from past projects, each project should be priced by taking account of the local conditions and requirements. Decommissioning costs cannot directly be correlated between different projects. It is also noted that considerable cost escalation can occur as the scope and complexity of decommissioning work becomes apparent [3.59]. The following examples are given for guidance.

In 1983, the Pacific Northwest Laboratory[2], in the United States of America, was engaged by the NRC to compile a comprehensive study on technology, safety and costs of decommissioning reference ISFSIs. Although the absolute costs will be outdated, the methodology may still be relevant [3.60]. The IAEA also issued a technical publication on the financial aspect of decommissioning in 2005 [3.61].

In 2012, the NEA, the IAEA and the European Commission published an internationally agreed structure of decommissioning costing [3.62]. The methodology described in Ref. [3.62] can be used as an internationally standardized approach to the decommissioning of a nuclear pool. Direct costs of decommissioning are estimated, including labour, materials, equipment and, where applicable, packaging, transport and disposal of radioactive wastes.

From the published information given in the various sections of this publication, it can be seen that projects can take more than a decade from inception to completion, while others are accomplished within a year. This illustrates the diversity of pool decommissioning activities, and will reflect the costs.

A detailed overview of pond decommissioning schedules and costs is given in Ref. [3.63], which addresses the large decommissioning programme for Magnox nuclear power plants in the United Kingdom. The typical annual cost of the pond preparation programme is around £2 million–£5 million per reactor unit. The active phase lasts a few years for each reactor. The total cost of the pond preparation programme for the entire Magnox fleet is estimated at £300 million. The scope of these activities extends to the reaching of a care and maintenance phase.

[2] In 1995, it became the Pacific Northwest National Laboratory.

3.3. UNCERTAINTIES IN THE TRANSITION FROM PLANNING TO EXECUTION

A number of regulatory and procedural issues are often associated with the post-operational phase of a nuclear facility. In the United Kingdom, for example, the regulator's experience and approach to the operation to decommissioning transition period for Magnox reactors is recorded in Ref. [3.64]. In the first instance, a decommissioning safety case (safety assessment) is needed. This requires early consideration of the safety aspects of decommissioning and the changes in risks and hazards. For Magnox reactors, a cooling period of 90 days is necessary before discharge to the pool. Defuelling of these gas cooled reactors can take up to two years.

While the overall nuclear and radiological risks may be reduced after shutdown, there are other risks that may increase. These could be from chemicals, asbestos removal, major dismantling work, changes in services (particularly electrical and water) and changes in management structure. There could also be an old and degrading plant that may be needed for the decommissioning task where failure risks have to be avoided by appropriate refurbishment. It has been suggested that there are four key aspects to be considered from the regulation viewpoint [3.64]:

— Clear demarcation between operating, defuelling and decommissioning;
— Regulation to ensure control and management of change;
— Skill retention and demonstration of capability;
— Fit for purpose of procedures and equipment and delivery hold points.

There are two examples where issues have arisen:

(a) Attention to standing alarms in control rooms to avoid missing relevant signals, which arose because, after shutdown, numerous redundant or spurious alarms were registered;
(b) Loss of cooling water from the Sizewell A ponds, in the United Kingdom [3.65, 3.66].

Section II–18 provides a further example of a situation where incorrect work planning and regulatory permissions caused difficulties. Section II–23 illustrates specific lessons learned related to time that can be taken when addressing regulatory and procedural issues.

There are often particular problems that arise when adjacent plant is in operation, and there is an interface between it and the facility to be decommissioned. Sometimes, the extreme complexity of nuclear establishments can affect the transition period and cause extensive delays. Examples are Dounreay, in the United Kingdom, INL and at the very large fuel cycle and legacy facilities at Sellafield and Hanford.

For example, the Demonstration Fast Reactor Establishment at Dounreay has been shut down since 1977, and it has been difficult to establish a true transition period after shutdown. Dounreay is a complex research site with around 50 of the 180 facilities on-site requiring nuclear decommissioning. The pool had been used for storing fuel from many test and research reactors around the world between 1994 and 2001 [3.67]. Decontamination of the pool was only achieved in 2008.

The Sellafield site has a legacy of redundant facilities in various states of care and maintenance and decommissioning (see Fig. 3.1). Planning and managing these is a huge challenge [3.68, 3.69]. A major transition contract was signed in 2008 between the UK Nuclear Decommissioning Authority and a consortium of contractors from the France, the United Kingdom and the United States of America [3.70]. Decommissioning of pools on the site is considered to be a major undertaking within this agreement.

There are pools which are quite complex in having a number of compartments and channels that communicate with the reactor for fuel transfer or with experimental rigs associated with research. This can complicate the projects, and all systems and facilities associated with a pool complex need to be investigated and their interfaces with other plants need to be explored. Failure to plan all activities and interfaces could cause serious delays in completing projects and could result in unfortunate incidents. Failure to isolate adequately between facilities can lead to serious problems.

FIG. 3.1. The Sellafield site, United Kingdom (courtesy of S. Hartley).

Certain situations could prevent or hamper the final decommissioning of a pool facility. A primary one would be the unavailability of suitable licensed interim storage facilities for waste and spent fuel. The construction of ISFSIs or alternately the opportunity to ship spent fuel off-site has allowed many planned pool decommissioning projects to proceed. Without these, many projects are on hold. Difficulties in returning spent fuel from research and power reactors in the decade after the fall of the former Union of Soviet Socialist Republics in 1991 prevented many decommissioning projects from proceeding for years. These issues have been largely solved, and large amounts of spent fuel have been transferred over the last ten years or so from Central and Eastern Europe countries to the Russian Federation.

Other uncertainties would be the lack of funding and suitably trained and motivated staff. In some cases where plans may exist, no action is taken because the pools being used as interim storage for spent fuel appeared to be benign. Regulators or public opinion and new legislation or revised regulations may, in fact, now prompt the execution of projects.

Difficulties in establishing an accurate inventory and condition details can also give rise to uncertainties and serious contractual problems during implementation. Sections II–4 to II–6 provide examples of strategies developed to mitigate the delays and costs associated with difficulties in characterization.

In some cases, the extent of soil contamination, for example deep penetration of activity into the substrata or some examples of large contaminated lakes or reservoirs, may result in the only recourse of controlling the area until radioactive decay of the most significant isotopes has reduced to safe or acceptable levels [3.12]. In other cases, environmental remediation may be required.

The key to successful decommissioning of pool facilities is effective and timely planning. This includes developing a detailed understanding of the facility to be decommissioned and the desired end state for the facility, as well as the techniques to be used to do the work.

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4. PRE-DECOMMISSIONING ACTIVITIES

Before the main decommissioning activities associated with decontamination and demolition can be undertaken, it is often necessary to undertake a number of activities. These will vary for each facility, but will generally involve the characterization of wastes to allow treatment and disposal, and removal of residual inventory (see Fig. 4.1).

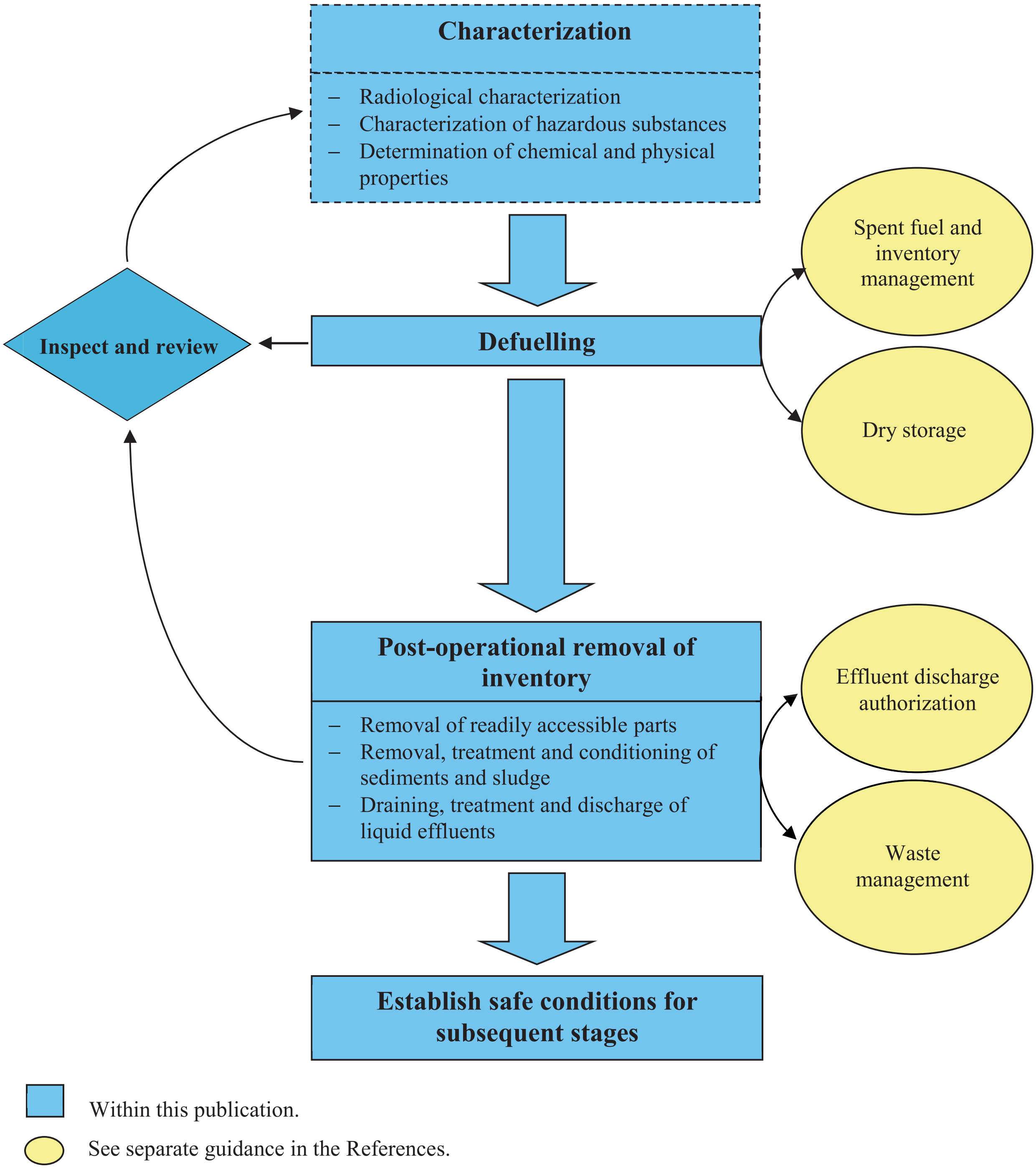

FIG. 4.1. Pre-decommissioning activities.

4.1. CHARACTERIZATION

Radiological characterization of the structure and the waste inventory provides essential input data for formulating the strategy and planning the decommissioning of a pool facility. Some characterization will have been done when the decommissioning plan was compiled, which should have been initiated during the operational years. The data included in the decommissioning plan are unlikely to reflect accurately the final radiological or structural status of the pool, and a review is necessary. If very long delays and other storage campaigns have taken place over many years, then a completely new survey will be needed. Where records have been lost or do not exist, then characterization and an in-depth survey of the facility will be necessary to avoid unexpected events that could be costly.

Characterization activities should include consideration of:

- Sediments and sludge;
- Solid wastes;
- Pool water;
- Working area radiological and contamination conditions;
- Surface contamination levels and depth of penetration into the structure;
- Non-radioactive hazardous wastes;
- Chemical and physical properties of wastes;
- Relevant plant, equipment and pool configuration and appropriate structural assessment;
- Waste location;
- Establishment and maintenance of up to date characterization records.

In addition, while spent fuel was being stored, it may have been unrepresentative or impossible to collect true data about pool contamination levels owing to dominating dose levels in the pool. Most initial characterization would have to be done underwater, and samples for analysis may have to be taken using robots or divers. In pools where severe corrosion of stored items has taken place and sediment and sludge accumulation has been significant, obtaining representative data may be problematic.

In spite of the uncertainties, characterization will also be necessary for estimating the amount of waste that will be produced during various stages of decommissioning. This will be needed for formulating a waste management strategy, for making dose estimates and ALARA decisions, and as a basis of a specification for inviting competitive tenders for decommissioning work.

Some of the difficulties in characterizing the pool inventory have been recorded in Sections I–5, I–6 and I–8. The role of structural characterization in determining decontamination requirements is given in Section I–9. The role of radiological characterization in managing decommissioning materials is exemplified by Section II–1.

Characterization will also be needed to estimate non-radioactive waste quantities and toxic and hazardous materials that may need special treatment. Examples are asbestos, oils, coatings and paints that may contain, among other things, polychlorinated biphenyls (PCBs) and lead. An estimate of the quantity of material eligible for unrestricted release should also be made as part of the characterization to ensure that management is planned and priced.

It should be noted that physical, chemical and radiological characterization is a complex activity, and that appropriate expertise needs to be applied to all techniques used. Where possible, sampling and laboratory analyses should be undertaken to support field measurements. Consideration should be given to the number of samples and measurements that have to be taken to be statistically representative. It should always be recognized that contaminated substances and surfaces are often heterogeneous. Therefore, a flexible approach always needs to be taken in the characterization process and the subsequent use of data. Statistics may play an important role in reducing the number of samples and measurements. However, regulator agreement on the use of statistical approaches may be required.

4.1.1. Radiological characterization

The extent of characterization required is determined by the data requirements for the subsequent decommissioning and disposal activities. It is often necessary to take physical samples for analysis, although there are remote techniques that may provide some benefit, where less detail is required. A number of advanced techniques exist for taking measurements and samples for radiological analysis. Experience and development of these are described here.

It was reported in an overview paper dealing with 1950s era legacy pools, ponds and wet silos, that in situ characterization of underwater radioactive sludge is an important technique in planning for retrieval and waste management [4.1]. A major hazard during the decommissioning of these facilities is the corrosion products from long term storage of spent fuel, reactor components and debris. This material is potentially very mobile.

Several techniques for underwater measurement include gross gamma counting, gamma spectroscopy and passive and active neutron counting or interrogation. The optimum technique depends on the radioactive inventory, access restrictions, integrity of inventory records and the extent to which fingerprinting can be done. Developments in this field have been on gamma and neutron detection technologies, digital advancements, data transfer, remote deployment improvements and provision of more rugged equipment. Modelling work has been done to determine performance envelopes and operational limitations.

One way to characterize and identify components and materials stored in the pond prior to their removal is to obtain physical samples of each component and material so that a laboratory analysis may be carried out. However, removal of material from the water can expose personnel to radiation and may also increase the risk of contamination spread. Furthermore, physical sampling followed by laboratory analysis is a very time consuming and hence costly process. Characterization of the component and material while it is submerged (i.e. in situ characterization) could offer significant advantages in terms of safety, speed and overall cost reductions [4.2].

One development along these lines is a special version of the fibre optic probe laser induced breakdown spectroscopy (LIBS) instrument that incorporates a submersible remote probe to identify the elemental composition of materials submerged in water at any depth up to approximately 10 m [4.3].

The US Department of Energy (DOE) produced a detailed assessment of remote underwater characterization systems [4.4]. This document is very detailed and covers technology, descriptions of devices then available, their performance, the applicability of the technology and alternatives, costs involved, regulatory and policy issues and some lessons learned. The equipment being discussed was demonstrated at INL, as part of the large scale demonstration project at Idaho Falls (see Fig. 4.2). Similar technologies also applicable to spent fuel pond decommissioning are described in Refs [4.1, 4.5].

Establishing the extent of soil and substrata contamination surrounding a pool facility is also necessary by sampling soil and drilling boreholes. The extent of ground contamination will, very often, determine the site clearance strategy. For some sites, measurement of extensive contamination may result in a restricted release status being the only achievable release level. Severe contamination may actually preclude any site release and, in this case, demolition of structures may only be cosmetic. A comprehensive description of a pond remediation project involving soil characterization, removal or leaving it in situ is given in Ref. [4.6].

At three shutdown Magnox nuclear power plants in the United Kingdom, the extent of pool concrete contamination has been investigated. A summary of the results of contaminated concrete characterization is available for Berkeley, Hunterston A and Trawsfynydd nuclear power plants [4.7].

The successful sampling for characterization of skips at Bradwell nuclear power plant, in the United Kingdom, was reported in 2007 [4.8]. Two samples were taken from nine skips using a magnetic based drill with a broaching tool to cut the metal samples, and mock-up trials had been conducted beforehand [4.9, 4.10].

There are many pools and silos at Sellafield that contain a wide range of historic wastes, and characterization of the inventories is essential. An example is an extensive survey on the FGMFSP at Sellafield using a submersible remotely operated vehicle [4.11] (see Fig. 4.3).


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FIG. 4.2. Remotely operated pool characterization and scanning device at Idaho National Laboratory, United States of America (courtesy of R. Demmer, Idaho National Laboratory).

The pond contains a large quantity of spent fuel, fuel skips in different locations, pond furniture, miscellaneous wastes and sludge. Experts have been examining over 5000 hours of video records in trying to create an accurate map of the pond. This information will greatly accelerate the final decommissioning of the facility.

At Dresden 1 spent fuel pool, a similar remotely operated device (remote underwater characterization system) was used effectively to obtain video and radiological dose information [4.12, 4.13].

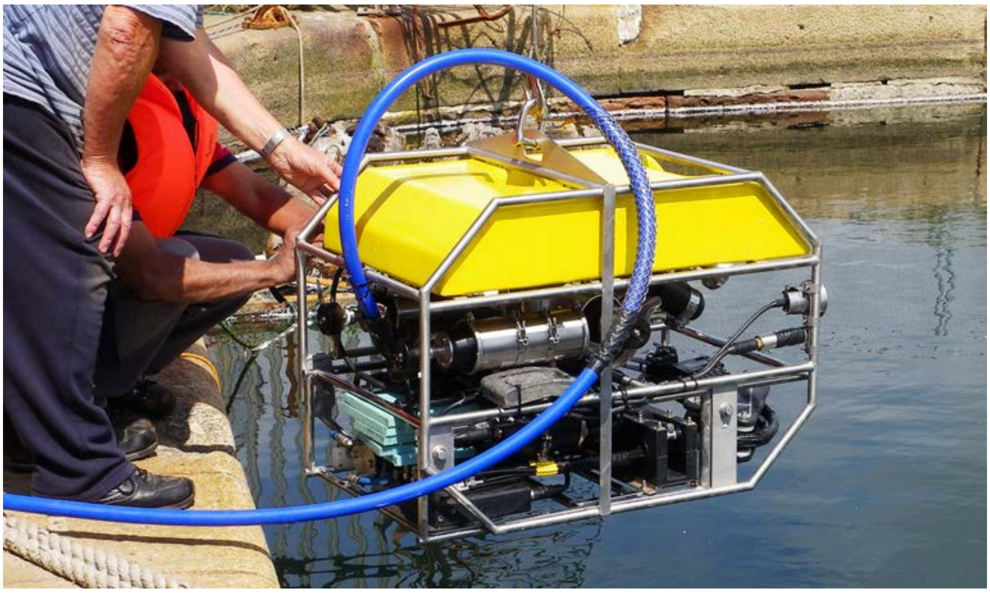

FIG. 4.3. Underwater remotely operated device used at Sellafield, United Kingdom (courtesy of Sellafield Ltd).

Experience of characterization of activated components based on sampling and monitoring at the Slovak V1 nuclear power plant is given in Ref. [4.14]. This demonstrates some remote access techniques that may be applicable or adapted to be applicable to pool situations.

Remote and underwater techniques for monitoring and characterizing are the subject of continuing R&D. One system under development utilizes a network of monitoring devices to provide more accurate information [4.15].

A specific problem of pool type research reactors is the activation of reactor core components and surrounding structures and equipment. Activation may add a significant radiological inventory to pool surface contamination and any sludge deposited. Depending on reactor configuration, the geometry and the shielding offered by pool water, neutron induced activation may also affect the floor and walls of the pool.

Neutron activation has an effect on generation and management of decommissioning waste, and may require decommissioning techniques different from those that are applicable to pools that are only contaminated. In particular, the higher dose rates associated with activated components and the different nature of activation versus contamination need to be considered during planning. In some cases, components may be both activated and contaminated, which may cause additional complications to dismantling and waste management.

The pool floor and walls may be activated to a depth that is not necessarily identical to that caused by migration of contamination into concrete pores and cracks. Moreover, neutron activation will not be prevented by a protective coating. If the activated portion of the concrete is significantly deeper than the contaminated portion, ad hoc techniques may be considered for characterization, removal of radioactive concrete and segregation of non-radioactive parts for potential clearance from regulatory control. An example of the activation and radiological characterization issues faced in a research reactor decommissioning project is given in Ref. [4.2].

4.1.2. Characterization of hazardous substances

The existence of other hazardous materials also needs to be established for inclusion in the decommissioning plan and before any decommissioning is commenced. Asbestos is a particular material that was used extensively in older plants and which may be present on piping systems associated with pools, within cladding and roofing components or even within concrete elements. The cost of removing and disposing of asbestos is not trivial. Other chemical waste may be present, and records should be consulted if they exist, and inspections made of the facility. There have been instances where dismantling activities have been halted because unknown and unexpected hazardous materials have been discovered. This can occur particularly at research reactors and laboratories. There is a case in Georgia where toxic beryllium blocks were being stored in the research reactor pool and required special consideration [4.16].

The existence of PCBs and lead contained in paint coatings can be a problem for disposal, especially when radiologically contaminated as it will create a mixed waste.

4.1.3. Determination of chemical and physical properties

To allow the retrieval, handling, processing and treatment of pool materials, it is necessary to determine physical and chemical properties. For example, it is likely that density, rheology, settling rates and particle sizes, among other things, will be required for designing equipment and processes for dealing with sludge wastes. Chemical properties will be required to demonstrate that adequate waste forms can be generated. Section II–5 summarizes some of the lessons learned in sludge characterization at the Sellafield site.

4.2. DEFUELLING AND FUEL STORAGE

According to state of the art criteria and regulations, spent fuel should normally be removed from the operations pool and shipped to a dedicated installation as soon as possible after final shutdown. However, in many cases, spent fuel is retained in pools for extended periods, resulting in enhanced decommissioning issues. The following provides an overview of spent fuel management options worldwide.

Defuelling of reactors will increase the demand for pool capacity for cooling of spent fuel before shipping off-site or before transferring to a dry ISFSI. This initial cooling period before any decommissioning work on a pool can commence may be from one to five years. Generally, a minimum design requirement for reactors has been the provision of sufficient pool capacity for whole core discharge for safety reasons, but pools have usually been very much larger to accommodate years of spent fuel accumulation and sometimes even lifetime arisings. The accumulation of spent fuel at US nuclear power plants has become much more difficult in recent years owing to the delay in opening a repository. This has prompted the construction or expansion of on-site interim storage facilities.

Because of increasing demands on pool capacity in the 1980s, dry storage in casks and vaults has been developed, and provision of this type of storage has continued. However, the dominant capacity for spent fuel is still wet pool storage [4.17]. The scope for increasing pool sizes at existing nuclear power plants was limited, but the approval of double stacking of assemblies at some nuclear power plants, particularly in the United States of America, increased storage capacity significantly.

The range of pool sizes for different types of reactors is wide, but generally of the order of 1000 m^3 or more. Research reactor pools are smaller, typically of the order of 100 m^3. Pools at fuel cycle facilities are generally much larger because they provide buffer storage prior to processing. The sizes of these pools can be up to 30 000 m^3, and fuel removal can present problems as they have often been used to store fuel that is unsuitable for reprocessing. For most shutdown research reactors, spent fuel has now been sent for reprocessing or storage at central locations (e.g. in France, Russian Federation, United Kingdom and United States of America).

In the United States of America in December 2005, the Spent Nuclear Fuel On-Site Storage Act (H.R.4538) was introduced as an amendment to the Nuclear Waste Policy Act of 1982 [4.18]. This amendment required commercial nuclear facilities to transfer spent fuel into ISFSIs and to convey title of all fuel to the DOE. The ISFSIs will be separately licensed. Funding grants may be available to cover the costs, or the transfer date may be extended. The DOE will take over all responsibility for possession, funding, stewardship, maintenance and monitoring.

In States such as Belgium, Canada, Germany, Hungary, Japan and Switzerland, dry storage was preferred [4.19]. France, Sweden and the United Kingdom use wet pool storage predominantly, except for a dry storage facility at Wylfa Magnox nuclear power plant, in Wales, United Kingdom.

A light water reactor can usually be defuelled in weeks, unless a core accident prevented this (e.g. Three Mile Island, United States of America, and Fukushima, Japan). For gas cooled reactors, the fuel quantities are usually very large, especially for Magnox type reactors (up to 80 000 fuel elements for twin reactors), and defuelling can take between two and five years and relies on the ability to ship spent fuel off-site. In the United Kingdom, in excess of 25 000 t of spent fuel has been shipped off-site to Sellafield over a period of more than 30 years.

Some pools may contain significant quantities of legacy fuels at the beginning of the decommissioning phase, particularly those at reprocessing facilities such as Sellafield and Hanford (see Section I–8). In some circumstances, the infrastructure (e.g. flasking arrangements and associated mechanical handling equipment) required for fuel export may not be fully functional. In this case, it will be necessary to either reinstate the infrastructure or develop alternative fuel export arrangements [4.20, 4.21]. An example using a combination of novel engineering and enhanced operational controls to facilitate an unshielded transfer of fuel from the pond to a flask located nearby is presented in Ref. [4.22]. This approach allowed safe transfer of fuel to a flask that could not be handled within the facility, without the need for extensive infrastructure improvements. This was the first fuel export operation since the pool ceased operation 40 years earlier.

A special case was the 'dry' removal of spent fuel from the EUREX pool in Italy. This approach was necessitated by the lack of a container compatible with the pool entry and exit routes [4.23].

4.3. POST-OPERATIONAL REMOVAL OF INVENTORY AND MATERIALS

When fuel is shipped off-site or transferred to an ISFSI, a considerable amount of residual radioactive material and debris is often left in the pools. A large part of this will be fuel skips and racks and sometimes activated components from the reactor. There could also be fuel fragments from failed or degraded fuel and items from research programmes. Section II–9 illustrates this issue. Many older legacy pools from the 1950s will contain large volumes of sludge from corrosion and also quantities of fuel fragments. A strategy needs to be devised for retrieving and conditioning this waste. Ideally, decommissioning of pools should not be started until spent fuel has been properly managed and there is an established waste management strategy for all waste streams. However, in some cases, it may be necessary to remove some inventory to gain access to fuels (e.g. if they are covered by sludge). Figure 4.4 is an example of sludge removal activities at Dounreay.

In some cases, the majority of the radiation comes from the sludge, so a project to collect and transfer the sludge while leaving the water in place should be considered [4.24]. A cleanout process may require a means of treating contaminated water, which implies an effective water treatment plant.

Most pools have multiple interconnecting bays with lock gates to isolate sections. This flexibility can be taken advantage of during decontamination and for equipment removal, for example some bays could be used for collecting, sorting, washing and rinsing or for waste and sludge transfer for temporary storage. Some pools have channels or tunnels communicating with the reactor for fuel transfer operations, and secure isolation from the reactor itself needs to be achieved at this stage (see Section I–8).

FIG. 4.4. Dounreay, United Kingdom, fast reactor pond sludge removal (February 2011) (courtesy of Dounreay Site Restoration Ltd).

The sequence for removing items from pools may be varied according to the nature of the pool inventory. For example, items may be removed to facilitate sludge removal, or some sludge may be removed to expose items. Detailed analyses of occupational exposures resulting from the removal of reactor components from a pool are given in Refs [4.25, 4.26].

4.3.1. Removal of readily accessible parts

A clear plan will be needed to retrieve removable items from pools that will include means of managing the waste. There could be residual fuel in some pools that will require handling. In addition, there may be a large number of redundant empty fuel baskets or skips after the fuel has been removed, and there may be other items of pool furniture that can be readily removed. There could also be other items of equipment for handling and inspecting fuel underwater. Many pools have also been used to contain and shield activated and contaminated items from the reactor or from experimental rigs. Relevant records of these items are sometimes inadequate or non-existent. Some items will be only surface contaminated, which could be treated, but many items may be activated and require shielding.

A problem associated with large items removed from the pool is their size and varied configuration. Large items may need cutting to be accommodated in waste containers (shielded if necessary) for transport elsewhere or for direct transfer to an encapsulation facility, if this has been planned and provided. Characterization to classify items into waste streams will also be needed [4.27]. Section II–16 describes lessons learned with minimizing worker dose exposure during waste size reduction activities. Section II–11 describes systems for managing worker dose.

The use of existing handling equipment (e.g. a skip or basket handling machine) may require extensive refurbishment if these devices have been unused for long periods or need adapting for special operations. However, consideration should be given to the structural integrity of the items to be removed.

Items removed from the pool will generally require some degree of washing and decontamination prior to and during removal. Sections I–9 and II–15 provide lessons learned about dose minimization during these activities.

Section II–10 describes simple techniques using premade bags to reduce worker dose uptake during the wrapping of contaminated waste items during their removal from ponds.

4.3.2. Removal, treatment and conditioning of sediments and sludge

Sludge is present in almost all wet storage facilities as a result of corrosion and activation products adhered to fuel that become loosened (fuel crud). In addition, sludge can be produced from external sources such as airborne dust, debris, algae growth and other extraneous material. The quantity of sludge and sediment in a pool reflects the amount of good housekeeping that has been conducted during operation. At some facilities, cleaning has been routine, which minimizes sludge cleanup. However, there are a number of pools where corrosion of fuel cladding and other metallic items has not been controlled by water filtration or processing or by suitable water chemistry control. Sludge and sediment can reach a number of metres in depth over decades of uncontrolled corrosion, degradation and ingress of extraneous material. Sludge in very large outdoor pools at fuel cycle facilities at Sellafield can reach thousands of cubic metres in volume. Section II–5 presents lessons learned regarding quantification and characterization. Section II–19 illustrates the difficulties of excluding extraneous materials from sludge processing routes. Solidification of some pool sludge material in special facilities has been achieved at INL [4.28] and Dounreay [4.29].

Magnox, in the United Kingdom, has focused on consistency of approach across sites (see Section I–9). Sludge retrieval operations are performed in two phases: bulk retrieval prior to drainage and final cleanup following drainage. Annex I provides examples relating to sludge removal, including:

— An underwater remotely operated vehicle;
— Consolidation and corralling of sludge;
— Direct pumping by placing a vortex pump on the sludge pile;
— Diaphragm pumps passing sludge through a rock basket to separate particulates;
— A freeze plate to assist with separation of solids and sludge for processing and disposal;
— Hydraulic resuspension and retrieval;
— Eductors;

— Water lances to redistribute sludge;
— Mechanical bucket grabs and mini digger type devices;
— Suction and settling techniques.

During sludge and sediment removal operations, there is a persistent risk of suspension causing loss of visibility and subsequent handling problems. Technologies exist to restore water clarity and should be considered during these operations [4.13, 4.30] (see also Section I–9).

If a pool has been used for long periods for fuel and waste storage and contains appreciable quantities of sludge and debris including fuel fragments, then the initial cleanout operation becomes more complex, and characterization of waste becomes difficult. This is because the sludge is not homogeneous or of uniform depth. The definition of when a fuel fragment is classified as spent fuel or as waste is contentious and needs to be agreed as part of the characterization.

If sludge is retrieved and dewatered for solidification in a cement matrix, then an additional liquid waste stream is likely to arise. During the processing of the decanted water, the concentration of particulates and radioactive isotopes on filters or captured by ion exchange media will have to be dealt with.

Examples of the challenges encountered and solutions found in retrieving sludge are given in the paragraphs below. The challenges associated with retrieval of sludge and debris in pools are also dealt with in Ref. [4.31].

A DOE audit report on the K basins sludge treatment project at the Hanford site describes the difficulties encountered in a project to retrieve 28.5 m^3 from a fuel pool facility [4.32]. The audit report highlights the importance of adequately characterizing the sludge inventory before project commencement and the need to complete appropriate nuclear safety assessment before progressing major procurement activities. Most importantly, the audit highlights the need to ensure that project and contract management practices reflect the level of technical risk associated with this type of work. While reports from the site now indicate that the sludge has been retrieved from the pond, failure to ensure proper planning and control of sludge retrieval activities led to delays of over three years and abortive work valued at in excess of US $43 million. An up to date description of the K basins’ cleanout history is given in Ref. [4.33].

Experience acquired during the Trojan decommissioning project in the United States of America is to be mentioned in this context. The characterization of all radioactive materials stored in the pool was a prerequisite for transferring its contents to dry storage in the ISFSI. The characterization included the separation, segregation and recording of the inventory of the spent fuel pellets and fragments, non-fuel-bearing components, and low level and greater than class C waste. It was also necessary to process and separate the material from the organic and inorganic filter media used over the operating life. A waste processing contractor conducted underwater segregation, size reduction and packaging of the waste materials in the pool and adjoining transfer canal from April to December 1997. The wastes were processed on-site in the mobile steam reformer to remove the hydrogen gas producing materials. The steam reformer successfully removed organics, moisture and hydrates from sludge, fine metallic dross and mixtures containing bits of spent fuel pellets, deteriorated organic filters and miscellaneous debris. The processing equipment provided a reliable, repeatable means to determine the end of run for each batch without having to perform sampling on individual batches [4.34]. See also Section 7 and Refs [4.35, 4.36].

In July 2006, it was reported from the INL site that approximately 50 t of radioactive sludge had been removed from three 1950s era fuel storage basins [4.28, 4.37]. The sludge contained desert sand, dust, corrosion products and radioactive sediment including ^{60}Co, ^{137}Cs and ^{235}U. All the work was done under environmental and regulatory control. Industrial divers from a DOE subcontractor used a vacuuming technique to capture the sludge, which was then pumped through a processing system directly into high integrity containers (HICs). Excess water was decanted and recycled. The recovered sludge was grouted in situ in the containers. The sludge had been characterized, which indicated that two different grout mixes would be needed according to the chemical and isotope mix. Any highly active debris that could not be grouted was removed separately. The HICs were fitted with mixing paddles that had to be operated remotely because of high radiation in the filling area. The containers will be disposed of on-site under authorized disposal regulations.

Working conditions in the basins for the divers presented some problems, and access difficulties were reported but overcome. Section II–20 describes lessons learned related to unreviewed accident scenarios resulting from changed circumstances (e.g. the execution of decommissioning activities).

In 1992, it was reported from British Nuclear Fuels Limited at Sellafield that preparation was in hand for a post-operational cleanout of the FGMFSP, which had been taken out of service in 1986. This included both the fuel storage pond and the decanning facility used for stripping magnesium alloy covering the fuel elements [4.38]. By 1994, a full cleanup strategy outlined all the processes and facilities that would be attended to. It was, at that stage, suggested that the cleanout phase would be completed in 2001 [4.39].

Significant delays were encountered in commencing the cleanout phase, with problems encountered in returning the facility to a condition suitable to carry out the work required and in developing waste treatment routes for the material held within the pond. Details of the scale and type of problem encountered were reported in 2006 [4.40], at which point, the cleanout work had still yet to begin. The detailed work required to get this facility back into an operating condition has been extensively reported [4.41–4.45], which includes the provision of a sludge packaging plant as an interim store for retrieved sludge [4.46].

A second redundant fuel pond at Sellafield, the pile fuel storage pond (PFSP), is also being progressed through the initial phases of decommissioning. This project is reported in detail in Section I–8, with particular focus on the decommissioning plan and sludge retrieval technologies. The successful commencement of desludging activities has recently been reported [4.47, 4.48]. Details of progress with desludging and some of the challenges related to sludge behaviour are reported in Ref. [4.49].

For Dounreay's fast reactor pond decommissioning, in-house designers developed a facility capable of immobilizing the pond debris in 200 L drums by mixing the debris with cement. A large pump was used to transfer the sludge from the pond floors into filter bags to remove excess water. The process worked by sucking up the debris using a peristaltic pump that transferred it to a tank to measure the volume. Cement was then mixed separately before the cement and sludge were transferred by gravity into a 200 L drum at the mixing station. A paddle mixed the drum contents for one hour before the drum was moved to a temporary storage area to solidify. The drum was then taken for storage as waste [4.29].

Lessons learned during the decommissioning of the experimental boiling water reactor at Argonne, in the United States of America, have been reported [4.50]. The reactor core assembly had been size reduced in the fuel pool, and a three part process was used to clean up the debris. Grips were used for large items, a scoop was used for medium sized material and hydrovacuuming for final tailings. Problems experienced were that the scoop failed to pick up cutting slag material properly and the vacuum got clogged. The lesson learned was to plan cleanup processes properly and to use waste collection tanks where possible. The underwater cutting process produced small, spherical, light, highly radioactive material that dispersed very easily and which was difficult to collect. Section II–22 describes lessons learned related to the storage of wastes in more detail.

The cleaning of the 907 pond in the high activity oxide AREVA building at La Hague, as a precursor to pond dismantling is described in Ref. [4.51]. This has involved draining the hulls (fuel casings) and various waste materials stored in the pond. The issues were further complicated because of the high radiological levels, the cramped working areas and the lack of visibility. The whole operation was therefore based on working remotely, using a specially designed arm, guided by command desks and control screens. The silt deposited at the bottom of the pond was highly mobile, and the slightest movement put it into suspension. It was therefore necessary to organize the operation into alternate periods of work and 'redeposition' to reinstate enough visibility.

It should be noted here that the chemistry of pond sediments is an active R&D topic, focusing on facilitating removal and conditioning of the sediments to aid subsequent decommissioning. For example, in the United Kingdom, storage ponds are used to store spent Magnox rods, which are uranium fuel rods covered by a magnesium alloy cladding. The rods contain large amounts of fission products that are highly reactive. The ponds are maintained to minimize corrosion. If the cladding corrodes in water, fine particle sludge may be created. In one or more of these ponds, the sludge is estimated to contain considerable quantities of plutonium. UK scientists made a model of Magnox storage pond liquid to study how plutonium interacts with the corroded Magnox sludge to find a way of removing the plutonium before the ponds are emptied. The model consisted of plutonium, a sludge simulant, sodium carbonate, polyelectrolyte and silica to replicate real conditions. One component of the sludge was brucite (magnesium hydroxide), which sequestered plutonium, forming a colloid. The scientists found that certain chemical and physical conditions resulted in almost all of the plutonium being filtered [4.52, 4.53].

As with all radioactive waste, unwanted sludge has to be handled with care to ensure the safety of workers involved in the cleanup process. In parallel projects in the United Kingdom, other teams of scientists developed techniques to sample and test radioactive sludge from a distance, using remote monitoring equipment [4.54, 4.55].

4.3.3. Draining, treatment and discharge of liquid effluents

As indicated in Table 2.1, some pools at fuel cycle facilities can hold over 10 000 m^3 of water, but pools at nuclear power plants and research reactors are smaller and range from 100 m^3 to approximately 3000 m^3 [4.17]. Most pools have multiple compartments with lock gates between bays. During processing of water, advantage can be taken of this flexibility. When pools are to be completely drained, a considerable amount of effluent will need to be discharged and may require processing and authorization. The discharge water is likely to be contaminated with ^{137}Cs and possibly some transuranics. Depending on chemical conditions prevailing during operations and other factors, processing this fluid may generate new waste streams. If so, compatibility with the active effluent treatment plant (AETP) should be ensured. Issues to be considered include:

- Existing equipment may be obsolete or degraded beyond useful operation;
- Modification to existing equipment may be necessary as water levels are reduced;
- Ever tightening discharge criteria and regulations, including non-radiological aspects;
- Changes in water activity and chemistry during decommissioning activities;
- Pondwater clarity and visibility issues;
- Existing plant capacity and throughput;
- Improvements in available effluent treatment technologies.

Where water quality is acceptable, filtration may be sufficient treatment alone. INL used filter systems to treat pond water and the Magnox drained pond 1 at Chapelcross, in the United Kingdom, using similar submersible filter systems (see Section I–9).

Radioactive ion exchange resins from water treatment plants are a special waste stream. The material can be very active, especially with concentrations of caesium, cobalt, traces of heavy metal fission products and other radioactive contaminants. Resins are considered potentially mobile waste. Encapsulation of organic resins may be difficult, owing to the chemical nature and water retention characteristics of the resin beads and the risk of gas formation. Very often, they have been stored in sealed containers and held in interim storage pending a conditioning and disposal solution.

It may be prudent to perform a degree of decontamination during the draindown of the pond. This will ease dose and contamination control and enables the water in the pond to be used as a shield during drainage operations (Section I–9 provides examples of this in practice). The degree of decontamination may be determined from measurements and characterization before pool draining takes place. Notably, Magnox characterize ponds using underwater core boring and underwater dose mapping, and develop dose models that are tested through drainage of the first 1 m depth of water. These models inform decisions of whether a light or aggressive decontamination method will be required during draindown.

A comprehensive discussion of worker exposure scenarios and dose estimates during water removal at Hanford's N reactor is given in Ref. [4.56].

It is noted that the 'wind/water' line can be an area of particularly high contamination, where active pool water has repeatedly splashed against the pool wall and subsequently dried, throughout the pool's operational life. This area may require special attention during decontamination activities. It may be an issue for outdoor pools with no wind/water line stainless steel protection.

There are also public relations and environmental issues to consider. For example, there are instances where effluent is within the discharge criteria and may be authorized for release, but discharge may be unacceptable in terms of public relations. There may, however, be higher discharge requirements from some complex sites at various stages of decommissioning. The political and environmental aspects need to be considered during the stages of planning and licensing of decommissioning.

R&D activities are ongoing at several pond decommissioning projects. In particular, removal of caesium isotopes in view of discharging pond water has been aggressively tackled at the Savannah River National Laboratory. Achievements of these studies are reported in Ref. [4.57].

4.4. ESTABLISHMENT OF SAFE WORKING CONDITIONS FOR SUBSEQUENT DECOMMISSIONING

One of the main objectives of the preliminary cleanup activity is to establish safer working conditions for future decommissioning operations. A particular requirement is to establish the true radiological status of the facility. The most effective period to undertake cleanup operations is as soon as possible after shutdown of a facility, although this may be when dose rates are highest. At this time, most of the experienced operating staff is likely to still be available. The benefits of experience gained over many years of operation is invaluable, will contribute to planning safe decommissioning activities and will avoid delays that often arise when unknown material or situations are found. Sometimes, structural alterations or refurbishment will have to be made to the buildings and handling equipment to provide safe working conditions for workers and the environment. Examples are the provision of a containment structure over an outdoor pool and enhanced health physics facilities and active ventilation.

There are practices reported where underwater divers have been used to undertake difficult decontamination and dismantling operations. This experience is reported in Section I–7. Clearly, stringent safety measures and precautions have to be taken and ALARA should be applied to make judgements on operator risk. It is usually advisable and good practice to conduct trials and to use mock-ups in radiologically clean conditions for operator training to minimize risks under hazardous conditions. It has been reported from some projects that there have been fewer accidents when using divers than when using operators working from the side of the pool [4.58]. Some water cleanup may be necessary, however, to reduce operator dose and improve water clarity when using divers.

Where pools connect with the reactor for spent fuel transfer, secure isolation needs to be achieved to ensure that the reactor does not impose any hazards on pool operations.

It should be stressed that non-radiological hazards can be more significant in decommissioning than radiological hazards. Comprehensive guidance on human factors (including competence, motivational, physical and organizational, among others) can be found in Ref. [4.59].

Section II–15 provides lessons learned about maintaining safe conditions and dose minimization during activities to remove redundant items of equipment from pools. Section II–16 describes lessons learned associated with minimizing worker dose exposure during subsequent waste size reduction activities. Section II–3 illustrates the difficulties of managing airborne contamination during decommissioning activities. Section II–11 illustrates how doses may be managed.

Decommissioning activities introduce a new range of worker activities that the building had not previously been designed for. Some of these may be non-routine in nature or are being undertaken for the first time. Section II–17 provides insights into ways for improving worker safety through holistic reviews of worker tasks.

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5. DECONTAMINATION

After shutdown and defuelling of a nuclear power plant, it is the pools and waste silos that are often identified as the most contaminated areas. This is especially the case if pools have been used for long term or lifetime storage of spent fuel and highly activated waste. The practical and most common use of water as a medium for cooling and shielding has the drawback of promoting corrosion and degradation of even the most durable of materials. Magnesium alloys are especially prone to corrosion, unless strict chemical conditions are maintained (e.g. with very low chloride concentrations). Extensive corrosion may be expected if unprotected low carbon steel has been used for pool equipment. The storage of other materials and redundant items, especially those dismantled after shutdown, exacerbates the situation.

Very often, the close control of water chemistry is abandoned after shutdown and pools contain a mixture of sludge, sediments, debris, fuel and other fragments. At some fuel cycle facilities, the use of outdoor pools has not helped, owing to the ingress of airborne contamination ranging from dust to animal matter.

The challenge of pool decontamination becomes a major undertaking for pools in poor condition, and the situation is not without hazards. One of the reasons why the decommissioning of so many legacy pools has been deferred is attributed to the formidable nature of the task. It is encouraging that attention is now being given to these legacy pools, particularly over the last decade. Pool surfaces can be decontaminated underwater or just above water level as the water level is lowered and when wet surface conditions are maintained. Pools are seldom decontaminated under dry conditions owing to dust formation, but it can be done if the contamination is very low. The optimum method will depend on contamination levels. An overview of decontamination methods and techniques for spent fuel storage facilities has been published by the IAEA [5.1].

A relevant technical report was published by the IAEA in 2006 [5.2]. This dealt with the understanding and ageing of materials in spent fuel storage facilities. Although closely associated with the conditions in storage pools, this detailed subject is not dealt with in this publication.

Figure 5.1 illustrates the flow of the main activities that need to be implemented during the entire decontamination process. Details are discussed further in this section.

5.1. DECONTAMINATION OBJECTIVES AND CRITERIA

The extent and degree to which decontamination should take place depends on the end state being targeted as well as other relevant factors (e.g. to support waste disposal or to assist with dose management during subsequent phases). Decontamination does not diminish the overall inventory of radioactivity in terms of total becquerels, as this only occurs by radioactive decay. The objective of the process is to reduce the risk from the facility and, if required by the overall strategy, to transform radioactive waste into a condition that will facilitate waste management and eventual disposal, as well as possibly reduce overall cost. Decontamination should not be an objective in its own right but should support the overall risk reduction and environmental protection strategy. In some situations, the best strategy might be not to decontaminate or to defer decontamination. Other techniques such as activity fixation may be beneficial under certain circumstances.

There are constraints and opportunities in the extent to which decontamination is taken. Some of these include:

(a) Controlling the total volume and mass of secondary waste to minimize the inherent possibility of increasing quantities;
(b) Establishing and agreeing radioactive levels for defining and categorizing waste streams;
(c) Establishing and agreeing with regulators and environmentalists acceptable levels for the unrestricted release of materials;
(d) Avoiding cross-contamination and the mixing of waste streams;
(e) Limiting dosages to operatives during the process by applying ALARA principles;
(f) Reducing hazards and the potential for release to the environment;

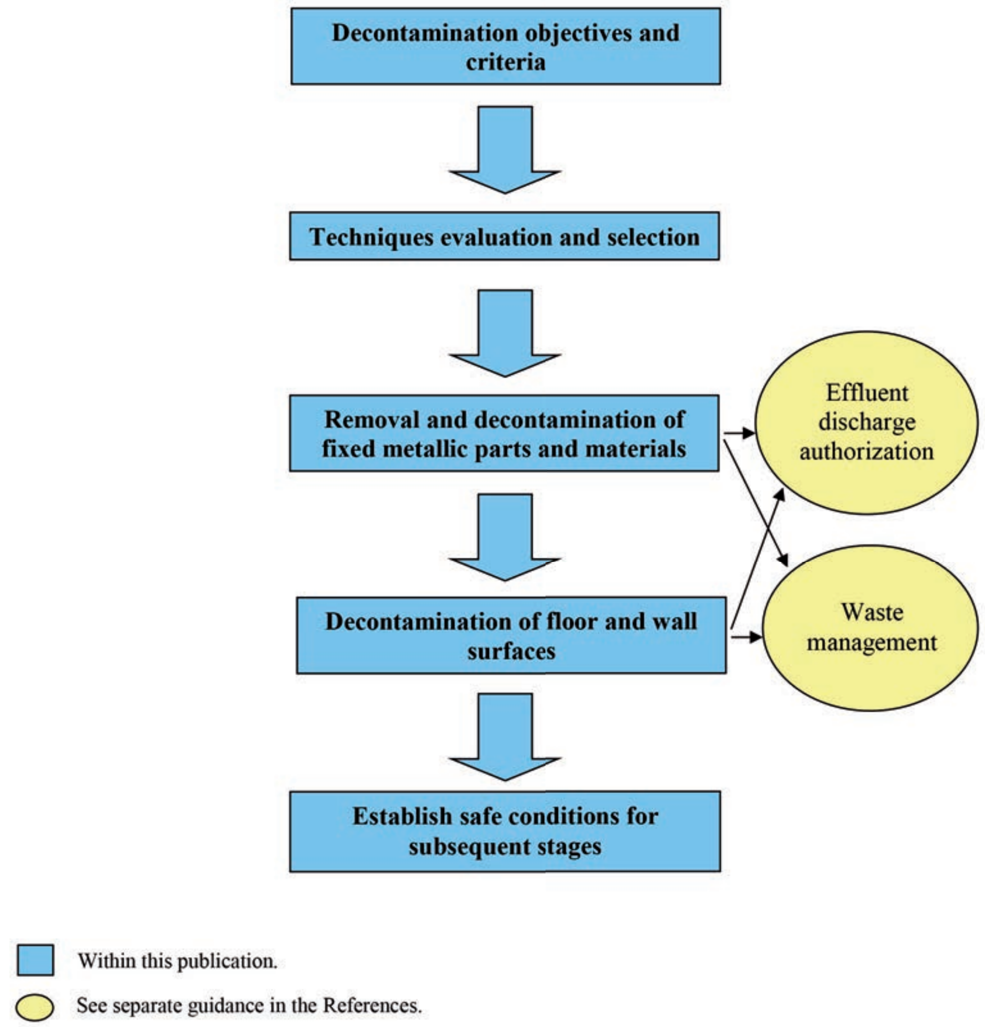

FIG. 5.1. Decontamination activities.

(g) Avoiding the use of aggressive chemicals that can cause problems with packing, encapsulation and disposal;
(h) Taking account of the need to decontaminate new equipment that may be introduced on-site to undertake decontamination operations;
(i) Being aware that extensive or excessive decontamination activities can increase the volume of waste unnecessarily;
(j) Taking account of available or planned waste storage facilities;
(k) Being aware that decontamination for decontamination's sake is not a good policy;
(l) Integrating and consolidating decontamination wastes into existing treatment and storage facilities.

Noting that where there are fuel fragments within the sludge and sediments on the pond floor is a special problem that may require consideration of accountancy, safeguards, criticality and waste handling.

5.2. TECHNIQUE EVALUATION AND SELECTION

There are numerous techniques that are available for decontamination, and only some have been identified in this publication. R&D continues to investigate new methods and procedures. Particular techniques and experience with advanced techniques are given in more detail in Section 7. The main ones that are well proven are:

— Water jetting and spraying of walls and components [5.3];
— Manual scrubbing using abrasive brushes on surfaces [5.3];
— Scrubbing of surfaces and components using power and remotely operated tools [5.3];
— Chemical cleaning of removable items with adsorbents [5.4];
— Sand or grit blasting [5.5, 5.6];
— Chemical leaching of concrete [5.6];
— Dry scarification of concrete [5.6];
— Ultra high pressure (UHP) hydrolasing using rotary nozzles [5.6];
— Carbon dioxide pellet blasting [5.7];
— Electrokinetic decontamination and electropolishing [5.7];
— Vibratory and ultrasonic finishing [5.7];
— Strippable coatings [5.7];
— Harmonic delamination [5.8].

A much broader spectrum and analysis of techniques has been presented in the Technology Reference Guide for Radiologically Contaminated Surfaces, by the United States Environmental Protection Agency [5.9]. This is a summary of extensive research, development and experience that has been accumulated and proven over a number of years. The techniques were considered in two main parts and included illustrations and technical data for each process:

(a) Part 1: Chemical decontamination using acids, foams, gels, oxidizing and reducing agents and technochemical extraction;
(b) Part 2: Physical decontamination including strippable coatings, shot blasting, concrete grinding, shaving, spalling, ice blasting, dry vacuum cleaning, electrohydraulic scabbling, robotic wall scabbling, grit blasting, high pressure water (hydrolasing), soft media cleaning (sponge blasting), steam vacuum cleaning and piston impact scabbling.

In 1998, the IAEA published IAEA-TECDOC-1022 on new decontamination methods and techniques in maintenance or decommissioning operations being developed or used in many different countries [5.10]. The IAEA has also produced numerous publications on waste management, but there are two that have particular reference to this publication. The first is a detailed technical report that gives guidance on minimizing waste during decommissioning activities [5.11]. The second is also a technical report that gives invaluable guidance on the management and disposition of large quantities of LLW for various types of facilities and includes strategies for releasing, conditioning and disposal opportunities for wastes [5.12].

The selection of a preferred technique depends on numerous factors and circumstances. Among these will be the depth of contamination, whether the pool had a lining or not, the level of contamination and dose to operators, clarity or obscuration of pool water and the national waste management strategy. For example, at the Berkeley nuclear power plant, in the United Kingdom, concrete was removed dry because activity was low and the available disposal route permitted dry unencapsulated waste. The dry process avoided the need to dewater concrete rubble [5.5]. There was an effective ventilation plant.

At Hanford, the surface concrete was removed underwater, and it was decided to encapsulate the sludge type waste in cement because of higher activity levels and the existence of a large on-site waste storage complex [5.13, 5.14].

Strategic guidance on management of installed pond equipment decontamination containing an evaluation of the various techniques available is given in Ref. [5.15].

5.3. REMOVAL AND DECONTAMINATION OF FIXED METALLIC PARTS

Pool furniture in the form of fixed items, such as fuel racks, underwater handling equipment, brackets, guides, jigs, can be extensive. These are considered differently from the loose items that were or should have been removed from the pools during cleanup operations (see Section 4.3). Fixed items pose more of a problem to decontaminate in situ, and removal is usually the best option. Removal from the floor and walls needs to be done with some care to avoid damaging any pool liner or coating. Items may have been bolted or welded in place. Underwater cutting is the preferred approach, but care needs to be taken not to leave excessive protrusions on the surface that could hamper subsequent decontamination. This can be done with underwater robotic cutting devices or cutting by manipulating devices remotely from the poolside, using divers or the overhead crane. If situations are complex or inaccessible, the use of workers in specially equipped diving equipment may be permissible in closely controlled radiological conditions. Experience with all these methods is given in Section 7.

An underwater shear compactor has been developed as a decommissioning tool, particularly for cutting rods and pipes up to 48 mm in diameter [5.16]. It uses a water hydraulic system and is designed to avoid underwater shock waves, which could be a safety issue. Extensive tests were done in shearing and compaction. It is deployed with a rig and platform off the side of the pool.

At the Obrigheim nuclear power plant, in Germany, various fixed brackets and consoles on the pool walls have been removed by wire sawing and placing the items into CASTOR casks. Facilities were available to lower the casks into the pool to a depth of 8 m. Trials were conducted at the University of Karlsruhe, in Germany [5.17].

A detailed guidance document was produced by the European Commission in 1996 on underwater dismantling using divers to install remote controlled equipment [5.18]. It covered various aspects of diving related activities including equipment, dose monitoring, operational procedures, organizational aspects and the execution of the dive. It then gave illustrations of cutting and sawing using various techniques such as plasma, arc saw and diamond cutting. Pool contamination was also dealt with.

When items have been removed from their fixings, there are options for decontamination. Many pools have assorted bays previously used for spent fuel management, inspections or other uses. A suitable secondary bay may be allocated for decontamination underwater or near the water surface. Radiation doses to operators and the risks of spreading wet or airborne contamination need to be considered. Section II–15 provides lessons learned about the risks of spreading airborne contamination during washing activities about the liquid surface. An effective degree of decontamination may be achieved by water jetting or by spraying and rinsing. If the use of a secondary bay is not permissible or available, then a special decontamination enclosure may have to be constructed. This should be preferably within the pool building enclosure and located above the pool if possible. The water used for decontamination should be recirculated through an active water treatment plant for contamination control.

Sample and swab measurements should be taken that are consistent with the envisaged waste stream. The aim should be to achieve LLW levels or lower. It is unlikely that aggressive chemical decontamination will be necessary, unless it can be shown that a lower level waste stream can be achieved economically and with confidence and that overall waste volumes are not increased.

The metallic items will then usually have to be size reduced for accommodation in chosen waste containers. If sufficiently high levels of decontamination can be achieved, then items may be able to be placed intact in standard transport containers. Section II–13 describes lessons learned in the development of metal decontamination techniques at Magnox nuclear power plants. Size reduction of large metallic items should be conducted within the pool building and in a tented controlled zone, if necessary. Section II–16 describes lessons learned associated with minimizing worker dose exposure during waste size reduction activities. If items are allowed to dry out, airborne radiological hazards may increase significantly.

5.4. DECONTAMINATION OF FLOOR AND WALL SURFACES

In cases where pools have bare concrete surfaces, penetration below the surface is inevitable. Even where lining or coatings are used, the risk of leakage below the surface is also common. Coatings and linings have not always been used, especially on very large pools. A problem with coatings is their limited expected life, especially under high radiation conditions. However, the later coatings (e.g. based on alkyd paints) are far more durable and overcome a number of contamination issues.

There are some cases in small research reactors where ceramic tiles set in bitumen have been used. This could have exacerbated the decontamination problems if penetration had occurred, but fortunately pool contamination was generally low.

Sampling and measurement of pool subsurface contamination is necessary to determine the depth of penetration, and it is generally believed that it is worthwhile to remove the top layer, which can very often be designated as a LLW stream. The aim would be to reduce bulk contamination of the remaining concrete structure to an average level that can be classified as very low level waste (VLLW) or unrestricted release material. To achieve this, surface removal in the range of 10–40 mm has generally been necessary. Where leakage has penetrated deeper and leaks to the outside have been discovered, the problem becomes more difficult. Suspected areas of deeper penetration will have to be established by sampling during pool structural demolition. Particular attention should be paid to construction joints and cracks.

The European Commission produced a study report on the pilot dismantling of the Belgium BR3 reactor [5.3]. A particular topic was surface decontamination of the refuelling pool walls and floors as a case study. The three options that were looked at were:

— High pressure water jetting;
— Manual decontamination using abrasive materials;
— Water screen flow to wash walls and control spread of contamination.

Examples of the first two techniques listed above are given in Figs 5.2 and 5.3. Both examples illustrate decontamination activities implemented in Dounreay site pools.

Manual decontamination is the most common method if doses are low — abrasive papers, sponges and wire brushes are used. Wall scrubbing may also be performed with automated devices, especially if powered and remotely handled equipment are used. Water screening is generally only a measure to minimize spread of contamination by running water on the walls and is unlikely to achieve much decontamination. Detergents are also available for improving decontamination and are effective when used with scrubbing. A more detailed list of techniques for decontamination techniques is given in Section 5.2.

Experiences with pool surface decontamination have been reported at numerous decommissioning sites, and those at Hanford, Sellafield, West Valley, Dresden, INL and other sites and particular examples and experiences are given below and in Section 7. Section II–2 reports specific lessons learned related to surface decontamination. Section I–9 summarizes experience of hydrolasing pond walls and floors. This includes the difficulties associated with floor decontamination using this method, where areas can become recontaminated as subsequent areas are cleaned.

The traditionally most effective way of removing concrete surface layers has been by using dry or wet scabbling equipment with abrasive cutting heads, but more recently, the use of high pressure hydrolasing with water jets of up to 240 MPa has been proven [5.6, 5.19].

It is possible to undertake scabbling under dry conditions if airborne contamination can be controlled. This was done at the Berkeley nuclear power plant, using a combination of dry planning, grit blasting and adapted rotary peening operations [5.5].

Surface removal is often done underwater to prevent spread of airborne contamination, and there are well developed robotic devices in use. However, there are examples of this leading to recontamination of the cleaned surface (see Section I–9).

Sometimes, workers in diving suits have also been used, particularly in difficult corners that may have to be dealt with by hand. The experience of the Idaho cleanup project on basin deactivation is well reported, including lessons learned [5.20, 5.21].

For a decontamination process to be effective, it has usually been necessary to remove all metallic fixtures below water level. This has sometimes been carried out effectively by divers, but may also have been done as part of the pre-decommissioning activities. Experiences with concrete surface layer removal have been reported (see Section 7).

Note: Once the sides of the pond are decontaminated, the water level will be gradually lowered until it can be completely emptied.

FIG. 5.2. Fast reactor pond high pressure water jet submerged below water level Dounreay, United Kingdom (courtesy of Dounreay Site Restoration Ltd).

FIG. 5.3. D9814 pond concrete decontamination, Dounreay, United Kingdom (courtesy of Dounreay Site Restoration Ltd).

Where pools have metal liners, problems have been found where lining integrity has failed. AREVA experts have reported on corrosion in steel reactor pool and pond liners [5.22]. Liner leaks by corrosion far outrange mechanical and weld failures. The main causes are believed to be because of the use of susceptible materials, the onset of chloride induced stress corrosion cracking (SCC) and residual thermal stress, particularly from welding during construction. The material commonly used is austenitic stainless steel (e.g. TP 304). For reactors, the introduction of cold water during refuelling can exacerbate SCC. The water often contains boric acid, which neutralizes the alkaline passivating properties of concrete. The solution proposed for leaking linings is to coat the inner surface with an epoxy or silicone based material. Some applications can be performed underwater.

There has been some experience of coatings for pools. Very often, these have been applied where leaks have occurred and repairs have been necessary to allow continued use of the facility. At INL, the development of epoxy coatings for sealing pools and for ease of decontamination have been reported (see Refs [5.23, 5.24]). The epoxy may constitute a special waste stream. Paints have been used on pool walls in some cases. It is known that PCBs, often found in paints, tend to complicate waste streams and may need special conditioning. Other work related to the development of underwater coating is given in Ref. [5.25]. It was also reported in the decommissioning project from the Big Rock Point, in the United States of America, that the management of waste containing PCBs may be a problem for disposal [5.26].

R&D has been undertaken on the use of adsorbent as a method of cleaning contaminated storage ponds. It has been suggested that this can be used in combination with high gradient magnetic separation and radiolysis techniques to manage products of the process [5.27].

5.5. REMOVAL, TREATMENT AND CONDITIONING OF DECONTAMINATION WASTE

Pools contain a large volume of water that will play a central role in all decontamination activities and which will need cleaning and recycling when pools are drained through an AETP before discharge. It is beneficial that the strategy and authorization for final discharge of pool water are established early, and for the volumes to be discharged and the potential variations in composition from previous routine discharges to be considered.

If the pool facility has an existing AETP, which is often the case, then attention will have to be given to decontaminating and dismantling the AETP itself and treating the resins and filter media at the end of the decontamination operations and before or during the dismantling and demolition of the pool facility. This will become an issue at the end of all decommissioning activities and will have to be addressed. The use of portable equipment or immersed filtration devices may be a solution [5.28].

The metallic waste from pool furniture, fixtures and other metallic components retrieved from the pool will probably need to have some surface decontamination, which is best performed within the pool or pool building. Section II–15 provides lessons learned about dose minimization during these activities. The most appropriate objective for items that have not been activated would be to decontaminate them to a level that would allow interim dry storage in containers pending disposal or, if necessary, encapsulation.

Size reduction of large items will nearly always be necessary for efficient storage, and some items of mechanical equipment may have to be dismantled. Establishing a controlled waste processing and handling zone will be necessary. It will be important to limit alpha bearing contamination to avoid exceeding dry waste storage acceptance criteria. Section II–16 describes lessons learned associated with minimizing worker dose exposure during waste size reduction activities.

Items that are activated and need shielding will require special equipment to handle and transfer them into shielded containers or casks. Special casks may have to be procured. It may be possible to contain these items grouted within concrete containers or boxes to provide the necessary shielding.

When large items have been removed, debris, residual sediment and fuel fragments that may not have been removed during the cleanout operations will have to be dealt with. It may be preferable to defer all concrete surface removal until as much debris and sediment as possible has been removed.

It may be difficult to separate miscellaneous waste into types or streams. This was revealed at the Humboldt Bay pool cleanup project, in the United States of America [5.29]. The material is likely to be classified as higher level waste in slurry form, and suitable scooping or vacuuming techniques may have to be employed to retrieve it. The acceptable maximum particulate size of this material has been discussed with the NRC, and an upper spent fuel fragment size of approximately 6 mm was proposed [5.29]. Spent fuel in fragment form is also a safeguards issue.

The debris and sediment removal operations would have to be done underwater, and the retrieved material would need to be collected in shielded vessels. Characterization of representative samples would determine the shielding thickness. Ion exchange resins and filter media from the AETP will be a source of medium to high activity, and these items may also have to be contained in shielded vessels. A decision will have to be made on the conditioning of this higher level and probably alpha bearing waste in accordance with the established national waste management strategy. Dewatering or treatment of this waste to a condition that is suitable for interim storage will have to be achieved.

Sellafield has produced a comprehensive catalogue on the expertise available on the management of plutonium contaminated materials. A large and comprehensive waste processing facility called the waste treatment complex was developed by 1994. This provided handling, compaction and encapsulation facilities for wastes of various types that could be encapsulated in drums. There is also a proposed plant to treat legacy waste from some pools [5.30]. More details are provided in Section 7.6.

Contaminated concrete rubble from surface scabbling operations will finally have to be retrieved in suitable baskets or containers. If this is done underwater, then using suitably perforated baskets allows the waste to be dewatered over the pool. The usual method of treating this waste is to encapsulate it in cement in a suitable container that would ideally be already licensed as a waste storage and transport package. However, other alternatives exist to satisfy transport and disposal regulations. Records need to be kept of all waste retrieved, and waste packages should have unique identification.

At the Trawsfynydd Magnox nuclear power plant decommissioning site, there are six ongoing and separate projects to recover waste streams. These streams are from fuel element debris, miscellaneous active components, concrete fragments from scabbling, retrieved sludge, miscellaneous active waste in vaults and resins from the pond, and other water cleanup operations [5.31]. The dry scabbled concrete is collected in drums for off-site disposal in shallow land burial.

5.6. EXPERIENCE IN POOL AND EQUIPMENT DECONTAMINATION

The decontamination and demolishment of the Hanford K east basins is a good illustration of how a major project with numerous technical challenges was accomplished, and this is described in Section 7. The final demolition experience was reported separately and is given in Section 6.5.

Because of the high radiation levels and the need for either shielding or remote application of the decontamination method, Hanford investigated for this project five technical approaches to remove or minimize the source terms from the floor and walls [5.6]:

— Chemical leaching;
— Dry scarification;
— Sand blasting;
— Engineered cover blocks;
— UHP hydrolasing.

UHP hydrolasing was selected as the preferred option. Further considerations were the recovery of underwater waste and the use of remote control devices (robotics). Mock-ups were built to test and verify the procedures. The lasing head was rotary with multiple cutting nozzles. A specialist company was engaged to develop the equipment further [5.19, 5.32].

Trials have been carried out at the contractors' works and then under actual conditions in the basins at Hanford. The equipment uses a special robotic arm with six degrees of freedom. The scrubbing and rotary blast head uses a water jet in the pressure range of 240–380 MPa. The cutting rate at 240 MPa was 45 m^2/h to remove 1.27 cm of concrete surface. This was expected to reduce the radiation dose by a factor of 10. The concrete chips and slurry were removed using a vacuum system and filters. Specially developed carbon fibre arms were provided to deploy the underwater cutting head. There were also underwater shredders and shears to deal with materials such as pipes and cables. The trials were all successfully completed and reported in 2005 [5.6].

Particular attention had to be given to an effective environmental compliance strategy for the entire basin decommissioning project. An environmental impact statement was needed. Establishing the safety issues, risk evaluation, compliance with all regulatory demands and meeting the approved action were significant priorities in obtaining regulatory approval [5.33]. The selection of technology for emission (release) control was based on assessment and evaluation of alternatives that result in a best achievable radiation control technology (e.g. the high efficiency particulate air filtration system was subjected to this type of evaluation). Lessons learned have been discussed and reported in some detail [5.34]:

(a) The fast track project resulted in inadequate attention to planning and estimating.
(b) There was much needed operational flexibility for testing and contingency.
(c) Pump fouling resulted from inadequate particle size clearance.
(d) Dilution and mobilization of sludge was more difficult than expected.
(e) Schedule recovery from delays owing to technical problems was effective.

In October 2004, it was reported from Hanford that there had been delays due to technical difficulties and the cost overrun had been approximately US $34 million since 2002 [5.35]. This was attributed by the DOE inspector to be because of inadequate planning during a critical phase. It was recommended that much more attention be given to planning for the remainder of the project. Further delays and increased costs are reported in Ref. [5.36].

A description of the project of emptying, decontaminating and eventually demolishing the 54 year old basins and the removal of a long standing hazard was published in 2008 [5.37].

A brief report from the Rancho Seco, a 913 MW nuclear power plant in the United States of America, indicated the desire to take advantage of attractive disposal prices and the decision to dispose of eleven fuel racks after characterization, removal, decontamination, packaging and transport [5.38]. The plant was shut down in 1989. Between 1999 and 2002, fuel was transferred to an ISFSI, and some dismantling was started in 1997.

A remotely operated excavator has also been used at the Dounreay site to work inside cells and a pond where human access is prohibited [5.39]. This is at a reprocessing facility, and an opening has been made in the walls to allow the device to be deployed on tracks. After almost 40 years of operation, the facility is still very contaminated, in spite of aggressive chemical cleaning. Internal components will be cut into small pieces for storage as intermediate level waste (ILW) in drums.

It was reported by SOGIN that cleaning of the spent fuel pool had started at the shutdown EUREX reprocessing plant at Saluggia, in Italy [5.40, 5.41]. The spent fuel from a number of other nuclear plants in Italy has now been removed from this pool. The pool was of concrete construction in three sections and was 5.5–7.5 m deep. The capacity was 675 m^3. The pool was double walled up to a level of 3.5 m with a cavity filled with sand that could be monitored. A contractor was engaged in 2006 to study alternatives for cleanup [5.42]. Subsequently, a contract was placed to undertake decontamination and dismantling after the fuel, fuel pins and plates had been removed to another storage facility (Avogadro storage pool) [5.43]. The feasibility study recommended underwater cleaning and decontamination.

Work started in 2006, and the loose crud was removed by suction and collected on filters. The crud was put in a removable collection vessel that was held underwater for filling. The walls and floor were next cleaned by a dual brush cleaning device. The pool water was to be discharged into a nearby river and had to undergo purification to permitted release levels. The water underwent electrocoagulation, ultrafiltration and final polishing using zeolite columns. Filter backwash was collected as sludge and solidified in a cement matrix. The surfaces of the pool were then sealed with paint and the facility was then left to await future demolition. Details of the equipment used to clean and decontaminate the pool were given at an international workshop at the IAEA in October 2007 [5.41] and at a waste management conference in 2009 [5.44]. More details of the decontamination and decommissioning activities were given at an international conference in 2008 [5.40]. The final conclusion of the project was reported in a European Nuclear Society news report in July 2008 [5.43].

Magnox have developed a range of tools and techniques that may be utilized to enable a flexible approach to be taken through active ponds across multiple sites (see Section I–9).

At Bradwell, the ponds were first cleared of furniture and residual sludge and debris. This was done using a Magnox developed mini digger modified for underwater operations and submersible pump and filtration units, including cyclone pumps. The ponds were decontaminated in parallel with draindown such that benefits could be taken for the shielding effect of the water. Decontamination took place using UHP water jetting, which was performed manually by workers operating from floating pontoons installed on the pond surface. Water clarity was maintained using electrocoagulation and vortex separation pumps. Sludge and waste by-products were consolidated in a bay at the centre of the pond, dewatered and the resultant concentrated waste was retrieved and separated using freeze plate technology. The ponds are now to be sealed with a polyurea sealant to enable managed storage and decay in line with the site life cycle model.

For disposal of fuel skips, Magnox have developed decontamination through milling. This method yields high decontamination factors for low material removal levels (see Section I–9).

Section II–21 describes lessons learned related to size reduction and waste generated during size reduction activities, and Section II–22 describes lessons learned related to storage of wastes.

5.7. WORKER PROTECTION

Decontamination of pool facilities can give rise to significant exposure to workers owing to the mobile nature of water and airborne contamination. Health physics records during operation at some nuclear power plants have shown that dose uptake in pool environments can be quite substantial for workers. This can apply equally to decommissioning conditions and environments, and worker protection is essential. Sections II–3 and II–8 illustrate lessons learned regarding preventing operator exposure to airborne contamination and potential problems during the use of personal protective equipment such as respirators and suits. Section II–11 also describes approaches to worker protection.

When all the spent fuel has been removed from a pool, the risk of direct radiation is reduced, but hazards from inhalation and ingestion still exist and can increase. Building ventilation systems need to be evaluated for efficacy, especially if they are degraded. Very often, temporary zones and contamination controlled areas with portable ventilation units need to be established because of the nature of work being undertaken. New facilities and monitoring equipment need to be provided, especially where there have been long delays after shutdown and most of the previous operating health physics systems and equipment have become redundant, obsolete or degraded beyond use.

The hazards associated with the decontamination phase will be significantly different from previous stages. Attention should be given to maintaining adequate worker protection, along with environmental control systems and procedures. Sometimes, provision of these can be difficult because of the degraded nature of the pool systems and structures. The integrity of all lifting and handling equipment needs to be confirmed. The buildings themselves may not provide the necessary containment for more hazardous retrieval, decontamination and waste management procedures. Pool areas were never designed as waste processing areas, and additional care and procedure need to be taken.

Industrial hazards should be also considered, such as working at heights, working above water and use of protective equipment. Section II–17 provides insights into ways to improve worker safety through a holistic review of worker tasks.

An example of a hazard during decontamination has been recorded (see Section II–15), including the administrative consequences. This was an incident that occurred at the West Valley nuclear site, in the United States of America, during the dismantling of fuel receiving and storage pool equipment. As a lifting rack was being raised above the water, an operator used a spray to remove some sediment. The spray was in the direction of the crane operator. An increase of airborne contamination was detected by three continuous air monitors, and some weeks later, some operators were found with detectable ^{137}Cs on whole body counts. There had also been a previous instance of spraying in air to remove sediment. The dose levels were not above the annual administrative dose limits. The operator, West Valley Nuclear Services, took the following actions in response to the incident:

— Strengthened hazard evaluation and monitoring;
— Used low pressure sprays only;
— Ensured all decontamination is done underwater;
— Used respiratory protection when the pool water is disturbed.

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6. DISMANTLING AND DEMOLITION

6.1. DISMANTLING AND DEMOLITION STRATEGY

This section deals with the final dismantling and demolition of pool facilities as illustrated in Fig. 6.1.

Activities associated with entombment or safe enclosure have to be discussed where an immediate dismantling strategy has not been selected. Where pools are an integral part of the reactor unit, as occurs with many research reactors and small facilities, then demolition may not be possible or feasible until the reactor itself is dismantled. In these cases, a safe enclosure strategy may be the most appropriate. Many reactors have primary pools, which are often integral with the reactor block, and secondary pools, where spent fuel is stored. Consideration will be needed in the strategy for decommissioning of the transfer routes. Pools will also have dispatch bays or facilities for handling transport casks for fuel removal.

Consideration should be given to the design of the pond and how it was constructed when defining the method and order for dismantling and demolition. Importantly, consideration should be given to the different approaches required for above and below ground structures. Below ground, there may be additional complications related to previous leakage to the ground, contaminated soil and structural access [6.1].

After the decontamination stage described above, and depending on its success, it will be important to undertake a thorough radiological survey of the facility as an input to determining the dismantling and demolition strategy. It is assumed, at the predemolition stage, that all pre-decommissioning operations have been completed and that the pool itself has been subjected to a determined level of decontamination that is consistent with the waste management strategy and ALARA principles. It is also assumed that the pool has been drained of water or is held with water that is ready to be discharged via an AETP.

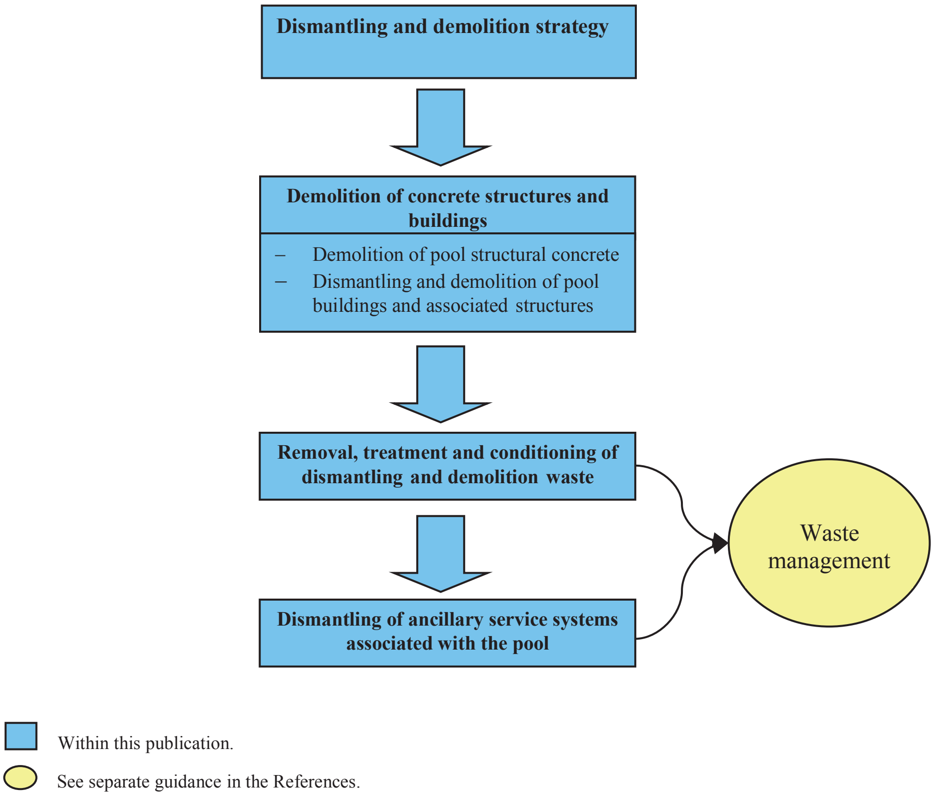

FIG. 6.1. Dismantling and demolition activities.

It is expected that, for most pools, the remaining specific activity will be low enough for classification as LLW or VLLW and that the bulk material will be predominantly unrestricted release material or at least suitable for shallow burial. Bulk monitoring will be needed to verify and record the activity in the waste material. If pool structures are still significantly contaminated above or near unrestricted release levels because further decontamination is not feasible or economic or does not meet ALARA principles, then alternative strategies of entombment or safe enclosure with appropriate care and maintenance may be adopted.

Planning for final dismantling and demolition will require safety and environmental assessment and will need regulatory approval. If an acceptable waste route is not available, then it would not seem sensible to create many thousands of cubic metres of contaminated rubble for interim storage or burial on-site. In this instance, delayed dismantling and demolition would be preferable to take advantage of radioactive decay.

Where leakage from pools during the operating life has been significant, which may be the case for pools with no secondary containment systems, then the remediation of soil is another consideration. This raises the difficult situation of determining how much soil remediation is necessary or environmentally acceptable and where the recovered contaminated material will be disposed of. It would not make sense to bury it elsewhere in uncontaminated ground. If it is to be stored in interim storage, then containment will be needed.

The potential reuse of the site or footprint of the pool is also a consideration. If a large site is expected to have numerous other structures under care and maintenance, such as the reactor block and waste and spent fuel storage facilities, then the site will remain a controlled area subject to surveillance and monitoring. The care and maintenance of a substantially decontaminated dry pool basin is unlikely to be a significant additional burden.

It is possible, however, that a decision to completely demolish a pool structure is taken for public relations reasons or that funds and resources are currently available and may not be in future. It is seen that decisions for final demolition of a pool structure need careful consideration and planning and need to be in accordance with an agreed strategy. If a pool is to be placed into care and maintenance, or entombment, the contents of the following sections (mainly Section 6.2) will not fully apply.

6.2. DEMOLITION OF CONCRETE STRUCTURES AND BUILDINGS

This is considered in two parts because it may be preferable to undertake some of the demolition before the containment provided by the pool building is lost, especially if residual contamination is expected beneath the pool lining or if dust is likely to be a problem. If it is possible to declare the whole pool facility to have contamination levels within unrestricted release levels, then conventional demolition may be permitted. This may be more common for pools that are lightly contaminated such as low power research reactors or where fuel failure has not occurred.

In demolishing a radioactive facility, a primary objective is to separate waste compatible for unrestricted release that can be recycled or disposed of at low cost by land burial at local or centralized and authorized locations. Some materials such as structural steel can have a value in recycling, but receptive markets need to be available to the project.

6.2.1. Demolition of pool structural concrete

Where pools have built-in steel linings, these may have to be removed as a special operation. Some linings are of stainless steel, and some may be of aluminium or other materials. It is assumed that plastic coatings or paint will have been removed during the decontamination phase. It is possible and likely that contamination has penetrated the steel lining, and removal will need to be conducted under radiological control or at least with appropriate monitoring. Fixings for linings are usually embedded, and removal with abrasive or flame cutting tools will be needed. There are some pools that have been lined with concrete blocks or ceramic tiles. Removal of lining material within the pool itself will allow size reduction and segmentation in a controlled environment. Monitoring will be needed prior to dispatch for further waste management.

Section I–1 describes experiences of the demolition of the superheated steam reactor spent fuel pool at Karlstein, in Germany. A good illustration of an excavator in operation is provided in Fig. 6.2.

FIG. 6.2. Demolition of the reactor pool at the Karlstein superheated steam reactor, Germany, using a remote excavator (courtesy of L. Valencia).

If the pool has no lining and the bulk residual contamination is within agreed limits, the structure may be released for conventional demolition (see Fig. 6.3).

The final demolition should be a dry process because a wet process may concentrate residual activity and increase soil contamination. However, water can be sprayed during demolition to keep airborne dust down (see Fig. 6.4).

Attention will have to be given to possible soil contamination when the subfoundations of the pool are being removed.

The interface of the pool with the reactor or other structures where this occurs should be considered to ensure that the demolition work does not affect or cause damage to any reactor structures or other related structures.

6.2.2. Dismantling and demolition of pool buildings and associated structures

Prior to the dismantling and demolition of the pool building and associated structures and systems, these should be surveyed to establish the extent of general contamination. It should be borne in mind that the pool building will have been subjected to a warm, moisture laden environment for most of the operating life and that corrosion is likely. Samples should be taken, as appropriate. Many pools are complex with multiple bay and lock gates, and may have fuel transfer channels communicating with the reactor. The effective isolation of these with the reactor will be necessary and will have to be maintained. Where interconnecting pipework has been isolated during previous phases, it will be necessary to confirm that dismantling does not affect these isolations.

An enclosed building is likely to have an active ventilation system that will also have to be monitored (see Section 6.6 for the dismantling of auxiliary service systems). Dismantling of the building can now be undertaken with appropriate monitoring and controls. This will involve removal and size reduction of large items such as pool overhead cranes for fuel skips, transport casks and other equipment. Where temporary containment structures have been provided, these can now be removed. Where building structures used asbestos containing materials, appropriate measures will be needed.

The Hanford K east basin was demolished and the rubble removed (see Fig. 6.5) in 2009. Reference [6.2] illustrates the highlights of the project.

FIG. 6.3. Demolition of FR-2 spent fuel pond, Germany (courtesy of L. Valencia).

6.3. REMOVAL, TREATMENT AND CONDITIONING OF DISMANTLING AND DEMOLITION WASTE

The waste arisings from dismantling and demolition activities will be large and could amount to thousands of cubic metres of steel and concrete rubble. The objective should be for this waste to be classified either for unrestricted release or as LLW suitable for shallow land burial. Ferrous material from the pool structure could be considered for recycling for reuse on-site or if there is external market demand.

At the stage of pool structure dismantling and demolition, there should not, ideally, be waste streams that will need special treatment (such as encapsulation) because management of the major waste streams will have been completed as part of the facility decontamination process described in Section 5. It is still possible, however, that some hot spots or undiscovered contamination will be found and some facility should be available for at least collection in waste containers. This should not mix with other waste because recontamination or cross-contamination of the dismantling material and demolition rubble should be avoided.

FIG. 6.4. Use of water as a dust suppressor during demolition of the 224-U facility, Hanford, United States of America (courtesy of US Department of Energy).

FIG. 6.5. Demolition of Hanford K east basin substructure, United States of America (courtesy of US Department of Energy).

If waste is to be transported to other locations for disposal or interim storage, then transport packages and transport regulations will need to be complied with.

If entombment or safe enclosure is selected, then it is still likely that parts of the building structure will be demolished to reduce the size of the residual structure and that waste quantities will arise. Some pools have been put into care and maintenance by filling with sand, sometimes mixed with weak grout and then covered with a concrete or similar low maintenance cover. The introduction of large quantities of presumably inert material into a contaminated facility will increase the waste volumes that will eventually need to be disposed of. The extent to which this additional material may become contaminated will eventually have to be realized. An example of this was the pool at a single pass reactor at Hanford where the contaminated pool was drained and filled with sand for an extended care and maintenance period and eventual removal of the contaminated sand contributed significantly to waste volume [6.3]. The work needed is described in more detail in Section 5.6.

There are cases, especially at large fuel cycle facility sites, where the pool environment remains substantially contaminated owing to leakage and also the site is unacceptably close to water courses or the sea or was the site of a major accident. In these cases, special measures and site remediation will have to be considered. An indeterminate quantity of waste may arise with the incumbent responsibility for disposal. There are examples at Hanford, Sellafield, Chernobyl and, to a much lesser extent, Trawsfynydd. Some details are given in Section 7.

In general, pools at nuclear power plants and research reactors are contaminated to a much lesser extent, although there have been some releases and environmental contamination. Most pool facilities are on a large nuclear power plant site where the final dismantling of the reactor will be deferred and residual pools can form part of an overall care and maintenance regime. Final demolishing of decontaminated pool structures and the arising waste volume will be minor relative to projects for the dismantling of the reactors. There have, however, been a number of small research reactors where the whole site has been cleared for unrestricted release and all waste was successfully shipped off-site.

6.4. DEMOLITION EQUIPMENT SELECTION

Provided that decontamination of the residual pool and structures has been successful and meets with regulatory and environmental approval, conventional demolition can be undertaken. Commercial contracts can be placed, but workers may still remain under appropriate surveillance and radiological control on what will remain a licensed nuclear site until clearance of all activity above an agreed level has been achieved and approved. Types of equipment may include:

- Excavators;
- Hydraulic and pneumatic jack hammers;
- Hydraulic jacks;
- Controlled explosive techniques;
- Diamond wire cutters;
- Circular saw cutters;
- UHP water jets;
- Thermal cutters;
- Hydraulic shears;
- Wrecking balls.

The selection of appropriate equipment and techniques may be governed by the local conditions surrounding and within the facility (e.g. local services and adjacent structures).

Demolition equipment is likely to be of the conventional type as supplied by demolition contractors. At the completion of the project, allowance will have to be made for monitoring and decontamination of equipment and tools before removal from the site.

6.5. EXPERIENCE IN POOL DISMANTLING AND DEMOLITION

In May 2008, it was reported that the K east basin at Hanford had been drained of over 3700 m^3 of contaminated water, which had been transported by 19 m^3 tanker trucks to the Hanford active effluent treatment facility [6.4]. Removal of the sludge and draining of this basin paved the way to final demolition. It had taken six years to remove all spent fuel and 300 t of debris.

After draining, it was reported that the basin cavity was filled with 3700 m^3 of sand mixed with grout to provide shielding from the residual activity [6.5]. In September 2008, work started on demolishing the K east basin superstructure and the upper walls down to ground level [6.6]. Work has continued around the clock. The superstructure contained large quantities of asbestos cement board, and this, together with the radioactive contamination risk and the decision to undertake outdoor demolition work, made compliance with environmental control regulations imperative [6.7]. Adequate preparation and planning had to be done. Sprayed fixatives were used when required. Weather conditions were a problem at times, owing to wind and high ambient temperatures.

Recovery of contaminated soil from beneath the basin aimed to reduce the risk of migration to the nearby Columbia River. Between October 2008 and September 2009, more than 2000 large containers were filled with contaminated excavated debris and sent to the Hanford LLW disposal facility [6.2, 6.8].

A lesson learned is that it should be expected that more contamination from previous pool leakage will be found as demolition takes place. This should be considered particularly when it is planned that sites are cleared for unrestricted release. An example of unexpected difficulties with concrete and soil contamination from pool leaks was at the Yankee Rowe nuclear power plant, in the United States of America. Yankee Rowe was shut down owing to reactor vessel safety issues in 1992 after around 31 years in operation [6.9]. Reactor decommissioning started in 1993 and was almost complete in 2001. Initially, it was expected that the spent fuel would be taken over by a federal ISFSI, but this did not happen, and on-site dry cask storage was eventually used in 2001. This opportunity finally freed the pool for demolition. It was initially thought that there were only a few centimetres of soil contamination; actually, significantly more soil had to be removed than anticipated.

Many lessons learned were reported and recorded by EPRI [6.10]. A particular problem was uncertainties associated with determining the amount of radioactivity associated with the concrete from the spent fuel pool and the surrounding soil. The decommissioning plan assumed 25% of the concrete would be contaminated and that many walls could be wiped clean. When decommissioning was started, it was necessary to assume that 50% of the soil and 75% of the concrete was contaminated above release levels. This resulted in significantly more soil being removed than expected. The increased volume resulting from the removal of extra concrete layers cost an additional US $1.4 million.

The DOE took an initiative to demonstrate innovative and improved decommissioning technologies through its large scale demonstration and deployment projects at Idaho [6.11]. This resulted in performance data being collected from a large number of projects. These included:

(a) Chicago Pile 5 research reactor: 22 remote technologies including for pool decontamination and structure removal;
(b) Hanford 105C reactor: 22 projects including complete removal of the fuel storage basin;
(c) Idaho fuel storage channels and underwater facilities: A two year programme to decommission underground and underwater decontaminated facilities.

It was concluded that the innovative technologies could be transferred to experienced decommissioning organizations that could immediately deploy the technologies.

In 1999, there was a workshop sponsored by EPRI in the United States of America on technology to characterize, model and remove embedded contaminated pipes and tanks [6.12]. This has been a common and difficult activity at many decommissioning sites. There was a good overview of the problem and available technology, and examples and experiences were presented from the Trojan project and Fort St. Vrain decommissioning project. Florida International University presented an integrated piping decontamination and characterization system, along with experiences of embedded pipe dose modelling, surveying and source measuring. The benefits of an embedded piping remediation project in providing substantial savings for decommissioning projects were reported by the NRC in a lessons learned report in 2007 [6.13]. The above applies to pool demolition because many embedded pipes are likely to be found in pool systems.

Another project was reported from the Hanford site. This was a reactor fuel storage basin demolition project that was reported in 2003 [6.3]. This was at the single pass reactor, which was shut down in 1970. It is now being put into interim safe storage and the basin (spent fuel pool) has been demolished. The basin had been used to store a mixture of wastes and debris and had been drained to a level of around 0.6 m and then backfilled with soil. The sediment and debris were very contaminated and contained 500 fuel baskets, 17 fuel elements and possibly fuel element fragments.

The demolition was implemented in two phases. The first phase was characterizing and removing the soil backfill and then removing the remaining highly active debris and base material. An outer wall was removed to give access to the basin. The second phase was executed in the following stages:

- Radiological mapping;
- Using a remote controlled excavator with lifting, cutting and shearing attachments;
- Characterizing the sludge and debris for disposal;
- Separating out the fuel elements and high dose rate items;
- Identifying the suspect fuel elements;
- Excavating, demolishing and backfilling the basin cavity.

Most of the radionuclide concentrations were ^{14}C, ^{137}Cs, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{63}Ni and small concentrations of fissile materials. A Geiger–Müller tube detector was used to make accurate dose measurements. A wireless remote monitor was used as an electronic dosimeter.

After each work shift, a soil layer was sprayed over the surface to minimize spread of contamination. Special training was needed for the operators, especially for using a remotely operated excavator. At approximately 95% completion, the dose uptake by operators amounted to 20 man mSv.

6.6. DISMANTLING OF AUXILIARY SERVICE SYSTEMS ASSOCIATED WITH THE POOL

Pool facilities have a number of services and systems that may be contaminated to a varying degree. There will be key timing decisions about when to dismantle these services and infrastructure. For example, the building crane may be useful for the removal of other items or systems and may need to be removed later in the schedule of activities.

The AETP will be the most contaminated facility, but has the potential to be flushed and cleaned by using the existing ion exchange (where fitted) and filtering equipment. A problem that may be encountered is the deposition of radioactive sediment in low sections of piping and in embedded piping. These are common problems in decommissioning piping systems, and solutions have been found. The proceedings were published of an embedded pipe decontamination technology workshop sponsored by EPRI [6.12].

The AETP plant will often be the last item to be taken out of service because it will be continually needed to allow water from other decontamination activities to be treated as the structures and miscellaneous equipment are dismantled. Where there is a centralized site water treatment plant, this can be taken advantage of. Temporary water treatment equipment can be used as a final cleanup system to allow all remaining water on the site to be released under permit.

The removal of active drains associated with a pool facility can present problems. If it is not feasible or practical to remove these for structural or other reasons, then they should at least be surveyed and flushed out as far as possible and sealed. Authorization may have to be sought to leave them in position.

Ventilation systems at a pool facility may be a potential problem because ducting is usually made of thin walled low carbon steel and is susceptible to corrosion, especially in a damp pool building environment. It is likely that airborne contamination will have collected in the ducts, and precautions would be needed when ducts are removed and size reduced (e.g. flattened). If ducting is significantly contaminated and degraded, then consideration should be given to replacement for decontamination and demolition activities. Sampling by swabs should be taken for analysis from all areas and systems to determine the extent of contamination. It is possible and probable that a number of items and components from pool systems will be classified as LLW and will need to be conditioned for interim storage or disposal. Large components such as heat exchangers and pumps may be difficult to decontaminate and may have to be disposed of intact after sealing. Smaller items are often encapsulated in a cement matrix if storage or disposal criteria require this, but sometimes it is sufficient to store or even transport and dispose of items in approved containment but without encapsulation.

The dismantling of services and systems associated with a pool should be carefully planned, especially regarding the sequence of dismantling and taking items out of service.

6.7. WORKER PROTECTION

Worker protection during demolition will still fall within the safety culture and practice on a decommissioning site and be subject to regulatory control. All workers would be subject to radiological health physics controls in force on the nuclear site. There will be an increased need to comply stringently with conventional health and safety regulations, and this should be normal practice on a demolition site. Decommissioning activities introduce a new range of worker activities that the building had not previously been designed for. Some of these may be non-routine in nature or are being undertaken for the first time.

Section II–16 describes lessons learned associated with minimizing worker dose exposure during waste size reduction activities following the dismantling of contaminated pond service systems. Section II–17 provides insights into ways of improving worker safety through a holistic review of worker tasks.

Where demolition contractors who may be unfamiliar with the nuclear environment are utilized, additional training and guidance will be necessary.

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7. DECOMMISSIONING EXPERIENCE

In this section, a number of experiences and selected topics have been included to illustrate the wide ranging activities that encompass pool decommissioning. Relevant examples of the main characteristics of pools that are part of reactor and non-reactor nuclear facilities were summarized in Table 2.1 and are given in a number of references, including Refs [7.1–7.20]. In addition, experience from national projects is included in Annex I and specific episodes and lessons learned are provided in Annex II.

7.1. EUROCHEMIC REPROCESSING PLANT, BELGIUM

The Eurochemic reprocessing plant decommissioning started in 1990 after completion of a pilot plant [7.17]. Two small structures used to store products from reprocessing were successfully demolished. The main plant building was large and complex, and contained over 100 cells. Contamination was significant, and large areas needed surface cleaning. There was a large open storage pool of 2000 m^3 capacity that was lined with concrete plates. The joints between plates were filled with bitumen.

The storage pool was mainly used as an overflow reservoir for other tanks on the site, and has accumulated low level beta and gamma wastes from various processes. In 1993, the sludge was removed for processing, and the inner surfaces were cleaned using a water spray. Preparation was later made for dismantling. It was necessary to remove concrete surfaces and material, which was done by planning and scabbling after the whole area had been tented. The removal of the bitumen layer between the inner brick walls and the outer prestressed concrete walls of the pond was accomplished with the help of an adapted milling cutter. The facility was then put in a non-operational standby position.

7.2. CHALK RIVER, CANADA

Atomic Energy of Canada Limited has reported that work has continued on the decommissioning of old structures on the Chalk River laboratory site [7.18]. An environmental assessment was approved in 2006 for the decommissioning of the NRX reactor fuel bays (A and B).

The regulator approved two work packages for the removal of water and the wooden structure over the bays. The A bays were cleaned as far as possible and were emptied in 2007. Decontamination work will continue. Sections of the B bays were filled with sand and other parts filled with water. NRX is currently in storage (i.e. a dormant state) with surveillance.

7.3. APSARA RESEARCH REACTOR, INDIA

In India, at the Bhabha Atomic Research Centre, a 1 MW(th) pool type research reactor called Apsara was built in 1956 and shut down in 2009 [7.19]. The reactor fuel and internals were removed, leaving the pool available for draining and decontamination. The pool was drained progressively while monitoring for hot spots. Additional material and debris at the bottom were removed. The lining was cleaned by water jetting using detergents. In summary, the defuelling and partial decommissioning were successfully completed in around six months, with a total dose consumption of 23.5 man mSv (approximately 10% of budget). The generation of waste amounted to a solid waste volume of around 20 m^3 (low level) and a liquid waste volume of 280 m^3 (low level).

A detailed description of achievements and plans for the Apsara decommissioning is given in Ref. [7.20].

7.4. VINČA SPENT FUEL STORAGE POND, SERBIA

The spent fuel storage pond at the Nuclear Facilities of Serbia, in Vinča, was built and commissioned within the RA research reactor complex in the late 1950s as a storage and cooling facility for irradiated fuel from that reactor. The pond is located near the reactor room inside the reactor building, and consists of five pools, each 6.5 m deep. One pool is dry and isolated from the other four. The four pools are interconnected by the transfer channel that also connects them directly to the reactor block.

RA reactor operated successfully for 25 years until it was taken out of operation in 1984. In 2002, after 18 years of an extended shutdown period, the Government of Serbia decided to permanently shut down the reactor and decommission the whole complex to uncontrolled free release level. Elaboration of the decommissioning plan, under the auspices and financial help of the IAEA took six years and was finished in 2009. It was decided to decommission the spent fuel storage pond first.

In parallel, post-operational activities at the spent fuel storage have been carried out. When spent nuclear fuel was removed from the storage pond by the end of 2010, work on pre-decommissioning activities had begun. Details of these activities are given in Section I–3 and in Refs [7.1, 7.21, 7.22].

7.5. VANDELLOS UNIT I, SPAIN

The Vandellos I 500 MW gas cooled reactor was shut down in 1989, and dismantling began in 1996 [7.23]. One of the first tasks was to start to decommission the pools by removing some of the internals and to plan for draining. The plan was to remove the graphite mud on the bottom of the pools while avoiding the creation of turbulence and obscuration. The method adopted was to remove large items and decontaminate them under a plastic covering and then to transfer them to another decontaminated pool. Water sprays would be used to reduce spread of contamination. The pool would be sealed with a thick concrete slab for an interim period.

Work started in 1996 with workers in masks and protective clothing. A significant rise in airborne contamination occurred sometime later. Airborne contamination continued to be a big problem requiring considerable changes in working practice and ventilation systems. Work on the pool lasted from 1999 to 2001, and then work continued to decontaminate the fuel pool building.

The building was finally dismantled and demolished in May 2002. The land has been restored for possible reuse on the site. The following amounts of waste were generated by the pool dismantling project:

— Material generated: 1219 t;
— Material released as clean waste: 1028 t (84%);
— Radioactive waste: 191 t (16%).

A report on the overall Vandellos project (see Fig. 7.1) was published by Enresa in 2003 [7.24] (see Section II–3 for more details).

7.6. SELLAFIELD, UNITED KINGDOM

Sellafield has six major storage pools, two of which have been taken out of operation and are currently going through the process of post-operational removal of inventory and materials prior to decommissioning and demolition. The scale and integrated nature of the Sellafield site offer a number of opportunities for waste disposal that are not available to standard reactor pools, but they also increase the complexity, owing to the proximity of other facilities and the large variety of inventories to be dealt with. The age, condition and inventories of the facilities being cleaned out, which are uncovered outdoor facilities, led to a cleanout programme lasting many years.

FIG. 7.1. Vandellos nuclear power plant, Spain, spent fuel pond almost dismantled (courtesy of Enresa).

7.6.1. Pile fuel storage pond

The pile fuel storage pond (PFSP) is the oldest pool on the site, and was built and commissioned between the late 1940s and early 1950s as a storage and cooling facility for irradiated fuel and isotopes from the two Windscale reactors. The plant operated successfully until it was taken out of full operation in 1962. It was then used for storage of miscellaneous intermediate level waste and fuel from the UK nuclear programme until the mid-1970s, when the plant and its inventory were placed into a passive care and maintenance regime. The decommissioning programme for this facility is described in detail in Section I–8.

7.6.2. First generation Magnox fuel storage pond

The FGMFSP was built and commissioned in 1959 for the receipt, storage and decanning of irradiated Magnox fuel, and took over fuel handling operations from the PFSP. Originally, the plant consisted of a single storage pool and associated facilities to import, decan and export fuel through a number of wet bays. The plant was extended several times over its lifetime to increase pool capacity and to accommodate different decanning methodologies.

Decanning operations ceased in 1988, when fuel processing moved to the new fuel handling plant, by which time, the plant had processed over 25 000 t of fuel. The legacy of this operating life has led to a plant with significant radiological challenges that need to be addressed as part of the programme to remove the inventory remaining in the pond which included the facility and which still contains large quantities of spent fuel, sludge (2000 m^3) and miscellaneous other materials (500 m^3) [7.25]. Initial estimates for the programme to remove the inventory from the plant, reported in 1997, indicated that it was expected that refurbishment would continue to 1999, then the walls and floors would be decontaminated, and the pond dewatered and repaired by 2002.

However, as the true complexity of the task became clear, delays were encountered, and in 2006, a report was published highlighting the difficulties in decontaminating and decommissioning the facilities [7.25]. It was acknowledged that, despite the facilities entering the cleanout phase in 1992 after receiving the last batch of fuel, no progress had been made in reducing the inventory. The decommissioning strategy was therefore revised to concentrate on a number of other priorities for the pool before full scale decontamination could be contemplated. These priorities included:

— Risk reduction;
— Contingency plans;
— Asset restoration;
— Preparation for retrieval and early remediation.

Between 1992 and 2006, significant effort had been expended in dealing with the first three points, including considerable refurbishment and refitting of old equipment and facilities. This addressed all services, design and refitting of the dispatch building, and refurbishment of the skip handling equipment. Replacing control and surveillance equipment was a particular challenge [7.26].

Risk reduction and contingency planning included emergency devices, securing possible leakage areas and providing new emergency pumping systems. There was also an extensive civil and structural assessment.

Since 2006, significant effort has been directed to progress sludge removal, fuel removal, redundant skip retrieval and removal of miscellaneous waste [7.27–7.29]. A key element of desludging and defuelling the pond includes the bringing back into service of the facility skip handling machine, which has been reported in some detail [7.30]. The significant radiological challenge associated with the pond has led the operator to develop a novel methodology for retrieving and handling the waste and maintaining the pond structure (typical examples are given in Refs [7.31, 7.32]). The scale of the challenge to clean the inventory from the pond will lead to a programme predicted to last over 24 years before the pond can be decontaminated.

7.7. MAGNOX REACTORS IN THE UNITED KINGDOM

There are ten Magnox sites in the United Kingdom, nine of which are shut down and are defuelling and decommissioning. The Wylfa facility, in Wales, was due to shut down in 2014 but has been delayed. Magnox ponds are reinforced poured concrete structures with an epoxy paint coating.

The decommissioning of Magnox ponds takes place once defuelling has been completed and is subject to an overarching fleet plan called the Magnox optimized decommissioning programme (MODP). The MODP has been determined to enable the most cost effective hazard reduction across the Magnox sites and to enable learning to be gained and transferred through delivering decommissioning as consistent programmes across all sites. For pond decommissioning, this involves the movement of experienced staff between sites to integrate with site teams and deliver the decommissioning of the ponds to a consistent methodology.

Magnox has a decommissioning and radioactive waste management strategy that indicates full decontamination and removal and backfill of ponds and reflects lessons being learned from work completed to establish the most practicable means of risk reduction for each site. A summary of current Magnox experience is given below. An up to date overview of pond programme experiences across the Magnox sites is available on the Magnox web site (see Section I–9 and Refs [7.32–7.36] for more details).

7.7.1. Berkeley nuclear power plant

This was the first Magnox power plant to shut down in 1989, and the two ponds were decommissioned by 2004. Details are given in Refs [7.37, 7.38]. The two adjacent ponds were within a building that also included a small pool for failed fuel, a long dry tunnel to each reactor for transfer of spent fuel, an active drain tank with pumps, an active ventilation system and a facility for loading spent fuel transport flasks.

Decontamination of the wall and floor surfaces was done using hydrolasing and dry scabbling. A remotely operated arm was deployed from above to remove the first few layers of contaminated concrete. The dry scabbling process was used to reduce large volumes of wet waste. Between 10 mm and 60 mm of surface material were removed in different areas. Corners were difficult to reach, resulting in the application of manual decontamination in these areas. The final activity level in concrete was less than 0.4 Bq/g, which is the unrestricted release level in the United Kingdom. The total collective personnel dose over the 17 month working period was 115 mSv.

Nine hundred and seventy 200 L drums were filled with contaminated concrete and placed in half height ISO containers for off-site disposal. The pond cavity was backfilled with rubble.

7.7.2. Bradwell nuclear power plant

The twin reactor Magnox nuclear power plant at Bradwell was shut down in 2002 after 40 years of operation, and was completely defuelled by October 2006. The pond presented one of the most challenging projects in the preparation for the care and maintenance phase of decommissioning [7.39, 7.40].

Hazard reduction has been achieved through removal of redundant plant, sludge and debris removal, decontamination of the pond walls using hydrolasing and drainage of the water. Experience has shown that hydrolasing is effective at decontamination of vertical surfaces, but less effective on horizontal surfaces where the cleaned surface is easily recontaminated by the liquid effluent. Hence, the pond floors have not been decontaminated, but have been sealed with a polyurea sealant to prevent paint degradation and remobilization of actinides.

Both proven and innovative techniques have been employed at Bradwell. The use of 'Videoray', a compact underwater explorer that was bought 'off the shelf', allowed identification of pond components that were not readily visible from the surface. Decontamination was performed manually by operators working on floating platforms (pontoons) on the pond surface, which is a system generally used in marine applications and identified originally at Hunterston for the pond decommissioning application. Residual wastes were collected in the centre bay by using Brokk machines fitted with squeegees and blades. Removal of the debris and sludge from the centre bay was performed using a freeze dredging technology, which is a system that is proven commercially in cleaning up sediments in waterways and chemical plants. A total inventory of approximately 21 TBq was removed.

The pond will be placed under institutional control during the care and maintenance phase and final decontamination and demolition will take place at site clearance with the reactor buildings. The residual activity will have decreased by over 70% in that time.

7.7.3. Chapelcross nuclear power plant

Although defuelling is ongoing at Chapelcross, use of the ponds ceased several years ago. Hence, pond decommissioning activities commenced in 2010. It is notable that the Chapelcross site has no active effluent treatment capability and that pondwater quality has been maintained through chemical dosing. Moreover, the ponds have been periodically drained during their operational life and the walls and floors cleaned and repaired as necessary.

Pond 1 has been drained and, owing to the history of pond cleaning, only light cleaning operations were necessary with discharges being filtered through a submersible filter unit.

Another notable feature of the Chapelcross ponds is the quantity of waste being stored in pond 2, including empty fuel skips, zeolite resins, sludge and waste activated components. A plan has been developed to coordinate waste retrieval and disposal with pond decommissioning activities. In addition, an active effluent treatment system is being developed to enable discharge requirements to be met prior to pond 2.

Following drainage, both ponds will enter a short period of quiescence, along with the rest of the site, before being fully decontaminated and removed to enable the site to enter its care and maintenance phase.

7.7.4. Hinkley Point A nuclear power plant

Bulk sludge removal has been completed at Hinkley Point A, and decontamination and drainage operations are under way on the two pond facilities linked to reactor 1 and reactor 2. It is notable that Hinkley Point disposed of their entire skip inventory into a 'beneficial reuse' process through a US smelting and recycling centre based at Oak Ridge, in the United States of America, thereby alleviating the pressure on the UK waste disposal sites (see Section I–9). These skips were blended with other active materials to produce shield blocks that are used elsewhere in the nuclear industry.

It was necessary to recover significant quantities of sludge from the Hinkley Point ponds; to simplify this process, the team developed a submersible mini digger from a standard off the shelf electric unit. This was done by replacing the drive systems with water carrying hydraulics. This mini digger enabled rapid consolidation of sludge into piles, which could then be removed through pumping.

A series of Dispatch Bay drainage trials commenced in January 2012. They enabled the pond characteristics to be determined and inform the selection of the decontamination methodology. It has been identified through these trials and associated modelling that a non-aggressive decontamination of reactor 2 pond is necessary and that an aggressive decontamination of reactor 1 pond is necessary.

Decontamination options for reactor 1 pond include hydrolasing (as used at Bradwell and Hunterston) or rotary disc ablation (as has been developed for sludge tanks at Hunterston). The advantage of the disc ablation system is that resultant waste can be vacuum collected from the workface.

Notably, the decontamination of the reactor 2 pond has been achieved through a high pressure wash, feeding the pressure washer with water from the pond.

7.7.5. Hunterston A nuclear power plant

The Hunterston pond is the largest single pond of any Magnox nuclear power plant. Pond drainage and decontamination commenced in December 2011 following skip disposal and bulk sludge removal activities. To enable drainage of the pond, an active effluent treatment system was installed.

The skips at Hunterston were unique in Magnox as they were constructed from aluminium. Decontamination was performed by pickling in nitric acid, and they were disposed of as low active waste. The nitric acid will be neutralized and used to generate grout for the encapsulation of other wastes. Sludge removal was performed using the same approach as proven at Bradwell and Hinkley Point.

The Hunterston pond is being decontaminated using hydrolasing during draindown, as has been performed at Bradwell. However, to maximize access to the pond walls, the entire surface of the pond has been covered with floating pontoons. This has also created a work area and eased space limitations in the pond facility.

Another notable development at Hunterston A is a rotary disc ablation and vacuum system that is being used for sludge tank decontamination. This dry system is being evaluated for use in decontamination of the Hinkley Point A reactor 1 pond.

7.7.6. Trawsfynydd nuclear power plant

At the Trawsfynydd nuclear power plant, defuelling was completed in August 1995. The pool has been drained and concrete surface removal is in hand. Before draining, the water chemistry was stabilized by chemical dosing to raise the pH to above 11. Caesium concentration was reduced using resin ion exchange units. The pool had to be kept above 19°C to minimize leakage from the construction joints. During the years of operation, the sludge was transferred to a separate sludge storage bay, and there was minimal sludge to remove during decontamination. The pond was finally drained in 1999 with the water discharged to the adjacent lake via an AETP. A radiometric survey of residual contamination in the walls and floor was carried out, and the walls were sealed with paint. No demolition of the structure has been done, owing to an inadequate ventilation system. This is being replaced to achieve acceptable airborne contamination levels [7.36, 7.41, 7.42].

It is notable that difficulties were experienced during decontamination of the construction joints and cracks in the pond owing to the degree of contaminant penetration. Moreover, there is known contamination in the land surrounding the pond and in the drains beneath the pond. Hence, a comprehensive characterization survey of the pond, the joints, the land below the pond and the drain system beneath the pond has been conducted. It has been identified that full remediation of all contamination will not be possible and nor is it beneficial because the surrounding land is contaminated to a greater degree. Hence, a safety and risk assessment is being conducted to identify an appropriate care and maintenance entry state that minimizes residual risks as far as is reasonably practicable.

7.7.7. Steam generating heavy water reactor, Winfrith

Current achievements of the first stage of decommissioning, the operation to decommissioning transition period, for the 100 MW(e) steam generating heavy water reactor have been reported up to 1995 [7.43] and in a progress report [7.44]. The decommissioning strategy adopted is one of deferral because the design is of the boiling water reactor (BWR) type that operated for 22 years, and some contamination of the secondary steam and turbo generator circuits has occurred. This is mainly ^{60}Co. Dismantling of the secondary systems will await the radioactive decay to reach tolerable levels. The dismantling of the primary containment will be deferred much longer owing to the high level activity. Stage 1 was planned to take six years and was considered in two parts:

(a) Preliminary operations undertaken for the first few months after shutdown, including defuelling;
(b) Extensive decontamination and preparation for a care and maintenance period.

By 1993, all spent fuel had been sent off-site to Sellafield, and there was no longer any need for pools. During the defuelling period between 1991 and 1992, considerable attention was given to the decontamination of large numbers of redundant fuel racks, transport containers and other removable items. Much of this material was decontaminated to clearance levels [7.45]. After all fuel had been dispatched, consultants were invited by competitive tendering to complete studies of the pool decommissioning options. There were complexities that were not easy to resolve.

There are essentially five pools (10 m deep each) for spent fuel, for use as a heat sink, and larger pools for pressure suppression and safety systems associated with the reactor. The reactor vessel and all pools are all part of an integral containment structure. A detailed video survey of the pools was carried out to reveal the extent of contamination, amount of sludge and the state of complex components.

Work to remove pool components and sludge started in 1995, and the pool wall decontamination was completed in 1996 within cost and schedule. Dosages to operators were only 25% of estimates. At one stage, divers were used to cut some underwater components. The project required approximately 24 000 worker hours. Approximately 40 t of LLW was removed. The success was attributed to good planning and a sound contract strategy. The achievements of this project are reported in Refs [7.46, 7.47]. Much of the decontamination was done underwater to reduce airborne particulates, and the dry ponds are now painted to seal the remaining small amounts of contamination. The pools are currently in a care and maintenance period.

7.7.8. Dounreay research establishment

A pre-decommissioning plan has been prepared for the decommissioning of the twin pools at Dounreay by Nuclear Decommissioning Services Limited, a nuclear consultancy service. As part of the preparations for pond decommissioning, a detailed radiological characterization was required. The ponds are mainly contaminated with caesium and strontium, and dose rates prevent normal working. A characterization tool to help with the ALARA application to optimize dose to workers has been developed by the Belgian Nuclear Research Centre (SCK•CEN) and is called the VISIPLAN 3D ALARA Planning Tool. A special user's workshop was given in Brussels by SCK•CEN to discuss and compare applications of the tool, and a specific application for the Dounreay pools was presented [7.48]. The requirement was to assess water, surface contamination, expected dose to workers and the activity collected on filters. Measurements were taken at a large number of locations, mainly at water surface level at the scum line. Confirmatory concrete sampling was also done, and a valuable working scenario was then developed.

It was reported in 2008 that the pools had been cleaned up [7.49]. The project was completed in 18 months using a team of 14 provided by four contractors with consultants. Working with respirators, workers emptied the pond of fuel racks and other equipment, filtered the water and then proceeded to cut out the stainless steel liner, remove some concrete and conduct a final radiological survey (see Fig. 7.2). The inner surface is now painted and a steel cover fitted.

Dounreay fast reactor pond workers in protective clothing scrubbed the sides of the redundant Dounreay fast reactor fuel pond using a high pressure water jet submerged below water level. Additional information about pool decommissioning projects at Dounreay is given in Refs [7.50, 7.51].

FIG. 7.2. Dounreay pond (D9814): Decontamination team at the end of cleanout, Dounreay, United Kingdom (courtesy of Dounreay Site Restoration Ltd).

7.8. HANFORD SITE REACTORS, UNITED STATES OF AMERICA

7.8.1. F basins

In 1965, the F reactor at Hanford was shut down. In 1970, the 6 m deep fuel storage basin was drained down to just 1 m of water to cover the empty fuel baskets, reactor hardware and other debris [7.52]. The basin was then filled with sand to cocoon the basin for nearly 30 years. In 1998, work started to cocoon the reactor itself, which meant removing the surrounding structures, including the fuel basin. In November 2002, the 5 m cover of upper sand was removed, monitoring equipment of various types was used to protect workers, and a remotely operated excavator was used to remove the sand. Eleven fuel elements were found in the lower 1 m depth, but more were expected. The elements were remotely handled into water filled containers. The remotely operated device was lowered into the basin and had four cameras to guide operation. There are nine similar reactors on the site, some of which have been cocooned.

7.8.2. K basins

Hanford's K east and K west reactors were built side by side in the early 1950s and operated until 1970–1971. Each of these reactors included a spent fuel storage basin (K east and K west), and are located approximately 400 m from the Columbia River. The basins, each with three bays, are covered by a superstructure, but were not environmentally controlled areas (i.e. doors opened directly to the outdoors). Each K basin is an open pool, approximately 22 m × 40 m × 7 m and filled with around 4500 m^3 of water to a depth of approximately 5 m. Prior to receiving fuel from the N reactor, the K west basin was drained, an 8 cm layer of sludge removed, and its floor and walls coated with epoxy paint. The K east basin was neither drained nor epoxy coated. In the 1970s, an appendage discharge chute leaked millions of litres of water into the ground. Leaks were sealed with grout. The east basin also suffered structural leaks, and was a priority for decommissioning.

In the 1990s, it was determined that K east basin had started to leak contaminated water into the ground, and the fuel rods stored in both basins had started to deteriorate, resulting in sludge (fuel corrosion particles, fuel rod fragments, metal fragments, sand and other materials) formation, which was easily resuspended. Removing the irradiated fuel rods and transporting them to the Hanford canister storage building began in 1994 and was completed in 2004 [7.53, 7.54].

Work on sludge removal started in October 2004, and both basins were cleared by January 2008. Details of the project are well documented [7.55, 7.56]. Reference [7.55] gives particular details of the difficulties and the equipment that was used or proposed. A suction system was used to transfer the sludge to large diameter containers. There was a proposal to stabilize the sludge and provide an assay and packaging centre constructed in an adjacent cold vacuum drying facility. Sludge was transferred from the east to the west basin and into consolidation containers to allow earlier decontamination of the east basin. A flexible twin walled pipe was used to transfer sludge some 800 m between the basins. Further information is given in Refs [7.57, 7.58]. The K east basin was then drained and liquid sent to an on-site treatment facility. The main contractor was Fluor Corporation, who had engaged up to 400 staff members. During operation, workers generally had to stand on gratings suspended over the water to undertake most in-pool operations.

One problem encountered was very active colloidal material left on the pool floors. When this was disturbed, it reduced visibility dramatically and hampered working. Fifteen candidate processes were evaluated for treating the sludge [7.55]. Some of the restrictions and constraints were hydrogen formation from corrosion, total volumes, availability of suitable drums, compliance with final disposal criteria and overall costs. The assessment resulted in the selection of an accelerated oxidation programme followed by cement grouting to produce a final waste form. Further work resulted in this process being abandoned [7.59]. Fissile content monitoring was important, and use was made of an image passive active neutron technique. Modelling and development work was needed to establish the final solution. Advantage was taken of the reuse of existing cleanup equipment and the avoidance of a large process installation by making equipment portable. The sludge was eventually consolidated in 200 L containers and stored in the central waste complex on the Hanford site [7.60, 7.61].

In September 2008, work started on demolishing the K east basin superstructure and the upper walls down to base level [7.62]. Work has continued nearly around the clock (two 10 h shifts per day). The superstructure contained large quantities of asbestos cement board, and this, together with the radioactive contamination risk and the decision to undertake outdoor demolition work, made compliance with environmental control regulations imperative. Adequate preparation and planning had to be done. Sprayed fixatives were used when required. Weather conditions were a problem at times due to wind and high ambient temperatures. Lessons learned included:

- — Fixative applications were effective;
- — Misting devices and water sprays were effective for dust control;
- — Demolition of the basin could be done with the superstructure in place;
- — Good planning was essential.

The treatment and demolition of the K east basin above surface structure was completed in 2009, and crews completed removing the below ground equipment and structures in 2011. The sludge removed from the K basins will be transported to facilities being installed inside Hanford's T plant, where it will be stored. Ultimately, this material will be treated and then packaged for disposal at the Waste Isolation Pilot Plant in New Mexico for permanent burial with other remotely handled transuranic waste from Hanford site cleanup [7.63]. Reference [7.64] describes in detail the application of the technology readiness assessment methodology to appraisal and selection of technologies for the K basin sludge treatment project.

7.8.3. N reactor

The N reactor operated from 1963 to 1987. When the reactor was shut down, over 4000 m^3 of contaminated water was left in the storage basins, along with approximately one third of Hanford's supply of irradiated fuel rods. The 105-N fuel storage basin provided for storage of spent fuel and consisted of a discharge pit, a view pit, a water tunnel, a fuel examination facility, two storage basins (north (6 m × 33 m × 3.3 m) and south (7.5 m × 33 m × 8 m)) of unlined reinforced concrete and cask pits (north and south). The basins were contained within a facility (i.e. not open to the outdoors). The facilities were constructed of reinforced concrete. The north basin floor was entirely covered and the south basin partially covered by a modular array of cubicles formed by borated concrete posts and borated concrete panels. The cubicles were used for storage of fuel canisters. Fuel canisters, fuel baskets and other contaminated hardware remained in the basin.

The basins held around 159 kg of spent nuclear fuel fragments scattered around the bottom, along with other equipment. The bottom was also covered with contaminated sediment ranging from a thin layer to of the order of a metre deep. The work was complicated because the basin's bottom design and murky water made it difficult to see what was underwater. Filters were installed in May 1997, which solved the problem.

Because of higher than initially anticipated basin wall radiation exposure rates, a 0.3 m concrete shield cover was placed over the top of the basin, before water removal began, to minimize dose to workers and control airborne radioactivity. Workers pumped the contaminated water out through a filtration system to tankers that transported it to an effluent treatment facility at Hanford for treatment. The irradiated fuel segments were placed in canisters and sent to the K basins and later moved to the canister storage building until a national repository can be built to accept them. The sediment was removed using slurry pumps to move it into containers, and was solidified with cement. The sludge containers were shipped for burial at the Hanford site. Deactivation, which included scrubbing of the bath tub ring with long handled tools and high pressure washing of basin surfaces, was completed in July 1998.

7.9. BIG ROCK POINT NUCLEAR POWER PLANT, UNITED STATES OF AMERICA

Big Rock Point has successfully employed a well planned and executed process to clean out the fuel pool in around 13 months, as reported by the site decommissioning project [7.65]. The success was also reported by the contractor [7.66] and in an independent publication [7.67].

The reactor was a 67 MW BWR, which was shut down in 1997. Full decommissioning and unrestricted use of the site were achieved in 2007. The contractors were familiar with the site as they had successfully cleaned up another pool on the site in 1996. When completed, approximately 4800 TBq of waste, consisting of channel assemblies, control blades, satellite rollers, in-core detectors and other miscellaneous components, had been removed and shipped for storage or disposal. The project was within the ALARA dose budget, within the project cost budget and schedule, with no reportable incidents.

7.10. TROJAN NUCLEAR POWER PLANT, UNITED STATES OF AMERICA

At the Trojan nuclear power plant, it was found that operation of the existing spent fuel pool cleanup systems after shutdown was costly during the period that the fuel was waiting to be sent to an ISFSI. The existing system was interlinked with other systems on the site. It was found to be less expensive to provide an independent cooling and cleanup service for the pool. This allowed other decommissioning activities to be continued. The EPRI report provides a guide to establishing an independent fuel pool auxiliary system [7.68]. This was needed for the period prior to transferring fuel to dry storage in an ISFSI. In June 2002, EPRI published another report summarizing the experience and changes that had been made at a number of plants in providing an independent spent fuel pool cooling and cleanup system [7.69].

A Swedish report was aimed to benchmark the decommissioning of Ringhals 2 nuclear power plant in Sweden against the Trojan project [7.70]. The following pool related highlights from Trojan experience were [7.70]:

“— ...The original plan was to use mechanical cutting techniques to separate the liner from the concrete pool foundation. Due to the large number of liner anchors that were embedded in the concrete, the actual execution of this work used cutting torches to separate the liner from the concrete foundation.

....

— A modular spent fuel pool cooling and demineralizer system was installed so that the main cooling systems could be deactivated and removed prior to moving the fuel from the pool.
— The piping into and out of the spent fuel pool was isolated and the throughwall penetrations on both the inside and outside of the pool walls were capped, thus preventing inadvertent cutting of pool piping that could have resulted in loss of water from the pool.”

7.11. FORD RESEACH REACTOR, UNITED STATES OF AMERICA

In June 2004, the University of Michigan published the decommissioning plan for the Ford nuclear reactor [7.71]. This was an open pool type reactor that operated at a power level of 2 MW(th). The reactor pool had a capacity of 200 m^3 of water and was lined with white ceramic tiles to protect the concrete and to ease decontamination. After analysis of options, the preferred approach was decontamination to a level that would allow termination of the reactor licence. The work would involve removal of all radioactive components and the decontamination of all surfaces and piping system. The reactor was not highly contaminated. In June 2006, the NRC approved the decommissioning plan and the project work began.

The original approved project budget was US $9.8 million. However, the impacts and changes noted in the following paragraph account for approximately US $4 million in additional costs. They have also included US $600 000 for contingencies, bringing the anticipated estimate for the project to US $14.4 million.

Two major activities have driven the cost above the estimated budget. Concrete removal of the old reactor pool walls and floor has been an integral part of the project in order to make the facility as usable as possible in the future. This process has involved cutting around 300 m^3 of high density concrete into manageable size blocks for shipping to the disposal site in Utah. The concrete cutting activities took substantially more effort than originally anticipated. The impact was primarily because of embedded components in the concrete. Other decommissioning activities were planned and scheduled around the anticipated cutting production rate and were, in turn, impacted by the slower rate [7.72].

7.12. UNIVERSITY OF VIRGINIA REACTORS, UNITED STATES OF AMERICA

There were two research reactors at the University of Virginia. CAVALIER operated at a maximum power of 100 W from 1974 to 1988. The other reactor (generally referred to as the UVA reactor) operated at a maximum power of 1 MW or 2 MW from 1960 to 1998. The water contained in the pool was utilized to provide shielding during the segmenting and removal of highly contaminated components in the pool. This work was performed by divers using plasma arc cutting equipment. A cask liner was first placed in the reactor pool. The higher activity items were preferentially loaded nearest the centre of the cask, and the lower activity items loaded in the liner annulus to provide shielding. Because air sampling performed during segmentation proved that no airborne contamination was produced, no confinement structure was necessary.

After shipment of the removed components, the remaining pool water was sampled and confirmed suitable for discharge to the sanitary sewer (through filters). Decontamination of the pool structures was performed using a water jet cutting process. Once the pool surfaces had been cleaned to bare concrete, surfaces were sampled for activation. The only activated concrete was detected radially around the beam tubes through the pool wall [7.73, 7.74].

7.13. AMES LABORATORY RESEARCH REACTOR, UNITED STATES OF AMERICA

One of the earliest decommissioning projects was the dismantling of the small research reactor at Richland, in the United States of America, completed in 1982 [7.75]. The pool was lined with stainless steel embedded in grout on the walls and floor. This was all cut away, and the pool was released as substantially clean. However, the site remained as a controlled area because of some low level contamination in the reactor building. The cost was given as US $4.3 million. The whole decommissioning project took from 1977 to 1981.

7.14. WEST VALLEY REPROCESSING PLANT, UNITED STATES OF AMERICA

A team of specialists involved in the decommissioning of the West Valley fuel reprocessing demonstration plant have been using divers to assist in removing equipment and decontaminating the fuel receiving and storage area [7.76]. This facility had operated for 30 years. The last of the 125 fuel assemblies were shipped in casks to the Idaho site in 2001. There are two adjacent pools, one for fuel storage and the other for cask loading.

A cross-functional team of experts developed the decommissioning plans, and mock-ups were used to identify potential problems. The first phase was to remove 149 fuel canisters. After trials, the canisters were removed within a month and decontaminated, as necessary, by water spray, coated to seal residual contamination and placed intact into 11 special storage boxes ready for shipment.

The next phase was to remove 11 rows of aluminium storage racks fixed to the pool floor, and divers were used for this. The dry diving suits were insulated against the cold water and had special precautions to minimize contamination of the workers and to reduce contamination pick-up on the suits. Underwater burning operations to remove some items caused a few problems with water clarity, but a filter system helped to minimize this.

During the next part of the decommissioning work, the pool was drained in phases as the pool sides were cleaned and coated to prevent airborne contamination [7.77]. The pool was initially drained 2 m while a strippable coating, and then a permanent coating, were applied. The pool water was treated with 1 μm filter cartridges and an ion exchange system to clean the water prior to release to on-site, outdoor ponds. The pool floors were vacuumed, and the sides were manually scrubbed (leaning over from the pool sides), and containers of waste materials were sealed underwater and removed. Long term plans for decommissioning are given in Refs [7.78, 7.79].

7.15. IDAHO NATIONAL LABORATORY, UNITED STATES OF AMERICA

After vast quantities of sludge had been successfully removed from three 1950s era basins at the INL site, it was decided to entomb the residual structures [7.80, 7.81]. Before this could be done, the task was to remove the 5000 m^3 of water. The residual water was characterized because it was suspected that some activity suspended during sludge removal might change the activity levels. The water was displaced by slowly introducing the grout. The decanted water was filtered as necessary and then pumped across the site to a large evaporation pond.

The grout mix for the basin was carefully chosen, and some mock-up tests were carried out. The volume of grout added to the basins was 5000 m^3, and was completed in around ten weeks. The whole project took approximately two years. The Idaho cleanup project at INL faced major challenges. The deactivation of three large pools (basins) and a reactor canal using commercial divers were reported in 2005 [7.82]. The four facilities were somewhat different:

— 2 900 000 L epoxy coated concrete basin;
— 447 000 L stainless steel lined test basin;
— 95 000 L unlined reactor canal;
— 43 500 L unlined concrete basin.

The three spent fuel pools were used at INL to develop and pioneer the coating process, and the resulting procedures are well documented [7.83, 7.84]. A total of 14 different (mainly epoxy based) coatings were evaluated to determine an acceptable product (see Fig. 7.3). The criteria used to evaluate coatings were:

— Ease of application;
— Adhesion;
— No effect on water chemistry;
— Non-hazardous;
— Proven in underwater applications.

Various problems and lessons learned are well recorded [7.83]. For the largest pool at INL, dose exposures to divers were well within limits, and the project was deemed highly successful. The cost was under budget at US $1.7 million.

At Dresden Unit 1, some evidence of leakage had been found, and it was decided to seal the concrete surfaces with an underwater applied coating that had been extensively developed by INL.

Extensive preparation had to be done before applying the underwater coating technique [7.85], and a survey and characterization of the pool were necessary [7.86]. The spent fuel had been removed previously, and the water could be cleaned in the adjacent pool operating systems as far as possible. Water cleanup was the biggest task.

FIG. 7.3. Underwater epoxy coating of the Materials Test Reactor pool at Idaho, United States of America (courtesy of R. Demmer, Idaho National Laboratory).

Divers were used to clean the bottom and wall and to apply the coating. A remotely operated underwater vehicle was used to map visually and radiologically areas that were not readily accessible. The whole project was a success. The number of worker hours and doses to operator were well below estimates. There were 281 dives, each around three hours long. The lessons learned were recorded.

7.16. OAK RIDGE RESEARCH REACTOR, UNITED STATES OF AMERICA

At the Oak Ridge research reactor, aluminium corrosion of the pool 6 mm liner was noted to be worst near areas where radioactive components were stored [7.87]. The pool operated from 1958 to 1987, when all spent fuel was removed, leaving only radioactive components. It was realized that penetration of the wall and release of contamination would seriously affect future decommissioning activities. The extent of corrosion was quantitatively assessed using a Fourier transform profilometry technique to give a three dimensional depth measurement. The material loss from the corrosion pit has been successfully evaluated. Thermodynamic modelling was also done to assess the chemical processes associated with the corrosion and to compare with measurements. The corrosion results given were between 5.6×10^{-4} mm/year and 8.2×10^{-4} mm/year.

7.17. SAVANNAH RIVER, UNITED STATES OF AMERICA

Two large reactor complexes, P and R (105-P and 105-R) at the Savannah River site, in the United States of America, underwent in situ decommissioning (ISD) [7.88]. The P and R reactors were operated for the production of nuclear weapon materials from 1953 to 1988. Each of these facilities have large spent fuel pools (disassembly basins) that are integral with the reactors, and each with a volume of around 4900 m^3 (see also Ref. [7.89]). The ISD work was completed during 2011.

The ISD concept for these reactors includes placement of grout that has been specifically formulated for use with these facilities to achieve a safe, cost effective closure. The grout has a high flowability, well controlled set and cure times, and high strength to allow the movement of heavy equipment during superstructure dismantlement and placement of a cap over the facility. The choice of this type of closure was dictated by a DOE strategy to use in situ closure and entombment of certain facilities where it offers a safer and more cost effective method. In particular, this project presents the advantages of permanently stabilizing the residual contaminants in the pools, is less costly and poses fewer worker risks than dismantling, transporting and disposing of these large, contaminated structures.

7.18. HUMBOLDT BAY NUCLEAR POWER PLANT, UNITED STATES OF AMERICA

When the Pacific Gas & Electric Company was planning the cleanup of the Humboldt Bay nuclear power plant spent fuel pool, a problem and dilemma arose concerning how small fragments of fuel should be classified [7.90]. This could be a problem for many nuclear power plant cleanup projects. Around 100 fragments in the range of 1–25 cm have been found, and more may be discovered. They are now stored in two fuel fragment containers placed in a dry storage cask. The bulk of the spent fuel is being prepared to be stored in five large containers. One container will be held back to take any more fragments that are found. There is no NRC regulation that specifically addresses these fuel fragments, although 10 CFR Part 74 [7.91] requires licensee control over all special nuclear material in spent fuel. For practical purposes, Humboldt Bay will only recognize anything above 6 mm in size to be spent fuel, while anything less than this will be disposed of as greater than class C waste. It is proposed to consider even larger fragments as waste in the future because of the logistics of placing the fuel into long term storage in the ISFSI. The NRC has said they will deal with fuel fragments on a case by case basis.

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8. KEY CONCLUSIONS

This publication addresses all phases of a decommissioning project for pools in nuclear facilities, ranging from strategy, preliminary characterization, planning and implementation, to final agreed end state. The publication also addresses design, construction and operational aspects that influence decommissioning. Proven and state of the art technologies are discussed. The evidence presented in this publication demonstrates that decommissioning of pools in nuclear facilities is achievable. Where conditions present in the facility complicate decommissioning, adoption of innovative methods and new technologies may be required. However, as the number of facilities being decommissioned rises, the knowledge and range of available tools and techniques to resolve these issues also increase.

All parties involved in planning and implementation of pools in nuclear facility decommissioning projects should consider the following within the domain of their roles and responsibilities.

8.1. STRATEGY

(a) A decommissioning strategy for the nuclear pool facility should be prepared early to provide a basis for initial decommissioning planning and other relevant arrangements.
(b) A strategy of doing nothing is not considered acceptable, and, where practicable, immediate dismantling is preferred.
(c) During preparation of the strategy, consideration is given to balancing various competing factors including:
- The ongoing hazard associated with the facility;
- The context within the site, other operations on the site and alignment with site end state objectives;
- Economic factors.

(d) The strategy sets out an overview of the work required in terms of:
- Planning and organizational requirements;
- Pre-decommissioning requirements, including, where appropriate, characterization, defuelling, removal of remaining inventory and establishing adequate conditions for the subsequent decommissioning phases;
- Decontamination objectives and requirements;
- Dismantling and demolition objectives and requirements;
- Clearly articulated interim states as well as a final end state, including any reuse options.

(e) Engagement with the regulatory bodies and other stakeholders throughout the project is undertaken, especially during strategy development.The strategy reflects a graded approach proportionate to the hazard and targeted end state.

8.2. PLANNING AND PREPARATORY ACTIVITIES

(a) A specific decommissioning plan is prepared to implement the strategy.
(b) Previous operating staff, if available, as well as records, should be used to help prepare the plan to make best use of available information.
(c) Available engineering information is reviewed to ensure it is adequate to underpin the plan, projects and safety assessment. Where necessary, identified gaps should be addressed.
(d) Available experience discussed within this publication and within the wider literature is used to help to inform and underpin decision making. Information and guidance from other organizations with relevant experience should be sought.
(e) Consideration should be given to the wide range of available technologies to support decommissioning activities, with preference being given to utilizing proven technologies.
(f) Within the plan, conventional safety hazards (including those associated with chemicals, asbestos removal, major dismantling and demolition work) should be considered, as well as radiological hazards.
(g) Consideration should be given to the sequence of waste removal and dewatering based on the pool inventory and conditions.

(h) Characterization activities should be comprehensive and address the pool, waste inventory and work area. Establishing and maintaining up to date characterization records is essential.
(i) The plan should include consideration of the management of sludge wastes that experience shows are problematic to characterize, handle and retrieve.
(j) Where sludge is present, consideration should be given to the use of techniques and technologies to maintain or restore pondwater visibility.
(k) Waste retrieval techniques need to be flexible enough to accommodate uncertainties or variations in waste properties.
(l) Waste retrieval, treatment and disposal techniques, decommissioning activities and safety assessment should be underpinned by characterization data.
(m) A comprehensive waste and materials management plan, including conditioning, packaging and interim storage facilities, recycling and reuse or disposal routes, should be established and be robust to uncertainties or variations in properties.
(n) Consideration should be given to verifying the adequacy of the pool infrastructure required to support decommissioning.
(o) Consideration should be given to the adequacy of the pool effluent treatment and discharge arrangements, which experience shows may be subject to sustained and increased challenges during decommissioning activities. Measures to manage airborne contamination and work area dose rates need to be considered during all pool decommissioning activities, particularly during decontamination.

8.3. EXECUTION AND IMPLEMENTATION

(a) An appropriate decommissioning organization with clear roles, responsibilities, accountabilities and authorities is to be established.
(b) Adequate training, induction and familiarization of staff and operators are essential because the skills and hazards associated with decommissioning are different from those encountered during operations. For example, pool decommissioning may considerably alter the radiological conditions as surfaces that had remained wet throughout operations become dry or exposed, and aerosols and active dust hazards may increase. New activities will be required that may be very different from those previously undertaken within the facility. These may introduce new reagents, new equipment and new conventional safety hazards that are more normally associated with construction and demolition, non-routine in nature and may present challenges to a workforce that are used to steady state operations.
(c) Consideration should be given to engaging specialist contractors and consultants for activities where the operator does not have in-house expertise.
(d) Retention of experienced staff with knowledge of the facility is valuable, and should be considered.
(e) Where contractors who may be unfamiliar with the nuclear environment are utilized, additional training and guidance should be provided. This may be particularly pertinent during demolition activities.
(f) Assumptions relating to the status of adjacent site facilities and services should be monitored throughout execution to ensure the plan remains valid. This is of key importance where the pool itself has been used to support decommissioning of other facilities or when decommissioning of the pool takes place after other site facilities. In these situations, services required to support the work may not be available.
(g) Careful monitoring of the AETP may be required as the challenge during decommissioning may be greater than during the pool's preceding operational phase.
(h) Arrangements should be made to review and update the strategy and plans as experience is gained and further characterization data are obtained throughout decommissioning activities. As an example, it may not be possible to assess activity penetration into pool walls until the water level is lowered.
(i) Any lessons learned should be captured and shared with others involved in similar activities.
(j) Estimates relating to the radiological and physical conditions for the work area should be reviewed throughout the execution phase to ensure the worker protection arrangements remain adequate.
(k) The decommissioning project should be formally closed when the agreed end state conditions are met.

Appendix

SPENT FUEL POOL DECOMMISSIONING AFTER A SEVERE ACCIDENT

A.1. INTRODUCTION

Most decommissioning related publications by the IAEA [A.1–A.4] and other organizations clearly specify that their scope applies to the decommissioning of nuclear facilities under planned conditions. It is generally specified that decommissioning of facilities that have been subject to a severe accident is excluded from the scope of these publications. This is because of the peculiar, and generally unpredictable, circumstances resulting from a severe accident, including, among others, high radiation and contamination fields, abnormal waste and unexpected configuration changes.

Based on the literature, there is no unique definition of a severe accident. All definitions include various consequence (damage) types (evacuees, injured persons, fatalities or costs) and a minimum level for each damage type. The differences between the definitions concern both the set of specific consequence types considered and the damage threshold.

For the purposes of this publication, the scope of this Appendix encompasses only facilities (spent fuel pools) that have been seriously contaminated and physically damaged to the point that planned routine decommissioning strategies and techniques are unusable or impractical.

It should be noted that there are three phases typically associated with a post-accident phase: stabilization, recovery and decommissioning. Stabilization refers to the immediate aftermath of a nuclear accident, and implies controlling of conditions so that impacts to the environment and public are controlled and minimized. Recovery entails the planning and implementation of activities to limit, and subsequently reduce, the extent of abnormal conditions, and prepare the plant for achievement of a longer term, safer configuration. Recovery can be viewed as a precursor to decommissioning. However, there is no clear-cut line between the three above mentioned phases. In fact, conditions generated by the accident and its evolution may initially be recognized, faced and dealt with during the stabilization and recovery phases, or later during decommissioning. For example, treatment of liquid waste initiated during the recovery phase may continue well into the decommissioning phase. It is only in planning for or implementing decommissioning, however, when access to structures, systems and components of the plant is re-established, that the full extent and actual or potential issues are identified and necessarily tackled.

This study uses the decommissioning of pools (in this case, spent fuel pools) as an example of decommissioning activities that, after a severe accident, have to be planned and implemented in a different way from planned shutdown. The study is mostly based on the recent Fukushima Daiichi accident, but relevant information is also extracted from other reactors that have undergone severe accidents.

A.2. DECOMMISSIONING OF POOLS

In general, it is possible that the impact of the Fukushima Daiichi accident on spent fuel pools may lead to a regulatory shift towards accelerated removal of spent fuel from pools to off-building dry stores. However, the advantages and disadvantages of such a policy change should be carefully considered. It is unclear whether the potential risk reduction due to lower amounts of decay heat and caesium in used fuel pools would offset the real increases in risks, occupational safety hazards, operational impacts and costs associated with a policy decision to transfer used nuclear fuel from storage pools at an accelerated rate [A.5, A.6].[3]

The Fukushima Daiichi accident, which involved nuclear power plant spent fuel pools, focused attention on problems associated with the decommissioning of these facilities. As a preliminary note, one major difference between the decommissioning of BWRs, such as Fukushima Daiichi, and pressurized water reactors is that BWRs are designed so that the spent fuel pool is located in the reactor building, rather than in a separate building that can

[3] See the Information Portal for the Fukushima Daichii Accident Analysis and Decommissioning Activities, at https://fdada.info/index.

be isolated from the rest of the facility. This eliminates the possibility of decontaminating and decommissioning the remainder of the facility while leaving the spent fuel pool building as a 'nuclear island'.

The decommissioning roadmap is split into three phases, the primary targets of which are: the removal of fuel from all four used fuel pools, the removal of melted fuel from the damaged reactor cores and the demolition of the reactor facilities.

The impact of the tsunami at Fukushima Daiichi caused the spent fuel pools of Units 1–4 to temporarily lose their cooling function, but the injection of coolant water using concrete pumping vehicles maintained the cooling of fuel in the spent fuel pools. By 10 August 2011, all spent fuel pools were switched from the water injection system, which functioned some five months after the accident, to a circulatory cooling system. For the first time since the Fukushima Daiichi accident, all four damaged reactors at the plant were using circulatory cooling systems with heat exchangers.

Cooling function needs to be maintained until fuel removal is complete, so the maintenance management of the equipment will continue, with equipment replacement as necessary, to maintain and improve reliability.

The need for desalination was because Tokyo Electric Power Company (TEPCO) injected sea water into the pools as an emergency measure for cooling the fuel during the accident. However, seawater chlorides may cause significant corrosion to fuel elements, and need to be removed as soon as possible. Desalination was accomplished through reverse osmosis and ion exchange, and the results of analysis of radioactive substance concentrations in the spent fuel pool water indicate that most of the fuel is in sound condition [A.7].

A.2.1. Plan of activities at Fukushima Daiichi

TEPCO, the Fukushima Daiichi operator, plans to remove all of the used fuel from the four pools within ten years, during which time it will determine what reprocessing or storage methods will be used to deal with the used fuel [A.8].

The upper parts of the reactor buildings for Units 1, 3 and 4 were damaged, and rubble was scattered over the refuelling deck and into the spent fuel pools. As a result, fuel removal needs to be preceded by the use of heavy equipment and fuel handling equipment to clear rubble from the fuel handling floor and the spent fuel pools. After that, the covers have to be installed to protect the fuel replacement areas and to maintain a working environment for fuel removal by blocking wind and rain. New fuel handling equipment has to be installed inside for the fuel removal work. The soundness of the fuel handling equipment in Unit 2 has not yet been fully checked because of the high dose rates within the reactor building. In future, the equipment will be inspected and repaired after decontamination makes it possible to approach the fuel handling equipment. The steel frame construction for the fuel removal cover at Unit 4 was installed in 2013 (see Fig. A.1) and all fuel assemblies were removed by December 2014.

The movement of undamaged fuel from the spent fuel pools to the common pool employs existing or newly constructed on-site transportation containers. If fuel is ascertained to be damaged, it will be placed in newly designed and manufactured storage drums; then, it will be placed in on-site transportation containers for movement so that it can be handled with the same level of safety as moving undamaged fuel.

Removal of fuel from the spent fuel pool differs between units in aspects such as fallen rubble, damage to buildings, equipment and fuel, and dosage levels, so periods required for preparation and movement will also differ. Therefore, the plan will consider the state and characteristics of each unit, and specific plans for later units will reflect knowledge and experience gained in earlier ones. Other than receiving the removed fuel, the common pool will be used in parallel for the inspection of existing dry casks, placement of fuel into dry casks and relocation preparations for receiving removed fuel and other diverse operations.

As with most reactor decommissioning projects, priority is given to the removal of used nuclear fuel because fuel removal is the single step that makes the biggest difference to the safety of the site as a whole. The plan for fuel removal from Fukushima Daiichi Units 1–4 is being considered and formulated to optimize the fuel removal process as a whole, with the focus on ensuring safety and removing fuel as early as possible.

Units where dose rates are high in working areas will have fuel handling equipment and on-site transportation containers capable of remote operation. In preparation for receipt of removed fuel into the common pool, the equipment will be inspected and restored, and dry cask temporary storage equipment will be installed. More than one year after that, fuel will be gradually moved from the common pool to the dry cask temporary storage equipment, to clear the space necessary for receiving the removed fuel. The newly installed fuel handling equipment

FIG. A.1. Steel frame construction for the fuel removal cover at Fukushima Daiichi Unit 4 (courtesy of TEPCO).

will be used to remove rubble from inside the pools, the fuel will be investigated and preparations will be made in the reactor buildings and the common pool.

Unit 4 nuclear fuel removal will be followed by Unit 3. The rubble will also be investigated, and then a specific plan for Unit 1 will be studied and formulated. For Unit 2, decontamination of the building interiors and use of shielding will be based on the establishment of remote decontamination technologies. Once it is possible to approach the fuel handling equipment, the equipment will be investigated, and then a specific plan for inspection, repair and fuel removal in Unit 2 will be studied and formulated. Fuel removal from Units 1 and 2 depends on the conditions on the site and other factors.

It was assumed, based on the envisaged future working environment, that removal of undamaged fuel in Unit 4 may employ the same equipment, working organization and procedures as in normal operation. If a normal environment can be produced in Unit 2, it would take around 18 months. If dose rates are high in Units 1 and 3, fuel removal by remote operation would use newly installed fuel handling equipment and transportation containers, necessitating detailed consideration in the future. The target is to take 2–3 years per unit. The working environment, the state of the fuel and other factors will be evaluated. Working organizations, procedures and times will be considered to formulate specific follow-on plans.

Other preparatory activities include[4]:

- A survey of the operating floors was conducted to help with the planning of fuel removal from spent fuel pools.
- At Unit 1, a camera attached to a balloon was used to take footage and to measure dose levels. A maximum dose of 53.6 mSv/h was measured at a distance of 1 m from the operating floor.
- At Unit 2, a remotely controlled robot was used to take footage and measure temperature, radiation and humidity levels. A maximum dose of 880 mSv/h was measured at the top of the reactor well.

[4] See the Information Portal for the Fukushima Daichii Accident Analysis and Decommissioning Activities, at https://fdada.info/index.

A.2.2. Possible issues

The following issues, which could affect the process, need to be solved to achieve fuel removal according to plan. The work will be implemented through collaboration and liaison between all those involved, with the highest priority on ensuring safety.

A.2.2.1. Rubble removal

Many aspects of rubble scattering and dosage levels have yet to be confirmed, and it is possible that the work could be prolonged or require additional tasks. This activity is not without risks, as the location of interfering debris is often unclear. Removal operations at spent fuel pools can cause uncontrolled changes to the location of such materials (e.g. unstable pieces of steel girder fell into the fuel pool during debris removal at Unit 3) [A.9]. Figure A.2 shows the removal of the steel beam that fell into the pool (when being lifted). TEPCO removed a large steel truss from the pool of Unit 3 in February 2013. The operation, during snowy weather, took 3 h and 20 min and was not without incident. Moving the twisted and partly submerged truss caused a bulky piece of debris, identified by TEPCO as the refuelling machine mast, to slip into the water. An investigation confirmed the movement of this 1.5 t item had made no difference to the pool's water level, chemistry or levels of radioactivity, indicating that it had done no damage. The truss itself also broke into two pieces in the middle of the job, causing a delay [A.10].

A.2.2.2. Installation of covers for fuel removal

The purpose of the structure is to protect the used fuel pool and the equipment used to remove fuel from the pool and package it. There are several uncertain factors, such as the condition of building damage, dosage levels and the condition of underground structures that obstruct foundation construction. Highlights of these activities for Unit 4 are given, for example, in Ref. [A.11].

FIG. A.2. Debris removal from the upper part of Unit 3 reactor building: Removal of the steel beam that fell into the pool (when being lifted) (courtesy of TEPCO).

A.2.2.3. Common pool restoration and removal of fuel from the common pool

Equipment is being checked for the restoration of the common pool, and it is possible that unanticipated faults could occur or be discovered, necessitating repairs.

A.2.2.4. Step by step handling up to the start of usage

Equipment related to fuel removal will be approved through a process with the steps from design to manufacture to installation to the start of operation, and the process will be created with the approval periods in mind.

A.2.2.5. Confirmation of fuel soundness

This process began by visual characterization as described in Ref. [A.12]. Preliminary results appear to show that no significant damage has occurred [A.13]. Effective confirmation methods and procedures will be devised with working efficiency in mind.

A.2.2.6. Removal of fuel from the pools

If the proportion of damaged fuel is higher than anticipated, or the degree of damage is more severe, it is possible that the work could be prolonged or require additional tasks. There is no experience of remote operation, and particularly of handling faults, inspection and repair, and the handling of physical distortion of fuel through remote operation. The aim will be to improve equipment reliability and safety and to decrease the length of time that the work takes. Equipment and working procedures will be improved to reflect knowledge and experience gained on the earlier units.

A.2.3. Research and development related to the handling of fuel

Fuel removed from the spent fuel pools will be stored in the common pool for the time being. At the same time, assessment of the long term soundness of fuel (taking the effects of sea water into account), related countermeasures and R&D on reprocessing will be implemented. Future processing and storage methods for spent fuel removed from the spent fuel pools will be decided on the basis of assessment of its long term soundness and the results of R&D into its reprocessing.

Another development was prompted by the NRC as part of the post-Fukushima reassessment of US nuclear power plant safety. The NRC now requires the plants to install enhanced equipment for monitoring water levels in each plant's spent fuel pool.

The spent fuel pool level instrumentation at US nuclear power plants is typically a narrow range, and is therefore only capable of monitoring normal and slightly off-normal conditions. Although the likelihood of a catastrophic event affecting nuclear power plants and the associated spent fuel pools in the United States of America remains very low, beyond design basis external events could challenge the ability of existing instrumentation to provide emergency responders with reliable information on the condition of spent fuel pools. Reliable and available indications are essential to ensure plant personnel can effectively prioritize emergency actions. Spent fuel pool level monitoring helps prevent exposure and overheating of spent nuclear fuel rods that could lead to the spread of radioactive debris during accident conditions.

The NRC has determined that the spent fuel pool instrumentation required by a newly issued order represents a significant enhancement to the protection of public health and safety and is an appropriate response to the insights from the Fukushima Daiichi accident [A.14]. A US company recently offered new products as an ideal solution for the recent NRC requirement that reliable spent fuel pool monitoring equipment be installed in all 104 US commercial nuclear power plants [A.15, A.16].

A.3. TECHNOLOGIES FOR SPENT FUEL POOL DECOMMISSIONING AFTER A SEVERE ACCIDENT

The most critical issues remain associated with the retrieval of fuel fragments, contaminated debris and sludge, not unlike those experienced at Sellafield. See the main text of this publication for more information. With regard to Sellafield and other UK pond facilities, an ongoing R&D project is described in Ref. [A.17].

One recent development from Chernobyl's Interdisciplinary Scientific and Technical Centre (ISTC) 'shelter' is described below. This includes technology to remove transuranic elements from silt of radioactive storage ponds under ISTC Project 330. Efficient technologies and equipment for pumping silt from ponds and classification and decontamination of the waste solution have been developed by ISTC. Intensive laboratory studies were carried out to optimize the leaching of long lived radionuclides from the pond silt.[5]

The water within spent fuel pools facilities is often heavily contaminated with radionuclides, in dissolved or suspended form, originating from corroded (and possibly molten in an accident scenario) spent fuel assemblies. During the cleanout phase of the decommissioning work, it is necessary to characterize and identify components and materials stored in the pool prior to their removal. The need can be more acute in a post-decommissioning scenario owing to the unknown chemistry of such materials. One way of achieving this is to obtain physical samples of each component or material so that a laboratory analysis may be carried out. Removal of material from the water can expose personnel to nuclear radiation and may also increase the risk of contamination spread. Furthermore, physical sampling followed by laboratory analysis is a very time consuming and hence costly process. Characterization of the component or material while it is submerged (i.e. in situ characterization) could offer significant advantages in terms of safety, speed and overall cost reductions. This is an active R&D field, and some example technologies are described in the following.

A special version of a fibre optic probe laser induced breakdown spectroscopy (LIBS) instrument that incorporates a submersible remote probe is able to identify the elemental composition of materials submerged in water up to around 10 m. The probe operates by ejecting a small amount of gas (air or preferably argon) through the nozzle aperture of the probe. When the probe is in contact with the component under investigation, the water is displaced from the optical path of the laser beam by the gas flow, thus allowing LIBS analysis of the material to be conducted in a gas medium rather than a liquid medium [A.18].

A variety of underwater radiometric characterization methods have been identified in Ref. [A.19], which provides plant operators with the ability to determine the fissile content and radionuclide composition of diverse sludge compositions.

Materials with a wide range of gamma activity can be characterized in situ in legacy pools and silos without the need to procure complex neutron based detection equipment in downstream processing facilities. These methods also offer technical advantages over the neutron drum assay approach in that matrix related 'dead zones' (owing to the neutron moderating and absorbing effects of hydrogen present in sludge) are avoided, thus eliminating reliance on the uniform source distribution assumption that often underpins neutron based drum assay. Methods suitable for underwater surveying of sludge include:

- High resolution gamma spectrometry;
- Low resolution gamma spectrometry;
- Intermediate resolution gamma spectrometry;
- Dose rate measurements;
- Neutron measurements;
- Monte Carlo N particle modelling.

In addition to assaying fully corroded sludge, the method allows measurements on underwater pieces of spent fuel ranging in size from small particles through to whole fuel elements. An optimal system design has been identified that, together with appropriate operational procedures, has been specified to provide an acceptable level of confidence in the characterization of residual sludge content of legacy wet storage facilities. This technology can allow decommissioning teams to safely and efficiently retrieve and repackage spent nuclear fuel sludge and other debris waste.

[5] See the Symposium on the Application and R&D of the Technologies of Decontamination, Remediation and Restoration of Environments, Tokyo, 3 February 2012.

The fuel pool of Fukushima Daiichi Unit 4 was inspected by an underwater robot as an early step in the programme of work to remove the used nuclear fuel from the building [A.20]. TEPCO sent a small camera equipped robot made by GE Hitachi Nuclear Energy through the depths of the 11.5 m deep pool. A comprehensive overview of robotic developments based on concrete experience in decommissioning is given, for example, in Ref. [A.21]. Figure A.3 is an example of robotic characterization work at Fukushima Daiichi. Underwater applications of robots in the context of nuclear decommissioning are of specific interest. This is particularly relevant to spent fuel pool decommissioning (see Fig. A.4). One such line of research is described in Ref. [A.22].

FIG. A.3. Robotic characterization work at Fukushima Daiichi (courtesy of TEPCO).

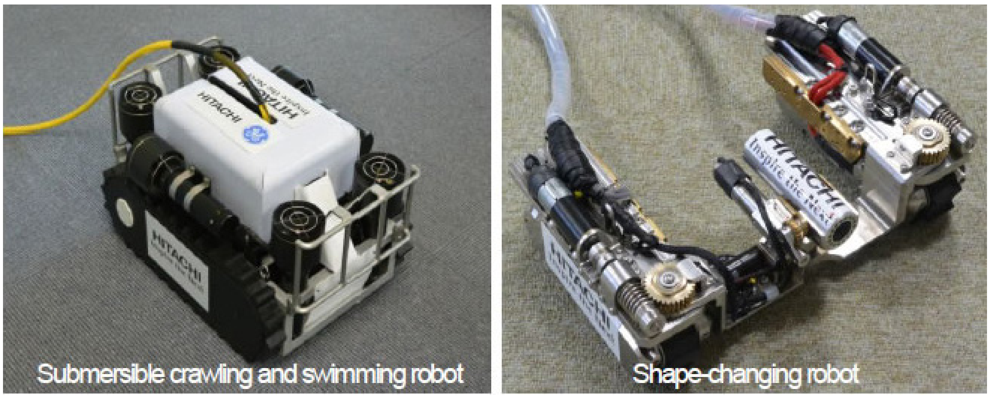

FIG. A.4. Type of remotely operated vehicles to be used at Fukushima Daiichi (courtesy of TEPCO).

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Annex I

EXPERIENCE FROM NATIONAL PROJECTS

The examples provided in Annex I cover the organization of decommissioning and detailed technical aspects in both large and small facilities. The descriptions should be useful to provide practical guidance on how pool decommissioning projects are planned and managed in various States. The examples given are not necessarily best practices. Rather, they reflect a wide variety of national and corporate legislation and policies, social and economic conditions, nuclear programmes and traditions. Although the information presented is not intended to be exhaustive, readers are encouraged to evaluate the applicability of the sections below to a specific decommissioning project. These national sections reflect the experience and views of their contributors and, although generally consistent with the main text, are not intended as specific guidance.

I–1. DEMOLITION OF THE KARLSTEIN SUPERHEATED STEAM REACTOR SPENT FUEL POOL, GERMANY

The Karlstein superheated steam reactor started operation in October 1969 (see Fig. I–1). A number of failures in the fuel elements, associated with a concept design problem, resulted in final shutdown in April 1971. The reactor was then used as a test bed for reactor safety experiments from 1974 until the end of 1991. The spectrum of experiments simulating accidents under design and beyond design conditions included simulation of aeroplane crashes, earthquake experiments, material parameter studies, loss of coolant accidents (LOCAs), hydrogen distribution, hydrogen deflagration and burning experiments.

The reactor was a boiling water reactor (BWR) with a thermal power of 100 MW. Superheated steam at a temperature of 460°C was generated by means of core internal superheating, at a pressure of 7.4 MPa. The steam was then supplied to the 25 MW turbine of the adjacent coal fired power plant Dettingen, which was located on the same site. A station was provided on-site for the reduction of the steam parameters to those required by the turbine, and therefore a machine hall was not required.

FIG. I–1. Superheated steam reactor at Karlstein, Germany.

Because of the short operating period of the reactor, the activity inventory and the ambient dose rates encountered in the controlled area prior to the start of dismantling were rather small. However, hot spots associated with fuel remnants were detected in an inaccessible part of the spent fuel pool sump (see Fig. I–2). The activity inventory of the activated components, consisting of the reactor pressure vessel (RPV), the biological shield and the steel linings in the refuelling water system near the reactor, was approximately 1.6×10^{10} Bq (without resins), while the activity inventory resulting from contamination amounted to approximately 6.5×10^{9} Bq. The ambient dose rate at the inner surface of the activated RPV was around 70 μSv/h (in 1994), and so personnel access to all rooms and plant sections was possible without additional shielding.

The relatively small activity of the RPV was found to be below the threshold value of 200 Bq/g for the declaration of steel for controlled reuse. Hence, material from the RPV, which was dismantled using a propane cutting system, could be transferred to controlled reuse by melting. Dismantling of the RPV (see Fig. I–3) was carried out in situ with subsequent disassembly into pieces suitable for drum storage in ‘melting drums’ of 180 L in volume (T180 drums) in the former fuel element storage pool (see Fig. I–4). After melting, the RPV sections were transferred to controlled reuse.

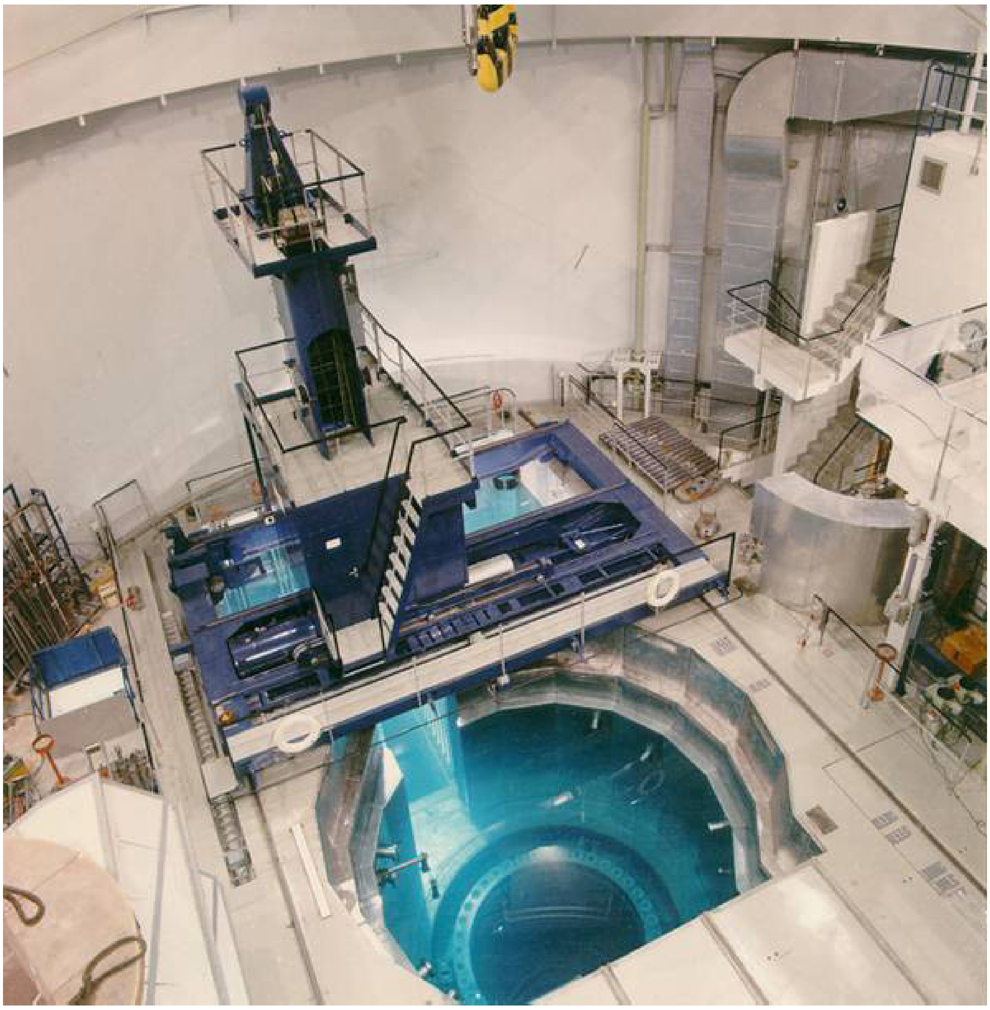


FIG. I–2. View into the Karlstein superheated steam reactor and reactor pool.

FIG. I–3. Segmentation of the reactor pressure vessel with a propane torch.

FIG. I–4. Final cutting of the reactor pressure vessel in pieces ready for melting.

The inner containment walls were exposed to considerable wear by the water jet and steam deposition in the impact range of the ‘blowdown’ flows during the LOCA experiments, and in certain locations, significant erosion damage to the walls was evident. Burning tests caused soot traces to be left in the building, and these were very difficult to remove. Contamination penetrated into the surface cracks of the concrete structures, which had been generated by earthquake experiments. The widespread contamination encountered was relatively low, but had to be removed when it exceeded the surface specific limit value of 0.475 Bq/cm^2 for ^{137}Cs required for free release.

After the removal of all containment systems, dismantling of the activated concrete structure associated with the biological shield took place using the controlled explosion technique. The remaining contamination was removed in the controlled areas and the floor surface was sliced off. All surfaces, except for the annular gap, were subjected to clearance measurements, and confirmation that the material met the licensed clearance limits was given by experts of the independent technical board. Figure I–5 shows the reactor pool area after removal of the stainless steel liner and clearance measurements.

FIG. I–5. View into the reactor pool after liner removal and clearance measurements.

Following the removal of the activated concrete structures, decontamination of all accessible concrete surfaces in the reactor building took place. The clearance measurements were confirmed by the independent expert board using in situ gamma scanning, material sampling and direct measurements with portable monitors. Then, a partial release of all accessible areas (except for the inaccessible annular gap) was issued by the competent authority.

The potential contamination of the annular gap, caused by the condensate produced during the LOCA experiments, required decontamination of the entire concrete structure with subsequent clearance measurements of the front and the rear sides. Therefore, release to conventional demolition was not possible on the standing structures. Consequently, the following procedure was required:

(a) Progressive demolition of the concrete structures such that the concrete wall adjacent to the steel shell remained standing. Removal and transfer of the material to storage on the adjacent free premises prior to sorting and segregation and subsequent reuse within the framework of conventional demolition.
(b) Progressive demolition of the remaining wall structure into around 30 individual segments per level. The segments were brought into a horizontal position so that the contaminated rear surface became accessible. Decontamination, if necessary, clearance measurements of the segments, as well as control measurements on specified individual segments, were performed by the independent technical board (see Fig. I–6(a–d)). Within the above mentioned demolition procedure, the hot spot in the sump, discussed earlier, was cut out (see Fig. I–7) and sent for further treatment to the central waste treatment facility of the Karlsruhe Research Centre.
(c) Installation of scaffolding near the steel shell and decontamination of the steel shell, including the reactor hall crane and clearance measurements.
(d) Declassification of the controlled area inside the containment.
(e) Closing and sealing of the containment until release of the entire plant from regulatory control.

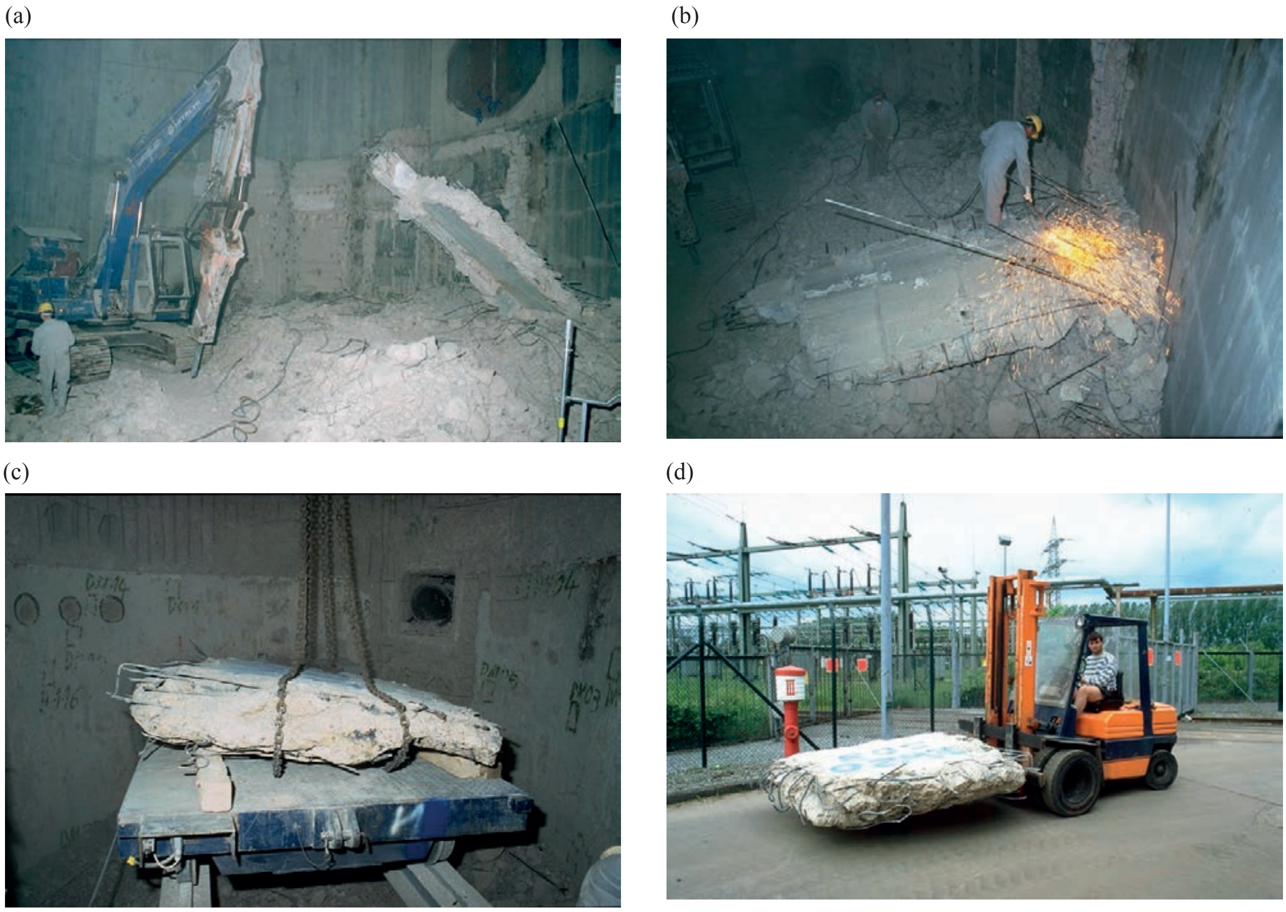


FIG. I–6. Demolition of the outer concrete wall structures and clearance of segments.

FIG. I–7. Sump of the Karlstein superheated steam reactor pool containing hot spots with fuel remnants.

The concrete separation and demolition was accomplished by means of diamond rope saws, concrete mills, concrete core drills and soft pyrotechnical explosions. Rebar and reinforcing steel structures were cut using thermal cutters or clippers. For the removal of contaminated layers, pneumatic hammers, scabblers and impact needles were used.

To minimize the possible emission of radioactive aerosols, mobile, backflushed high efficiency particulate air (HEPA) filter units were used in to addition to continuous aerosol control in the dismantling using mobile aerosol monitors with alarm indicators.

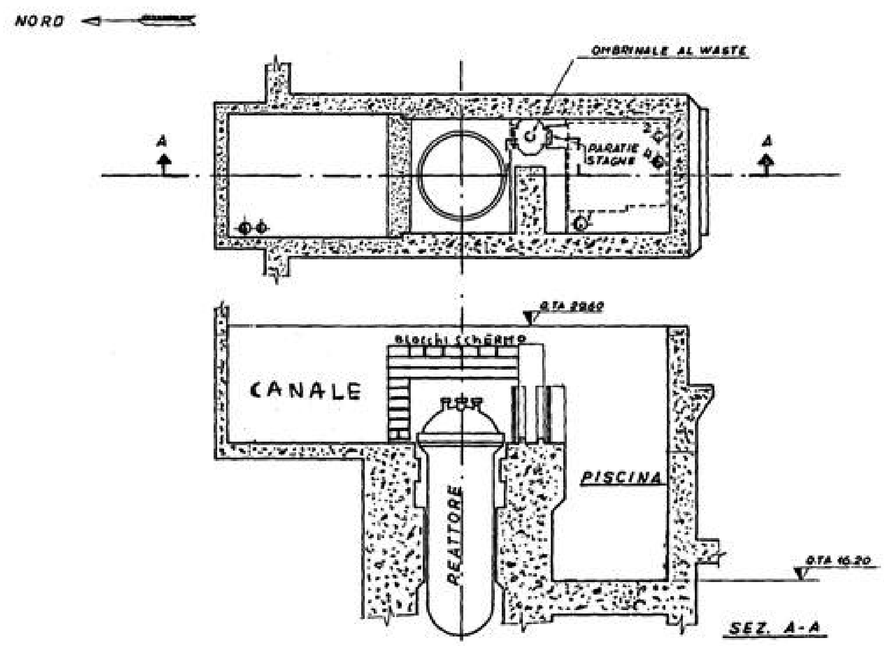
I–2. GARIGLIANO NUCLEAR POWER PLANT, ITALY: DECONTAMINATION AND REARRANGING OF REACTOR CANAL AND SPENT FUEL POOL

I–2.1. Work plan

Garigliano nuclear power plant was a 506 MW(th), first generation, dual cycle BWR. It started operation in 1964 and finally shut down in 1978, following the discovery of serious damage to a secondary steam generator [I–1]. This section describes decontamination activities carried out in 1991–1993 in preparation for safe enclosure of Garigliano reactor building.[1] Activities were carried out after completion of spent fuel transport off-site (1985–1987). A schematic of the spent fuel pool and adjacent areas is provided in Fig. I–8.

Decontamination activities included the following:

(a) Agitation and resuspension of pool sediments using water jets and water filtration.
(b) Lowering of water level and parallel decontamination of pool walls with high pressure water jets of approximately 700 kg/cm^2.
(c) Removal, decontamination and interim storage on gangways of equipment located on the pool south-east wall.
(d) Removal, decontamination and storage of the fuel transport container platform.
(e) Removal of four fuel racks to their pool wall bearings, decontamination and transfer to the fresh fuel room.



Note: Blocchi schermo — shielding blocks; canale — (reactor) canal; nord — north; ombrinale al waste — scupper to waste; paratie stagne — watertight bulkheads; piscina — (spent fuel) pool; reattore — reactor.

FIG. I–8. Schematic of the spent fuel pool, reactor and reactor canal (courtesy of ENEL).

[1] Initially, the decommissioning strategy selected for Italian nuclear power plants was safe enclosure and deferred dismantling. Later, the strategy was turned into immediate dismantling.

(f) Decontamination of the vessel head platform, removal from the reactor canal, brushing and coating to allow preservation and fixing of loose contamination. Eventually, this component was placed back in the reactor canal.
(g) Construction in the reactor canal of an interim structure supporting fuel racks. At the completion of the work, this structure was dismounted, decontaminated and removed.
(h) Removal of fuel racks (five at a time) to their pool wall bearings, decontamination and interim storage in the reactor canal.
(i) Gradual lowering of the pool water level to some 50 cm from the pool floor and parallel decontamination of fixed structures and walls.
(j) Discovery by visual inspection and radiological checks, of activated components on the floor of the pool (see Table I–1). Retrieval of all this material, segmentation as needed, temporary storage in containers and later transfer to the high activity store on-site.
(k) Removal of sludge and crud from the pool floor and final decontamination where the material had a thickness of a few centimetres. This removal was effected with a combination of:
— Vacuum cleaners;
— Centrifugal pumps following agitation with water jets;
— Manual tools.

TABLE I–1. ACTIVATED COMPONENTS REMOVED FROM POOL FLOOR

Component/item (No. of pieces)	Temporary storage prior to conditioning	Activity refers to Co-60 (GBq)
In-core guide tube (1)	In container CRSC	2220
Springs (100)	In container CRSC	370
Bolts and washers (50)	In container CRSC	18.5
Steel nuts (10)	In container CRSC	11.1
In-core guide tube coupling box (1)	In container CRSC	148
Springs (70)	Shielded container of volume 50 L	259
Bolts, washers, miscellaneous items (30)	Shielded container of volume 50 L	81.4
Vacuum cleaner filter (1) and miscellaneous steel items	Shielded container of volume 200 L	37
Sludge and crud, and small activated materials	Shielded container of volume 200 L	185
Total		3330

Note: CRSC — Centro Regionale Siti Contaminati (Regional Centre for Contaminated Site).

All liquids and sludge were transferred to the nuclear power plant radwaste system (see Tables I–2 and I–3). It should be noted that the decontamination workers were all reactor staff (from various sections: operations, maintenance and health physics). It should also be noted that the objective of the project was to minimize loose contamination, not necessarily fixed contamination. The ultimate aim was to reach radiological levels (e.g. airborne contamination) that would keep access safe during the long, safe enclosure period.

TABLE I–2. SLUDGE AND CRUD AMOUNTS RETRIEVED FROM THE SPENT FUEL POND DURING DECONTAMINATION

Retrieval methodology and transfer route	Amount (kg)	Activity refers to Co-60 (GBq)
Injection of and dilution with 600 m^3 of water and transfer to T-27 tank (radwaste system)	120	1110
Removal with homemade remotely operated tool, dilution with water and transfer to T-27 tank (radwaste system)	200	1850
Total	320	2960

TABLE I–3. MATERIALS REMOVED FROM SPENT FUEL POOL

Material type	Activity refers to Co-60 (GBq)
Activated material	3330
Sludge and crud	2960
Total	6290

I–2.2. Radiological monitoring

The working areas were monitored using the following means:

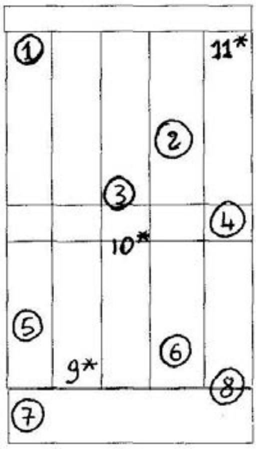
- — Monitoring of room exposure rates before any significant working step (e.g. before lowering of water level or retrieval of activated components);
- — Initial and periodic checks of loose contamination (alpha and beta–gamma);
- — Periodic checks of airborne contamination (alpha and beta–gamma);
- — Final monitoring of room exposure rates;
- — Final checks of airborne contamination (with 'dry' pool);
- — Final checks of loose contamination (alpha and beta–gamma).

During the work, alpha and beta–gamma airborne concentrations were maintained below 0.1 Bq/m^3 and 10 Bq/m^3, respectively. Loose surface contamination levels were reduced to some 50 Bq/cm^2 (equivalent to a decontamination factor of around 100) (see Fig. I–9), and for room exposure rates (with no water shielding), a reduction factor of around 300 was estimated. At the completion of the work, the residual activity remaining in the pool was estimated at around 20 GBq for beta–gamma concentrations and 16.6 MBq for alpha concentrations.

I–2.3. Protection of the workforce

Personal protective equipment typically included a cap, cloth coveralls and boots, cloth or rubber gloves and rubber overshoes. In certain critical phases (especially during water jet decontamination and the manual retrieval of crud from pool floor), the personal protective equipment also included waterproof coveralls, rubber boots and a full face mask.

Componente : Rack n° 1	Punto di Misura	Contaminaz. asportabile β-γ Bq/cm²	Contaminaz. asportabile α Bq/cm²	NOTE
	Prima della decontaminazione			
	1	600	0,00	
	2	800	0,20	
	3	600	0,50	
	4	2.500	0,20	
	5	800	0,30	
	6	1.000	0,50	
	7	2.000	1,00	
	8	3.000	2,00	
	9	800	0,30	
	10	1.000	0,50	
	11	800	0,20	
	Dopo la decontaminazione			
	1	50	< 0,01	
	2	50	0,06	
	3	25	0,03	
	4	100	< 0,01	
	5	25	0,03	
	6	35	< 0,01	
	7	30	< 0,01	
	8	100	0,09	
	9	25	< 0,01	
	10	15	< 0,01	
	11	25	< 0,01	



NOTE: - ⊗ Punto di misura anteriore rack
- X * Punto di misura posteriore rack
- Intensità di dose media a 10 cm ~ 300 μSv/h prima della decontaminazione
- Intensità di dose media a 10 cm ~ 100 μSv/h dopo della decontaminazione

Note: Contaminazione asportabile — loose contamination; dopo la decontaminazione — after decontamination; intensità di dose media a 10 cm — average exposure rate at 10 cm; prima della decontaminazione — before decontamination; punto di misura — measurement point. The encircled numbers refer to the front of the rack. Numbers with * refer to the back of the rack.

FIG. I–9. Loose contamination levels on pool rack No. 1 before and after decontamination (courtesy of ENEL).

During and on completion of the work, the workers were monitored for:

— Internal contamination through nose smears (daily) and whole body counting on a random basis;
— External contamination through body monitors upon exit from working or controlled areas.

No personnel contamination was detected throughout the decontamination work.

I–2.4. Working times and occupational exposures

Occupational exposures were estimated using pen dosimeters that were provided daily to the workers in addition to ordinary film badges used in controlled areas. During certain critical activities (i.e. with high exposure rates), alarm dosimeters were provided (calibrated at 1 mSv per working day).

Because the retrieval of sludge from the pool was carried out manually, as fixed structures welded or solidly anchored to the floor prevented the effective use of remote tools, worker rotation was required to distribute doses uniformly. During this phase, room exposure levels (2–5 mSv/h) were experienced.

The following parameters were estimated for the work:

— 25 part time workers;
— 5600 worker hours;
— 1500 worker hours in radiation areas;
— 99 man mSv as the collective effective dose;
— 20 mSv as the effective dose to one worker from the health physics section.

I–3. DECOMMISSIONING OF THE SPENT FUEL STORAGE AT THE RA REACTOR FACILITY, SERBIA

I–3.1. Introduction

I–3.1.1. Brief history

Nuclear research reactor RA was constructed in the second half of the 1950s (see Figs I–10 and I–11). It was designed in the former Union of Soviet Socialist Republics (USSR), where the main components were also manufactured. The reactor became the largest research nuclear facility in the former Yugoslavia, and was a multipurpose research reactor providing a relatively high neutron flux in the core. It belonged to the second generation of research reactors that gave an important contribution to nuclear technology development in the country.

The RA reactor was a tank type reactor using heavy water as a primary coolant and as a moderator. The primary cooling system circulated heavy water to cool the fuel elements in the core and remove heat by upward forced circulation. Its nominal power was 6.5 MW.

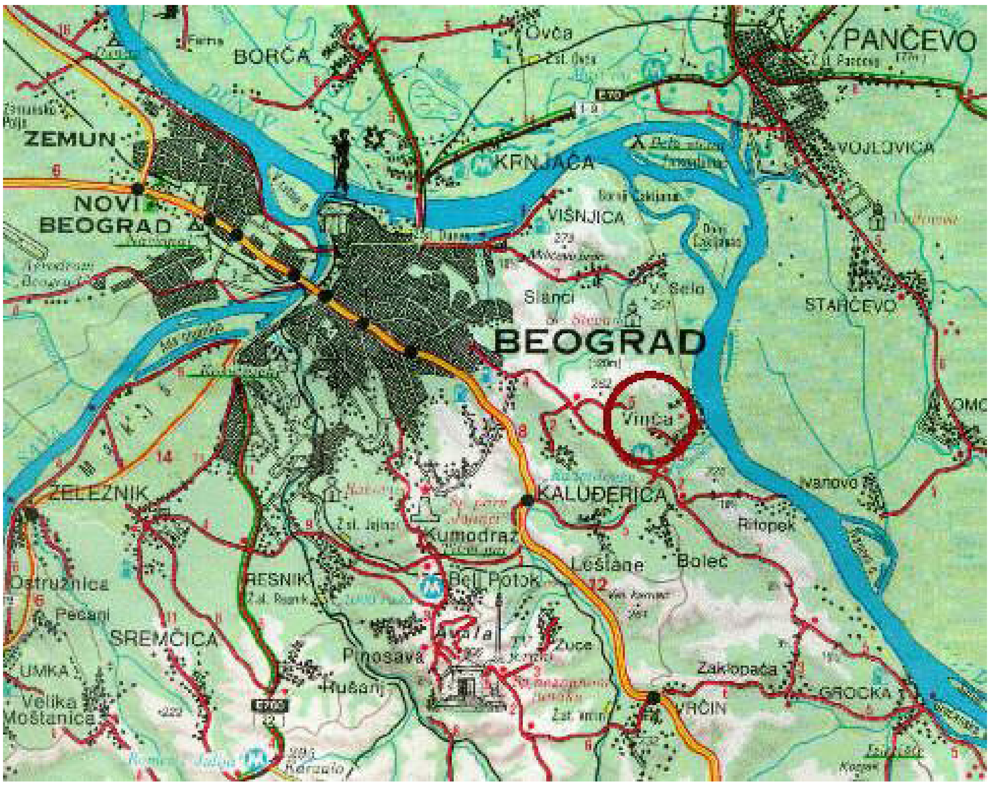


FIG. I–10. Map of Vinča region (courtesy of O. Šotić).

FIG. I–11. RA reactor block (courtesy of O. Šotić).

The facility went critical in December 1959 and was temporarily shut down in August 1984. During this period of operation, the reactor was successfully used for scientific research, but also for commercial purposes. From its first commissioning in 1960, until 1975, the reactor used low enriched uranium fuel (2% of ^{235}U). In 1976, the original fuel was gradually replaced by a high enriched fuel (80% of ^{235}U) that was developed and qualified in the former USSR.

After temporary shutdown in 1984, followed by a set of thorough examinations of its systems and equipment, it was decided to reconstruct the reactor systems to enable safe and continuous operation in the future. The reconstruction, with financial help from the IAEA, started in 1986, but owing to international sanctions imposed upon the former Yugoslavia in 1992, the reconstruction work has never been finished. The facility was then left in an extended shutdown regime under passive care and maintenance.

I–3.1.2. Spent fuel storage

The spent fuel storage is located in a special ground floor room of the RA reactor building, which is next to the reactor room (see Fig. I–12). The two rooms are separated by a corridor. The storage pond consists of five pools, one of which was intended for dry storage only (the so called dry pool, which contains various activated and contaminated components of the reactor equipment). The others were intended for wet storage and contained spent nuclear fuel elements. The storage pond was designed as a temporary storage for spent nuclear fuel [I–2]. The pools for wet storage, which are separated, are interconnected by a transfer channel, which, by its other end, connects them to the reactor block. Through this channel, spent fuel assemblies were transferred from the reactor core to the pools. Each pool has double gates: one towards its interior and the other towards the transfer channel. The gates are handled by means of hydraulic shutters located on the operating platform of the storage. Side walls, the bottom of each pool and the transfer channel are all lined with stainless steel (10 mm thick plates).

The pools in wet storage, along with the transfer channel, are filled with ordinary tap water. The depth of each pool is 650 cm, and the maximum height of water is 580 cm. All the pools are covered with 5 mm thick corrugated steel plates, which can be lifted. Underneath these plates, steel consoles are mounted, with profile I 200, which are fastened to 80 cm thick concrete partition walls, and onto which holders are welded for stainless steel containers designed for storing spent fuel assemblies (because of the insufficient capacity for storing spent fuel elements, aluminium containers in the form of barrels have been used since the end of the 1960s). Each pool is underneath the cover plates that, together with the upper surface of the concrete partition walls, form the

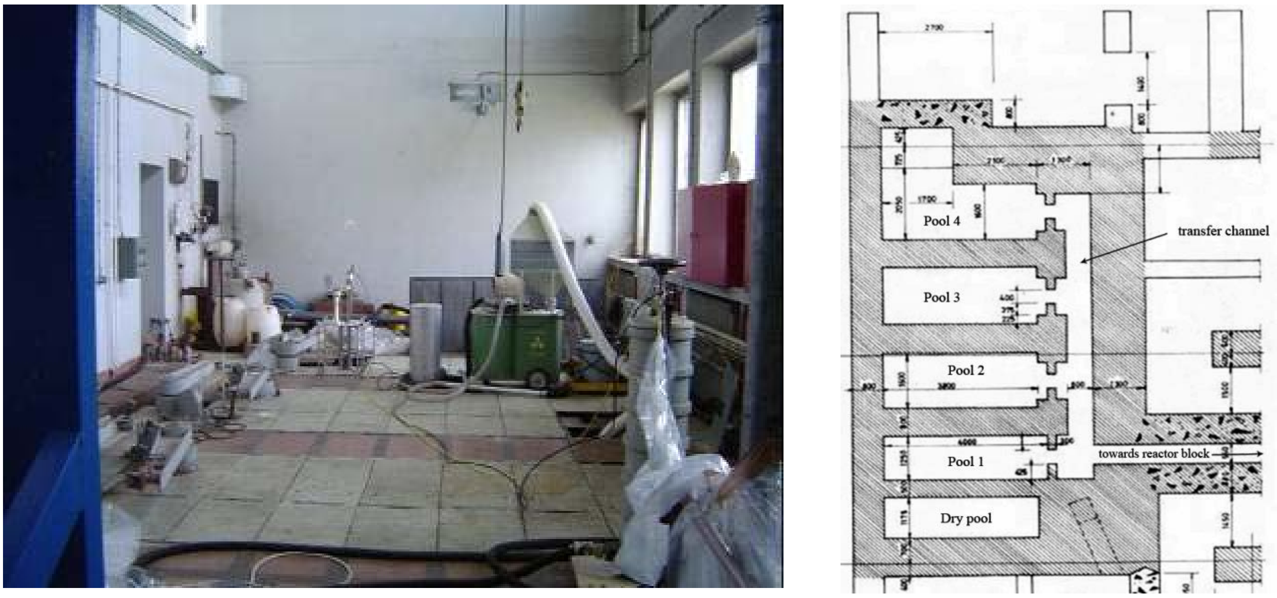


FIG. I–12. Spent fuel storage and cross-section of the pond (courtesy of O. Šotić).

working platform of the storage. The pools have openings for the ducts belonging to the special ventilation system in the RA reactor building used for removal of any gaseous, evaporable radioactive particles and any aerosols that may be generated.

The dry pool located at the far end of the storage room is filled with various activated and contaminated components that were used mainly in the reactor block (e.g. reactor fuel tubes, various structural components and experimental vertical channel tubes). Most of these pipe formed components are 5–5.5 m long. Because of the components stored inside, this pool represents a powerful source of radiation (intensity of gamma radiation dose in the vicinity of these components reaches values between 1 and 10 mSv/h), it is covered by a 24 mm steel plate and encased by lead bricks on its sides. This considerably reduces radiation in its vicinity and enables the facility staff to move more freely on the working platform of the storage [I–3].

I–3.1.3. Facility decommissioning

After 25 years of successful operation, the RA reactor was temporarily shut down in August 1984, and has not been in operation ever since. Although many improvements to its equipment have been made in the meantime, continuous degradation of its systems and components, as well as a significant reduction of qualified and experienced staff, made the continuation of its operation very doubtful. Above all, it has shown that there was no significant interest at the institute, or the country, to use this reactor.

Taking all these facts into account, the Government of the Federal Republic of Yugoslavia, by the end of July 2002, issued a directive to shut down the RA reactor permanently and to repatriate all the fuel elements (both fresh and irradiated) to the Russian Federation.

In February 2004, the Government of the Serbia decided to proceed with immediate dismantling of the RA reactor facility, after shipping the nuclear fuel off-site. A decommissioning plan was elaborated in the following five years under the auspices of the IAEA [I–4, I–5]. Spent fuel storage was envisaged to be decommissioned first.

I–3.2. Post-operational activities

I–3.2.1. Storage equipment upgrade

To enable the post-operational cleanout of the spent fuel storage and also planned activities during decommissioning, it was necessary to upgrade some of the facility’s systems and equipment. In particular, preparing the spent fuel elements for transport required significant improvements of the reactor building infrastructure and the working environment [I–6].

A series of projects was initiated. The substantial ones were replacement of the existing bridge crane in the spent fuel storage with a new one (with remote control and frequency regulation of its motion), ventilation system reconstruction, manufacture of an interior rail transfer system (see Fig. I–13), an uninterrupted power supply system upgrade (see Fig. I–14) and additional radiation monitoring system installation. All of these modifications, including procurement of new equipment, were completed by the end of 2009.

FIG. I–13. Rail transfer system (courtesy of O. Šotić).

FIG. I–14. Diesel electric generator (courtesy of O. Šotić).

I–3.2.2. Sludge retrieval and water treatment

Over the years, a relatively large quantity of sediment and sludge had been gradually accumulated at the bottom of the storage pond. It consisted of the debris arising from metal component corrosion in the pools and from external sources such as airborne dust, debris and bio-organic materials.

To remove the sediment and sludge, a special device was designed that consisted of a pump with a small container, which was used to hold minor objects and pieces of rust that might pass through the suction pipe, and a large sedimentation tank (see Fig. I–15). The suction funnel of the pump fastened to a special metal holder was moved along the bottom of the pools and the transport channel, sucking in sediments and sludge. A mixture of water and sludge was brought into the sedimentation tank and, after a day or two, the water above the sludge was poured back into the pools, while the sludge was poured into 200 L metal drums reinforced with a concrete layer. After being dewatered, approximately 3.5 m^3 of sediments and sludge was removed from the pond and cemented into drums for final disposal. Only a small amount of sludge is still present at the bottom of the pools.

FIG. I–15. Sedimentation tank (courtesy of O. Šotić).

Water in the storage pools is rather contaminated, mostly because of the radionuclides ^{137}Cs and ^{90}Sr (as the storage facility lacked adequate conditions for long term storage, a number of fuel elements lost their tightness, which led to fission product release into water in the storage pools). To reduce radiation exposure of personnel in the storage area, it was necessary to remove these radioactive substances from the water. In the final years of the project, mostly during repackaging of the spent fuel elements, the pond's water was excessively filtrated by the caesium removal system using zeolite sorbent SIR-600 (see Fig. I–16). Water clarity is maintained by mechanical purification devices using fabric and quartz sand filters.

I–3.2.3. Removal of redundant structures

In one of the pools, two underwater metal structures had been installed. They were more than 40 years old. The first one was designed to be used for removing irradiated fuel elements from the pond, while the second one, consisting of two concentric tubes, was used for washing reactor fuel tubes. These structures were rather large and had complex configurations. Both were mostly made out of unprotected low carbon steel and had been heavily corroded. Because they occupied a lot of space in the pool, where the main components of the fuel repackaging equipment and devices were planned to be installed, it was decided to remove them.

The plan was to cut both structures underwater into several larger components and then to proceed with further cutting of these components inside the tent mounted on the storage platform so that the final pieces could be accommodated into standard waste containers [I–7]. Underwater cutting of the first metal structure was performed using contact arc cutting equipment, as planned beforehand. However, owing to high contamination of the components, further cutting was not performed (contact gamma dose rates on the surface of these components reached several hundred microsieverts per hour). Special metal boxes were constructed, and, using the bridge crane in the storage pools hall, cut components were taken out from the pool and packed into these boxes (see Fig. I–17).

To remove the tube blocks, a new procedure had to be determined because the upper parts of both tubes were almost completely torn off [I–7]. Instead of cutting them underwater, the tubes were partially pulled out and cut only once, at around the middle of their height. Both components were then placed into two separate metal boxes (see Fig. I–18).

FIG. I–16. Caesium removal system (courtesy of O. Šotić).

FIG. I–17. Removing metal structure components (courtesy of O. Šotić).

FIG. I–18. Removing the tube block (courtesy of O. Šotić).

An old, wall mounted fuel element transfer device (designed for transferring spent fuel elements from stainless steel containers into aluminium barrels), was also removed. This device was not planned to be used in preparing the spent fuel elements for transport to the Russian Federation.

I–3.2.4. Spent fuel removal

During exploitation, only the so called TVR-S fuel elements (low enriched and high enriched metallic uranium fuel clad in aluminium), manufactured in the former USSR, were used in the RA research reactor (see Fig. I–19). There were more than 8000 fuel elements of both types irradiated until August 1984, containing more than 2.5 t of uranium [I–3, I–8, I–9].

Repatriation of spent nuclear fuel was a complex and challenging task. Unique fuel elements, bad storage conditions and poor fuel handling capabilities on the one hand, combined with requirements to repackage all fuel elements on the other hand, demanded development of sophisticated operational methods and proper equipment design. Geometry models and fuel burnup calculation methods were developed to assess radionuclides inventory and gamma ray and neutron dose rates in the vicinity of the storage pools and transport casks [I–10 to I–13]. Four years of preparation, followed by repackaging and loading operations, were needed to prepare the RA reactor spent fuel for transport (see Fig. I–20). At the end of 2010, it was successfully transported to the Russian Federation [I–14].

FIG. I–19. TVR-S fuel element (courtesy of O. Šotić).

FIG. I–20. Loading transport casks (courtesy of G. Webb).

I–3.3. Pre-decommissioning activities

I–3.3.1. Characterization

After spent fuel had been removed, an extensive survey and detailed physical and radiological characterization of the spent fuel storage was undertaken. Poor records of materials and components, especially of the ones in the dry pool, presented significant difficulties in defining the waste inventory present in the pond.

The wet part of the pond was chosen to be characterized first. Approximately 210 m^3 of rather low contaminated water was present in four pools and the transfer channel. Specific activity is in the range of 60–70 Bq/mL. In stainless steel containers (aluminium barrels were dismantled and removed during repackaging of the spent nuclear fuel), approximately 1.5 m^3 of water is present (stainless steel containers are 6 m long tubes, closed at the bottom, where fuel assemblies had been stored (see Fig. I–21)). In some of the containers, the water has a relatively high specific activity of up to 10^7 Bq/mL (owing to damaged fuel elements). Before dewatering the pond, water from the stainless steel containers will be poured into the pools. However, if this water is significantly contaminated, it will be poured into a special tank and treated separately (it is expected that around 0.5 m^3 of such water will be gathered from these containers).

Determination of specific water activity in the stainless steel containers is performed by taking water samples from their interior. In the same way, pH and specific electrical conductivity are measured.

There are 305 stainless steel containers in the storage pools. In addition to water, they all contain remnants of reactor fuel tubes that were cut during repackaging of the fuel elements. Several containers have reactor experimental tubes, cadmium absorber rods and other structural components. The dry pool is overloaded with various irradiated and contaminated objects (see Fig. I–22). Most of them are long structures in the form of tubes and rods, and some have a rather high activity (contact dose rates of 10 mSv/h and more have been measured).

FIG. I–21. Stainless steel containers (courtesy of O. Šotić).

FIG. I–22. Dry pool (courtesy of O. Šotić).

I–3.3.2. Removal of inventory and materials

In 2011 and 2012, many components and tools were removed from the storage room [I–15]. Among the first were numerous pieces of equipment and tools used for repackaging and loading of spent nuclear fuel. These items were placed and installed over the storage room, mostly at the bottom of the pools. Many were quite large in size and had to be cut to be accommodated into waste containers (see Fig. I–23). Only a few components could be decontaminated. All contaminated items were packed into two specially constructed half height, half length ISO containers.

To perform the necessary cutting, a tent equipped with a mobile ventilation unit and a special cutting machine were mounted inside the reactor room (see Fig. I–24). This tent will not only be used during decommissioning of the spent fuel storage, but also during decommissioning of the whole reactor facility.

The next step will comprise removal of all the objects from the dry pool and all the stainless steel containers from the pond (which will be dewatered first). In the end, taking into account easily accessible components only, the gates of the pools and the caesium removal system will be removed (this system will be taken out during the dewatering stage, when filtration of water is finished). Each ion exchange column of this system will be stored in a properly shielded container, designed basically as a spent fuel transport cask.

The final stage of materials removal will be pond dewatering. The strategy of performing this task is still being developed. The existing caesium removal system will be used extensively to filtrate water and reduce water activity as much as possible. Evaporation and precipitation techniques are envisioned to be applied afterwards.

I–3.4. Decontamination and dismantling

The end state of the spent fuel storage is determined by the foreseen end state of the reactor facility in general, and cannot be assessed separately. Although, for the time being, the plan is to return the whole site to unrestricted release status, consideration should be given to its future use. If it is worthwhile and economic to dismantle the whole pool structure to the free release level is still to be evaluated.

FIG. I–23. Shelf for fuel canisters (courtesy of O. Šotić).

FIG. I–24. Cutting machine inside the tent (courtesy of O. Šotić).

I–4. DECOMMISSIONING OF THE SPENT FUEL POOL AT THE A1 NUCLEAR POWER PLANT, SLOVAKIA

I–4.1. Introduction

The spent fuel pool of A1 nuclear power plant long term storage facility (see Fig. I–25) was used for temporary storage of spent fuel after its removal from the reactor and cooling in the short term storage facility. The dimensions of the pool were 12 m × 7 m × 9 m (width × length × depth) and the bottom was at the −3.75 m level. Stainless steel plates with a thickness in the range of 3–5 mm covered the concrete walls and bottom of the pool, and the volume of water in the pool was 560 m^3.

Fuel assemblies were stored in casks filled with heat transfer media — chrompik[2] or dowtherm[3]. During storage, some fuel fission and corrosion products were released to chrompik or dowtherm, and, during handling of fuel and storage casks, these were released into the pool water. As a result, coolant media (chrompik, dowtherm and pool water) and all surfaces inside the spent fuel pool were significantly contaminated.

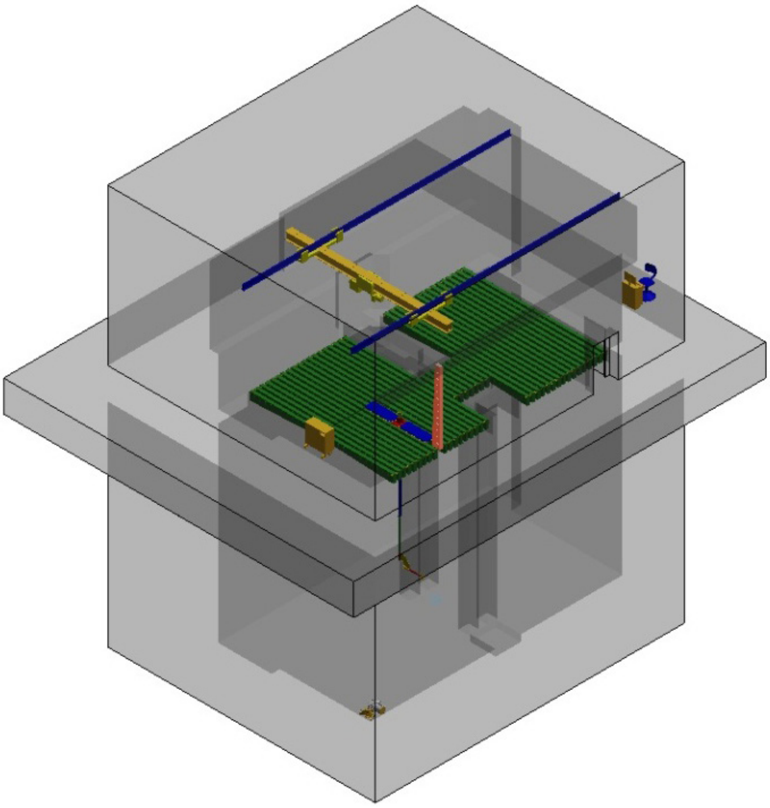


FIG. I–25. Axonometric view of the long term storage facility (the pool itself is under the green cover and the handling room is above the pool) (courtesy of VUJE Inc.).

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[2] Chrompik was originally an approximate 3% water solution of bichromate potassium used for cooling of irradiated fuel assemblies immediately after refuelling from the reactor. This fluid should not only ensure heat transfer but also inhibit cladding corrosion (beryllium–magnesium alloy) of the fuel elements (natural uranium). Because of the inappropriate chemical regime in the pool of the short term storage facility, corrosion of the cladding occurred. When the fuel assemblies were removed from the short term pool into the casks for long term storage, the medium that was used in the casks was around 3% water solution of chromate potassium (alkaline pH), also called chrompik.

[3] During retrieval of spent fuel assemblies before their repackaging for shipping to the Russian Federation, it was found that corrosion of the cladding had continued. It was decided to use a new heat transfer organic medium (dowtherm) in the casks. Dowtherm is a eutectic mixture of two chemically and radiologically very stable compounds: biphenyl 26.5% and diphenyl oxide 73.5%.

Even after the transfer of all spent fuel to the Russian Federation (completed in 1999), the spent fuel pool contained a significant inventory of radioactivity in different forms. To this day, it continues to be one of the major technical problems for the A1 nuclear power plant decommissioning process. The risk of leakage of radioactive substances into the surrounding space inside the reactor building constantly increases, owing to the expiration of the service life of the facility and lower protection by its physical barriers.

The radiological situation in the spent fuel pool and the inaccessibility of some pieces of equipment do not allow completion of physical characterization. These aspects were taken into account by the regulators, who require the emptying of the spent fuel pool and its decontamination by the end of 2018. Retrieval of radioactive waste from the spent fuel pool calls for the development and deployment of unique and technically complex equipment and implementation of non-standard technological processes.

I–4.2. Preparatory activities for spent fuel pool decommissioning

A specific project intended to decrease pool water activity was implemented from 1996 to 1998. The objectives were to improve the radiological situation in the spent fuel pool area and allow direct transfer of water to other underground storage tanks located outside the reactor building. Following a cleanup with selective sorbents and pumping water out of the spent fuel pool, the water level was gradually decreased from 2002 to 2005. Approximately 480 m^3 of radioactive water was pumped out and decontaminated in the spent fuel pool decontamination facility.

The pool contained a fine sludge with a low content of dry compound, around 25 m^3, which was retrieved and processed by in situ vacuuming of layers of the sludge above the bottom sediments. The bottom layers of sludge that contained dowtherm were retrieved later. The dowtherm was separated and incinerated, water was processed through an evaporator, with the concentrated sludge being solidified into an alumina silicate matrix during 2004, 2005 and 2007. Over two hundred 60 L drums with an activity of approximately 2.2 TBq were generated. Sludge processing using this technology was eventually discontinued because of pumping issues.

In parallel with this activity, the dowtherm was pumped from the spent fuel casks and incinerated at the incineration facility of Bohunice Waste Treatment Centre. It was necessary to decrease the activity of dowtherm to meet the acceptance limits to allow incineration. The resulting sorbents were fixed in fibre concrete containers to allow disposal at the national disposal facility at Mochovce.

It should also be noted that chrompik originating from the pool of the short term storage facility (18 m^3, ^{137}Cs volume activity of 1 GBq/dm^3) was vitrified from 1998 to 2001. The fine sludge and clear solution were treated together without any difficulties.

Taking representative samples for bottom sediment characterization was only possible after the removal of the water phase above the bottom sludge. A special camera delivered through the IAEA Technical Cooperation Project SLR/3/003 Management of Non-standard and Historical Radioactive Waste from the A1 NPP Decommissioning was used for monitoring of the sludge surface. The dry compound content, radiological characteristics and rheological properties were determined. It was found that in the pool, there was around 10 m^3 of sludge suspension containing 7% of dry compound and 13% of dowtherm. Total beta/gamma activity was 26 TBq, and total alpha activity was 12 GBq. The sludge was thixotropic and contained various objects that had fallen into the pond.

During that period, the Nuclear and Decommissioning Company (JAVYS), which is State owned and responsible for the A1 nuclear power plant decommissioning and radioactive waste management, decided to minimize the amount of waste not disposed of at Mochovce. One of the priorities of the ongoing second phase of the A1 nuclear power plant decommissioning project is the spent fuel pool radioactive waste treatment followed by decontamination and dismantling of the facility itself. The first step towards this objective is the processing of sludge from the spent fuel pool. This will be achieved through transfer of sludge from the spent fuel pool to a new storage tank and, following treatment of sludge, transfer into 200 L drums. The main reasons for the transfer of sludge are as follows:

(a) Collection of sludge in the tank that meets requirements for the storage of liquid radioactive waste (double wall storage tank with possibility to continuously monitor tightness of barriers);
(b) Homogenization of sludge to allow representative samples to be taken for appropriate radiological characterization;
(c) Provide opportunities to carry out physical and chemical pretreatment of sludge before its solidification.

Approximately 60% of the pond storage space is still occupied by casks where fuel was stored; this significantly complicates the transfer of sludge from the spent fuel pool to the new storage tank. A new piece of equipment called the Sludgerobot K1 and spraying equipment were developed for these difficult tasks.

Sludgerobot K1 is a small vehicle with a pump for radioactive sludge retrieval (see Fig. I–26). It is located at the bottom of the spent fuel pool, and retrieval of sludge is remotely controlled. Its main functions are to mechanically collect the sludge and pump it into the new storage tank. It is able to work on the bottom of the spent fuel pool only in those places where the storage casks are not located.

The spraying equipment for the spent fuel pool consists of a main support frame where spraying arms with water jets are mounted. The spraying equipment is moved by local cranes in the handling room above the spent fuel pool. The spraying equipment is used for the transfer of sludge from places where the storage casks are still located that are inaccessible to Sludgerobot K1. The main function of the spraying equipment is to mechanically disturb thixotropic sludge (bottom sediment) using several water jets. Released and diluted sludge can thus be pumped and transferred to the new storage tank. The entire process of sludge transfer is monitored using closed circuit television cameras.

Decontamination of the spent fuel pool will be implemented when at least half of the pool is empty. The conceptual design of the sludge treatment facility is currently in preparation, including the assessment of several options for facility locations, handling and transport routes. Other important aspects are the timing for final treatment and the disposal of radioactive waste generated. The stages for transfer of sludge and decontamination of the spent fuel pool include:

— Beginning of sludge transfer;
— New sludge storage completion;
— Initial decontamination of the spent fuel pool;
— Predismantling decontamination, after retrieval of all spent fuel casks from the pool.

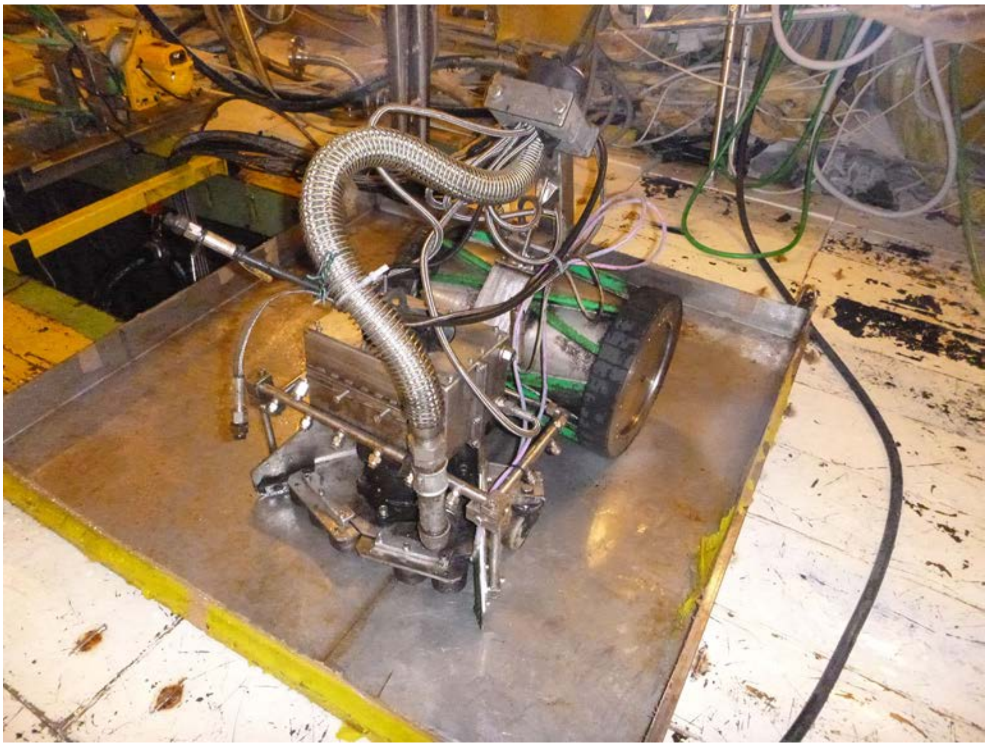


FIG. I–26. Sludgerobot K1 (courtesy of VUJE Inc.).

A brief summary of the activities undertaken since 2008 includes:

- Technical modifications of a new storage tank for sludge containing dowtherm;
- Replacement of a deep pool peristaltic pump;
- Manufacture, delivery, testing and commissioning of new sampling equipment;
- Manufacture, delivery, testing and commissioning of Sludgerobot K1;
- Manufacture, delivery and testing of the spraying equipment.

The plan for transfer of sludge from the spent fuel pool bottom to new storage was technically completed. Sludge solidification will take around 4–5 years, with the actual duration depending on available financial sources [I–16].

I–4.3. Management of spent fuel casks with radioactive waste

There are around 350 spent fuel casks with radioactive waste (e.g. dowtherm and decontamination solutions) in the spent fuel pool. Technologies for the management of generated radioactive waste are available. These are incineration of dowtherm after decreasing its activity on sorbents and subsequent sorbent solidification, cutting of casks at the cutting facility and decontamination of cask fragments. These procedures are time consuming, and implementation is dependent on the financial resources provided by the National Decommissioning Fund. It is expected that the overall process will be finished after 2020 [I–17].

I–4.4. Conclusions

The inventory of radioactive waste can, in many cases, be specified only during the implementation of particular tasks of the overall project. Thus, it can happen that there are some basic data changes during the decommissioning process (e.g. volume and specific activity of dowtherm).

Various items (i.e. small steel sheets, short tubes, clothing, a hose and metal plugs) and tools were found at the bottom of the spent fuel pool. This can be attributed to the lack of safety culture during the operation period (1972–1977) and up to the 1990s.

An unknown inventory of radioactive materials is still to be found in the area of the long term storage facility where the spent fuel was prepared for in-pool storage. This difficult to access area is planned to be monitored, characterized and decommissioned after 2020.

Decommissioning of the A1 nuclear power plant spent fuel pool is a technically difficult task that requires significant financial resources. The main technical issues have been solved, but future implementation will depend on the available finance provided by the National Decommissioning Fund.

I–5. INTEGRATED PLAN FOR THE IMPROVEMENT OF CIEMAT INSTALLATIONS DECOMMISSIONING, SPAIN

Enresa is the national Spanish agency responsible for the radioactive waste management and the dismantling of nuclear facilities. This section presents information about the ongoing dismantling project at research reactor JEN-1, Integrated Plan for the Improvement of CIEMAT Installations (PIMIC), Spain [I–18].

I–5.1. Introduction

The Research Centre for Energy, Environment and Technology (CIEMAT), formerly the Nuclear Energy Board, is located in downtown Madrid, within the university campus. It used to have more than 60 facilities in operation, which allowed a wide range of activities in the nuclear field. Particularly significant among these facilities were the research reactors, particle accelerators, hot cells and nuclear fuel manufacturing and processing plants.

Presently, CIEMAT, which is authorized as a single nuclear facility, includes various installations, some of which are now obsolete, shut down and in dismantling phases. In 2000, it started the PIMIC project.

The final goal of PIMIC is to have a model R&D centre, made up mainly of a set of conventional laboratories and facilities, along with some regulated radioactive installations. The scope of the project includes:

— Modernization of buildings and facilities, conditioning them for new needs;
— Improving and fixing infrastructure;
— Decommissioning of shutdown and obsolete facilities;
— Cleaning zones, removal of any residual contamination resulting from previous activities and recovery of the totality of the infrastructure for non-nuclear uses.

I–5.2. Scope of the project

The PIMIC decommissioning project, carried out by Enresa as the main contractor, includes the dismantling of four installations: JEN-1 research reactor, the spent fuel reprocessing plant (hot cell M-1), the radioactive liquid treatment plant and the radioactive liquid storage plant. This includes a small contaminated area caused by accidental leakage of radioactive liquid in the 1970s, which needs to be remediated and restored.

I–5.3. Historical data

JEN-1 was an experimental pool type research reactor, moderated and cooled by light water, with a thermal power of 3 MW, which first went critical in 1958. The reactor operated almost continuously from 1958 to 1984, using a total of 165 Materials Test Reactor (MTR) type fuel elements, primarily for the purpose of isotope production.

The pool was divided into three areas: a high power zone (a cylindrical well of 60 m^3 volume where the reactor was located), a low power zone of 228 m^3 volume with a rectangular shape and a transition area for storage of irradiated fuel. The reactor drainage system, consisting of three underground tanks, was used to collect and monitor water before discharging.

The reactor was upgraded in 1969, when a 1.5 mm thick stainless steel liner was added to the pool, and in 1984 when important modifications to the control system were made. The reactor was definitively shut down in 1987 before final defuelling in 1992.

During the 1990s, an R&D project financed by the European Union was carried out on the research reactor pool for development of underwater decontamination and cutting techniques for aluminium materials.

I–5.4. Preparatory activities

At the end of 2005, the decommissioning project for the reactor and pool was authorized. Preparatory activities were executed in 2006 to adapt the site to the requirements of the decommissioning project; in particular, it was essential that the facilities required to accomplish the dismantling of the active parts of the installation were provided.

During this period, the decommissioning area was isolated from the rest of the operating centre. Support systems and equipment (e.g. ventilation, firefighting, handling and electrical equipment) were modified to comply with new requirements. In parallel, auxiliary facilities and infrastructure for the conditioning and temporary storage of radioactive wastes were refurbished. For this purpose, the strategy adopted was to reuse existing buildings at CIEMAT.

The phase of preparatory work concluded with the execution of tests on the systems installed or modified during the work; the tests were evaluated by the regulatory body, as part of the authorization by Spain's regulatory body, the Nuclear Safety Council (CSN, Consejo de Seguridad Nuclear).

I–5.5. Decommissioning of active areas

In early 2007, work began on dismantling the active parts, which lasted three years and targeted the following buildings:

— Reactor building and underground tanks;
— Pilot plant for reprocessing of irradiated fuel;
— Liquid radioactive waste conditioning facility;
— Liquid waste storage facility.

The following section focuses on the dismantling of the research reactor and underground tanks.

I–5.6. Dismantling activities

Initially, Enresa performed a comprehensive radiological characterization of structures and systems of the reactor building to verify existing data and to update the radiological inventory. Particular attention was given to the remaining irradiated components stored inside the pool.

The next step included the removal of the miscellaneous elements (e.g. reactor structure, control elements, activated items and racks) from the pool. The higher activity pieces were loaded in containers shielded with lead. After removal of sludge and filtration, the water was drained from the pool.

All equipment above the pool structure was dismantled (bridge, auxiliary items, tank and equipment for underwater cutting). Later, systems and services that served the reactor, such as those for purification of pool water, ventilation, electrical systems or the control room were dismantled when they were no longer required to support the work. At the same time, components of the primary and secondary circuits were dismantled (e.g. pumps, valves, pipes and heat exchangers), as well as other equipment located in the reactor building.

One of the most difficult tasks was extraction of the six irradiation channels (3 m thick blocks) using diamond wire cutting. This step was intended to remove the activated concrete from the high power pool. This activity lasted one year, initially generating 190 t of activated concrete.

The metallic liner was removed from the pool by flame cutting, and the concrete surface was surveyed. The contamination of each surface, wall facings and floors was measured and marked for subsequent segregation. The concrete of the pool was sampled to ascertain the contamination penetration into the structure. The most contaminated area was found to be a section of the high power pool where a layer of 30 mm was contaminated and had to be removed. Decontamination was carried out using dry scarification until the desired level to allow unrestricted release was achieved.

The same strategy was followed for the dismantling of underground tanks. Some preliminary civil work was completed to remove soil over the tanks and to ensure structural integrity and safety during the work. Sludge was removed from the bottom of the tanks. Before all components of the drainage system (e.g. pipes and valves) were dismantled, walls and floors were decontaminated using manual dry scarification. Manual techniques were sufficient, owing to the low level of contamination detected.

During dismantling and decontamination, portable ventilation units with HEPA filters connected to the ventilation system of the reactor building were used to enhance filtration capacity in the work area. The as low as reasonably achievable (ALARA) programme for dose minimization was implemented by the various working teams. As a result, the occupational doses were optimized to a significant extent.

I–5.7. Clearance process and demolition

The surfaces of concrete walls located in controlled areas were monitored and declassified prior to their demolition, to enable free release of material. Enresa designed the surface clearance process, which was based on a multiagency radiation survey and site investigation methodology complying with the request of the CSN. An integrated team from the different organizations involved developed this methodology. The application of the surface declassification process allowed the demolition of the reactor pool structure and the underground tanks to be undertaken in a conventional (non-nuclear) way.

I–5.8. Demolition of the reactor pool

In 2009, the pool structure and auxiliary structures (e.g. control room, upper floor and ladder) were demolished using conventional techniques. Of the order of 1000 m^3 of conventional rubble was generated. Work lasted four months, longer than initially estimated owing to the presence of steel bars in the reinforced concrete, which had to be removed with thermal cutters. Finally, slabs of the reactor building were demolished to extract embedded pipes that connected the pool to auxiliary systems located on the basement of the building, and underground tanks were demolished and foundations filled with inert materials.

I–5.9. Conclusions

The specific issues associated with the PIMIC decommissioning project included:

- The variety of facilities with different types of contamination;
- Limitations in space: the project was confined within an enclosed decommissioning area;
- Interactions with the operating research centre;
- The significant social impact and visibility of the project were significant;
- The great variety of stakeholders with different interests.

Currently, decommissioning activities in buildings have been completed, and soil remediation is under way together with the final radiological characterization of the soil, including using surface samples and deep boreholes. Remediation of contaminated soil in the ‘lentil zone’ (includes decontamination, radwaste conditioning and refill) has been done with one further zone to be completed. The reactor building has been refurbished to be reused as a temporary store for radioactive wastes produced during remediation of the site.

I–6. JOSÉ CABRERA NUCLEAR POWER PLANT DECOMMISSIONING PROJECT, SPAIN

I–6.1. Introduction

The José Cabrera nuclear power plant is a single loop pressurized water reactor (PWR) of 160 MW(e) located in Almonacid de Zorita (110 km from Madrid). The plant started operation in 1968 and was shut down in April 2006. In February 2010, Enresa was authorized to initiate the dismantling of the José Cabrera nuclear power plant and received transfer of the site from the owner (see Fig. I–27).

This is the first total dismantling project programmed to be completed in Spain and has an objective of achieving green field status by 2016. The activities most relevant to this publication will consist of the removal and management of large components from the primary circuit, reactor internals, vessel, pressurizer, steam generator and coolant pump. These components should be size reduced to comply with the packaging requirements of the El Cabril intermediate and low level waste (LLW) repository. Four containers, including the most activated internals, will be stored in the dry spent fuel storage on-site. Upon completion of decommissioning, the site will be returned to the owner.

I–6.2. Preparatory activities

During the transition period from shutdown until the beginning of the dismantling, several post-operational activities were carried out. In 2009, the spent fuel was removed from the pool and is presently stored in 12 casks at an on-site temporary dry storage facility. A chemical decontamination (Nitrox/DfD process[4]) of the primary circuit was also performed.

[4] The Nitrox process followed by the Electric Power Research Institute (EPRI) decontamination for Decommissioning (DfD) process was developed in 1996.

FIG. I–27. View of José Cabrera reactor building (courtesy of Enresa).

In parallel, planning, licensing and engineering tasks required for decommissioning the facility were carried out. This included the radiological characterization of the facility, which is one of the most important steps in decommissioning planning. Generally, the characterization activities begin when the plant is still in operation, and continue until the decommissioning declaration (licence) is obtained. This characterization includes not only the installation but also the external environment that could have been affected by the operation of the plant. The characterization will help to determine the type and extent of contaminants present before any actual decontamination or dismantling takes place.

During 2010 and 2011, several preparatory activities were carried out to adapt support systems and auxiliary facilities to the new requirements of the decommissioning project. The electrical system was modified, which included the installation of a new electrical supply adapted to the needs of the decommissioning process. The water supplies (firefighting systems, general services and dilution effluents systems) and the ventilation systems of the reactor and auxiliary buildings were also adapted to the new situation (see Fig. I–28).

All support services and systems not required for decommissioning were deactivated (drained or de-energized) prior to equipment removal. This included clear identification of the isolation point for others systems still required to support decommissioning activities, and was achieved using a definitive tag out plan and risk reduction and elimination plans.

Some conventional dismantling activities relating to non-radioactive infrastructure were performed at this stage, which included the turbine building (see Fig. I–29), the diesel building, the electrical transformers and the cooling towers. Cooling towers were demolished to reuse the space created as a temporary storage area for conventional scrap before dispatch from the site (see Fig. I–30).

All the components from the turbine hall were removed and civil works were executed to transform the building into the new decommissioning auxiliary building for the treatment and storage of the radioactive wastes to be generated during the dismantling of radiological areas.

The reactor internals will be size reduced and sorted and segregated underwater, inside the spent fuel pool. The spent fuel pool will remain filled after the completion of the reactor internal dismantling project and may be used as interim storage for selected wastes.

FIG. I–28. New pumps for the firefighting system (courtesy of Enresa).

Radioactive wastes produced during dismantling will be sent from the reactor building to the decommissioning auxiliary building for final packaging and cementation via a transfer tunnel that connects the two buildings. Materials will be placed in canisters and removed from the pool using a shielding bell to avoid radiological exposure.

I–6.3. Preparation for dismantling of the internals

The reactor building houses the entire nuclear island, most of its auxiliary systems and the spent fuel storage area. The building consists of a reinforced concrete cylindrical structure, covered by a metal semispherical dome. Internal reinforced concrete walls and slabs define the cubicles housing the different equipment, and provide the required biological shielding.

FIG. I–29. Dismantling of the turbine components (courtesy of Enresa).

FIG. I–30. Demolition of cooling towers (courtesy of Enresa).

The spent fuel pool is located inside the reactor building adjacent to the reactor cavity. The dimensions of the pool are 7 m × 6.5 m, with a maximum water depth of 11.7 m. The floor and walls of the pool up to elevation 603.76 m (above sea level) are covered by a stainless steel liner. Walls above this elevation are concrete covered with an asphalt cover and phenolic paint. The pool is connected to the reactor cavity via the refuelling channel (see Figs I–31 and I–32).

FIG. I–31. *Initial situation of the reactor cavity (2011) (courtesy of Enresa).*

FIG. I–32. *Initial situation of the spent fuel pool (2011) (courtesy of Enresa).*

During 2011, some preparatory activities were carried out to prepare the spent fuel pool as a cutting area for the pool equipment. Initially, Enresa accomplished a detailed inspection of the spent fuel pool and a characterization of the different elements (e.g. racks, nuclear instrumentation and miscellaneous) remaining in the pool and in the reactor cavity. The objective was to verify the radiological inventory and to prepare these areas for the dismantling work (see Fig. I–33).

The next activity was the removal of miscellaneous elements stored in the pool and the reactor cavity. Most activated pieces were placed in canisters for later dismantling underwater (see Fig. I–34).

The channel to transfer spent fuel from the reactor to the pool was too narrow to move the reactor internals for dismantling. Therefore, it was decided to remove the concrete wall between the reactor cavity and the pool using diamond wire techniques: 24 blocks of 9 t each were generated by this operation, and these were all classified as very low level waste (VLLW) and LLW (see Fig. I–35).

Installation of a durable waterproof coating at the walls of the cavity and the unlined portion of the spent fuel pool, extending up to the maximum flood level during the dismantling, was necessary. Special attention was given to the sealing of construction joints. The reactor cavity floor was sealed with a concrete slab (see Fig. I–36). Tests were made during the pool and reactor cavity flooding process to verify the watertightness and avoid later leakages.

(a) (b)

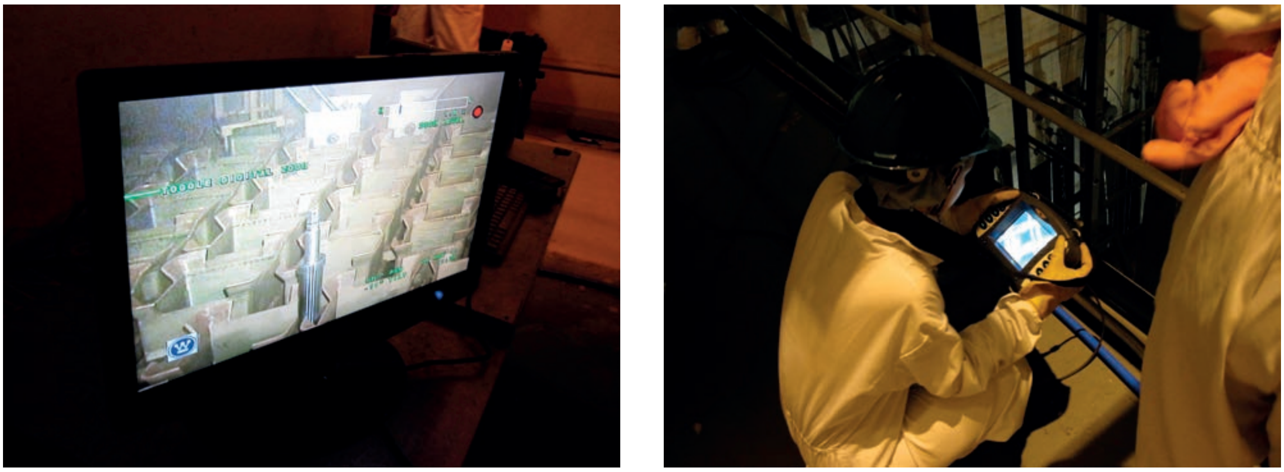


FIG. I–33. Underwater inspection of the spent fuel pool (courtesy of Enresa).

(a) (b)

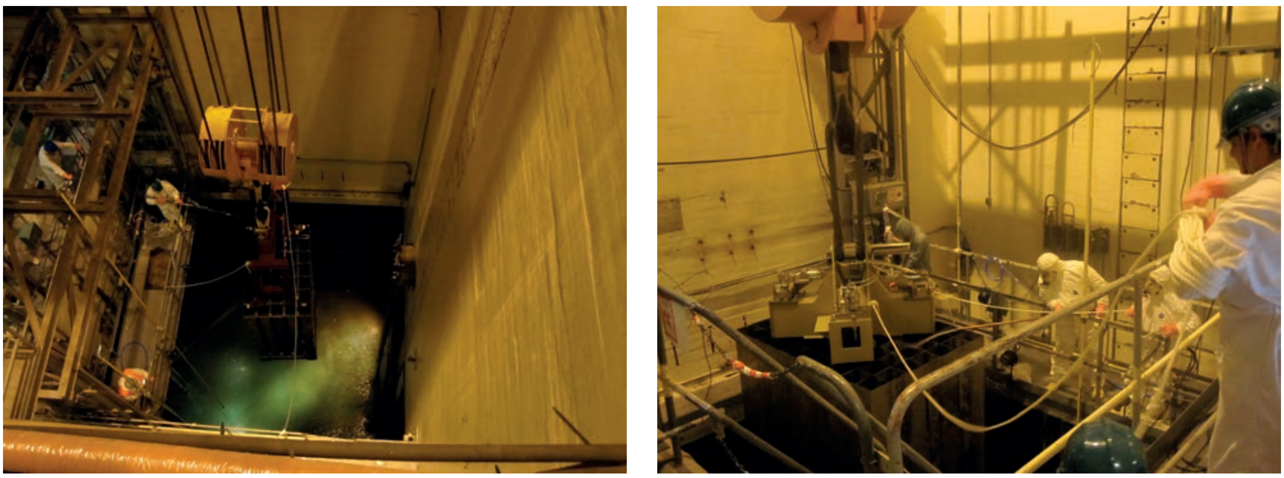


FIG. I–34. Extraction of spent fuel rack from pool (courtesy of Enresa).

FIG. I–35. Removal of wall between reactor cavity and pool (courtesy of Enresa).

FIG. I–36. New concrete slab in reactor cavity (courtesy of Enresa).

Auxiliary equipment required for dismantling activities has been installed, including a new pool platform (see Fig. I–37), where operators will remotely control underwater cutting tools, and a turntable to position the components to be cut.

Requirements for water clarity and radiological characteristics were established to control the environment during dismantling. In a first phase, sludge and debris accumulated on the floor of the pool were retrieved using direct pumping and hydrovacuuming, and were encapsulated in shielded containers. Following this, the ion resin filtration system of the plant was augmented with additional submersible equipment (see Fig. I–38, on p. 134).

FIG. I–37. New pool platform (courtesy of Enresa).

In March 2012, the reactor vessel head was lifted (see Fig. I–39, on p. 135), and the upper internals were transferred from the reactor cavity to the spent fuel pool to start the dismantling work.

I–7. EXPERIENCE AT SAPHIR RESEARCH REACTOR, SWITZERLAND

I–7.1. Introduction

The SAPHIR swimming pool reactor was commissioned on 30 April 1957, after a one year construction phase (see Fig. I–40). In the following years, the power was increased from 1 MW in 1957 to 10 MW in 1984. The reactor was finally shut down on 20 December 1993. The decision to begin decommissioning followed on 21 June 1994. In December 1996, securing the facility after shutdown was completed, and on 2 October 1998, it was decided to restore the site to unrestricted use conditions.

The pool had a volume of 192 m^3, was divided into a reactor compartment and an auxiliary compartment, and was fitted with a stainless steel liner. The concrete wall of the pool was backfilled with gravel. The reactor components consisted of aluminium, the biological shielding was made of barytic concrete and seven beamlines were available for training and research.

I–7.2. Decommissioning and dismantling

Decommissioning started with the removal of the highest activity material (i.e. the spent fuel). The spent fuel elements were shipped to the Savannah River site, in the United States of America. The unirradiated fuel could be sold to a research centre in a neighbouring country. Subsequently, the removal of activated beryllium reflectors followed. This work could all be done under the existing operating licence.

FIG. I–38. Submersible equipment for water filtration (courtesy of Enresa).

The report underpinning the application for a licence for the subsequent dismantling activities was completed in 1998, and the licence was issued by the Federal Council in 2000. The dismantling concept consisted of five stepwise deregulation and dismantling phases. The steps were as follows:

(1) Construction of a special personnel entrance to the controlled area and removal of experimental and other slightly activated or contaminated equipment;
(2) Removal of highly activated installations from the core followed by removal of the pool water;
(3) Removal of beamlines;
(4) Removal of the reactor structure and biological shield;
(5) Demolition of the building and restoration to green field conditions.

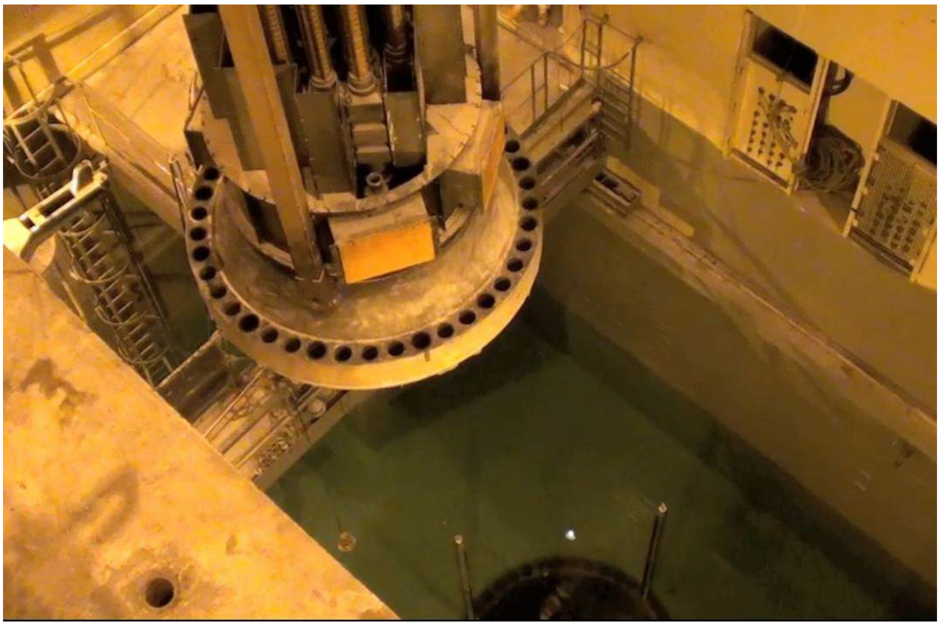


FIG. I–39. Reactor vessel head lifting (courtesy of Enresa).

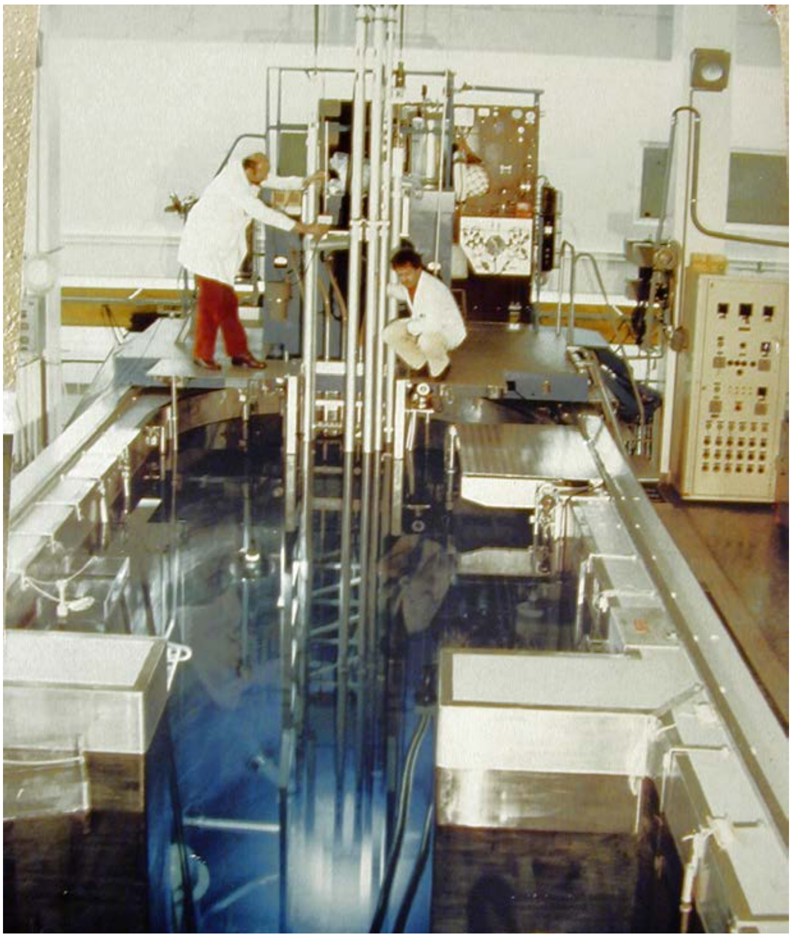


FIG. I–40. SAPHIR in operation (courtesy of Paul Scherrer Institute).

The dismantling of the contaminated and activated components and of the reactor structure was performed inside the existing building, utilizing the existing infrastructure [I–19]. It was therefore important to continue to maintain the building and infrastructure to a high standard throughout this phase. The dismantling team consisted of one project leader, one assistant, one system operator (decontamination expert), three members of the dismantling team and one radiation protection officer.

Waste treatment facilities existed on-site, including measurement facilities to support classification of waste for unrestricted release, facilities for decay storage of waste, facilities for conditioning of aluminium, concrete, steel, other metals and sludge generated during the cutting operations, and waste routes for incineration.

Highly activated installations were cut underwater, making use of the existing water shielding (see Fig. I–41). Pool water could be released batchwise after a radiological and chemical control into the nearby river. Additional shielding was provided for the beamlines to replace that provided by the water shielding (see Fig. I–42). The remaining steel liner could be decontaminated using simple means (wet swabbing, see Fig. I–43). Contaminated material was decontaminated using an ultrasonic bath, abrasives, decontamination paste and solvent (for painted surfaces). The pool structure was demolished using conventional techniques. Figures I–44 to I–47 show the use of a circular saw, diamond wire cutting, core drilling, a hydraulic concrete crusher and a concrete splitter.

FIG. I–41. Underwater cutting of the grid plate (courtesy of Paul Scherrer Institute).

FIG. I–42. Shielding of the beamlines (courtesy of Paul Scherrer Institute).

FIG. I–43. Decontamination of the steel liner (courtesy of Paul Scherrer Institute).

FIG. I–44. *Circular saw cutting of the pool wall (courtesy of Paul Scherrer Institute).*

FIG. I–45. *Wire saw cutting of the bioshielding (courtesy of Paul Scherrer Institute).*

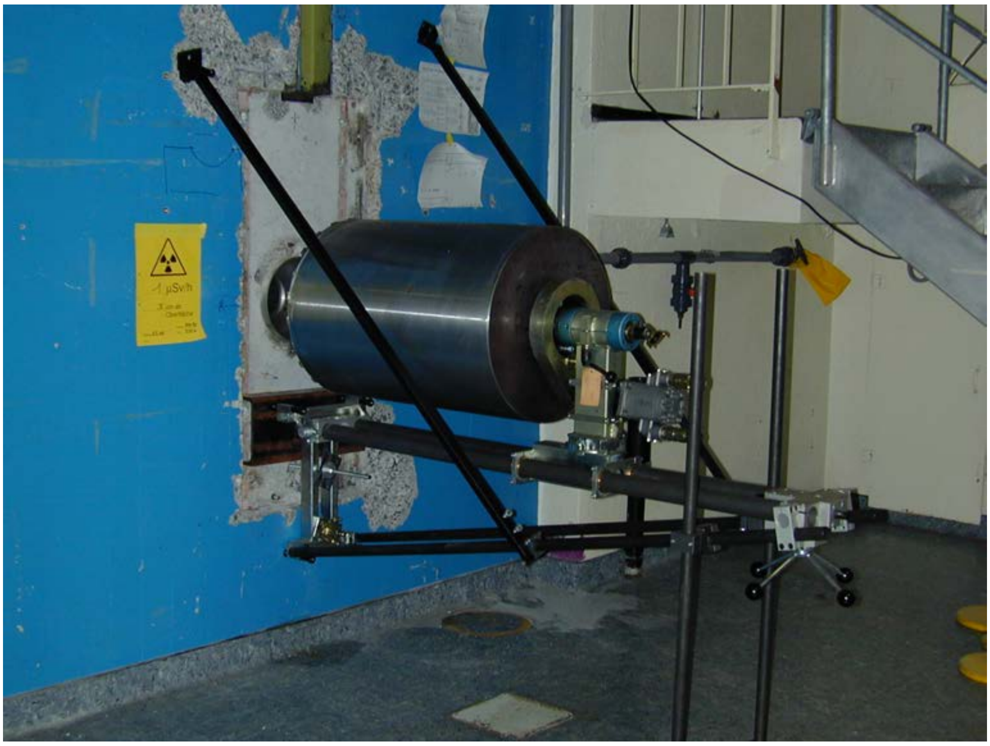


FIG. I–46. Core drilling (courtesy of Paul Scherrer Institute).

FIG. I–47. Concrete splitter in action (courtesy of Paul Scherrer Institute).

I–7.3. Waste generation, conditioning and disposal

In total, 1369.3 t of inactive waste was disposed of for unrestricted release after appropriate measurement. This consisted mainly of gravels, concrete and, to a much lesser extent, some metal waste. The clearance monitoring campaign (see Fig. I–48) is described in Refs [I–20, I–21].

In addition, 58 t of slightly activated material was stored in a decay storage facility. The following amounts of other radioactive wastes have been generated:

— Aluminium: 1.0 t;
— Technical waste: 50.3 t;
— Burnable waste: 1.0 t;
— Compactable waste: 0.2 t;
— Mixed waste: 1.7 t;
— Sludge: 11.7 t.

The radioactive waste has been conditioned in waste packages ready for final disposal according to Swiss regulations [I–22]. It is now stored in an interim storage facility.

I–7.4. Problems encountered and solutions

Relatively minor problems were encountered during the decommissioning of the SAPHIR reactor, two of which are discussed below:

(a) Before dismantling, 20 beryllium reflectors were present when the reactor was shut down: ten of beryllium metal and ten of beryllium oxide (BeO). Two of the BeO reflectors had damage, and there was a risk that a precipitate containing BeO could have formed at the bottom of the pool. Samples were taken from the pool bottom, analysed and found not to contain BeO. The two damaged reflectors were coated with a paint to seal and stabilize the surface as a form of conditioning. All 20 beryllium reflectors were sealed in welded gas tight steel cans. The cans were placed in a MOSAIK container (cast iron) and stored in the interim storage facility.

FIG. I–48. Unrestricted release measurements (courtesy of Paul Scherrer Institute).

(b) During dismantling, the beamlines were removed by core drilling. During the work, an unexpected large lead shielding was found within the concrete structure. This additional shielding was not shown on the drawings, and the problem was solved by accurately drilling around it.

I–7.5. Interim end state

In May 2008, step 4 (see Section I–7.2) was completed with the reactor completely dismantled (see Fig. I–49). The accumulated dose and the finances remained within the planned values. Step 5 is still pending owing to the ongoing use of the building.

I–7.6. Conclusions

The former SAPHIR research reactor has been dismantled completely without any significant difficulty. There are several factors underpinning the successful dismantling of SAPHIR:

- Good housekeeping during operation and after shutdown;
- Good maintenance of the infrastructure before and after shutdown;
- Experienced personnel with knowledge of the reactor history;
- Stable legal framework;
- Close cooperation with the regulatory authority;
- Excellent infrastructure of a large research centre;
- Stable financing;
- Stable organization, motivated personnel;
- Support from skilful local companies;
- Waste conditioning and treatment routes on-site and approved by the regulatory authority.

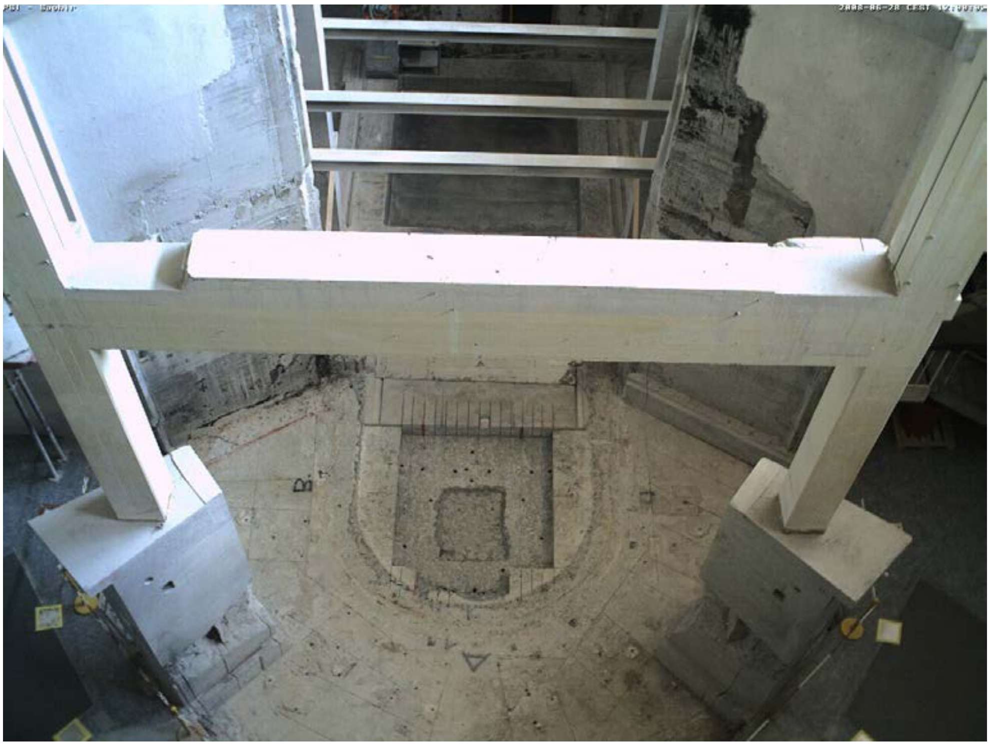


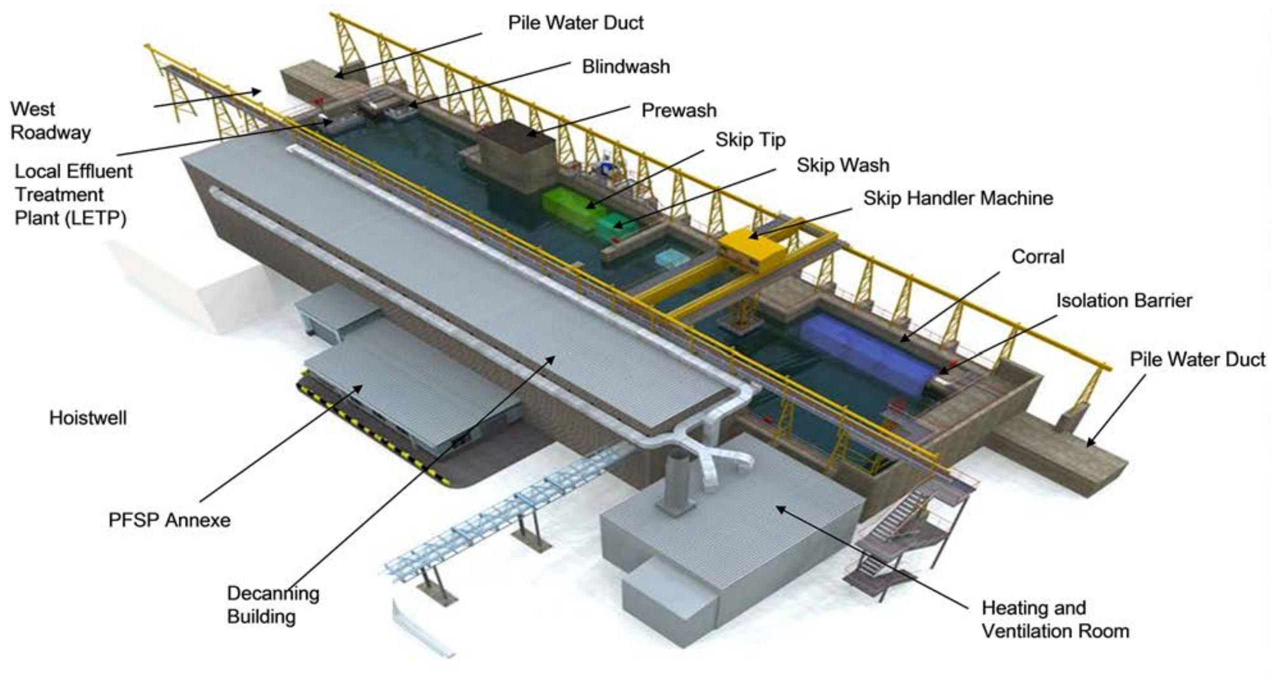
FIG. I–49. After dismantling (courtesy of Paul Scherrer Institute).

I–8. PILE FUEL STORAGE POND AT SELLAFIELD, UNITED KINGDOM

I–8.1. Introduction

The Sellafield site is the largest and most complex nuclear site in the United Kingdom, and has ponds at all stages of the operational and decommissioning cycle. The pile fuel storage pond (PFSP) was built and commissioned between the late 1940s and early 1950s as a cooling and storage facility for irradiated fuel and isotopes from the two Windscale reactors. The irradiated material was discharged from each reactor into large skips and then transferred to the pond via submerged water ducts. In the pond, the fuel was cooled then decanned underwater prior to export in small flasks for reprocessing at other site facilities. Figure I–50 shows the pond itself, while Fig. I–51 shows an overview of the pond in schematic form. The plant operated successfully until it was taken out of operation in 1962 when the first Magnox fuel storage pond took over fuel storage and decanning operations on the site. The pond was then used for storage of miscellaneous intermediate level waste (ILW) and fuel from the UK nuclear programme for which no defined disposal route was available. By the mid-1970s, the import of waste ceased and the plant, with its inventory, was placed into a passive care and maintenance regime.

FIG. I–50. Pile fuel storage pool at Sellafield, United Kingdom (courtesy of Sellafield Ltd).



Note: PFSP — pile fuel storage pond.

FIG. I–51. Pond schematic (courtesy of Sellafield Ltd).

By the mid-1990s, driven by the age of the facility and concern over the potential scale of the programme to dispose of the various wastes and fuels being stored, the plant operator initiated a programme of work to remediate the facility. The importance of this work was supported by the site regulators, who issued a regulatory specification defining the required delivery schedule for key elements of the work. The programme developed has to balance a number of competing drivers to deliver the optimum solution for the plant, which include:

(a) The pond is situated on a very congested part of the Sellafield site, and is surrounded on all sides by buildings that originate back to the earliest history of nuclear operations on the site. This limits the opportunity for new infrastructure, heavy lifting equipment and temporary facilities.
(b) The pond is not covered, has no secondary containment and is very close to occupied areas of the site. This limits the opportunity for high energy retrieval systems that could result in uncontrolled disturbance of activity or low shielding solutions.
(c) The PFSP is one of a number of legacy plants on the site. The waste streams from the pond are more varied but much lower in volume than many of the other plants. This requires the programme to take a responsive and opportunistic approach to movements within the overall site programme.
(d) The various waste forms within the pond present different challenges and hazards. In striving for the earliest hazard reduction, these need to be considered against each other and a sequence of operations selected that not only gives early hazard reduction but minimizes the risk overall. This is particularly key when full characterization of the inventory and condition is not possible, but safety cases need to be made to justify the selected retrieval activities and any increased risk during the retrieval phase.
(e) The pond infrastructure needs to be maintained and improved; balancing time and money spent improving infrastructure against hazard reduction is a key part of the programme.

The programme developed and implemented consists of the following six interdependent phases of work that link together towards the overall goal, with each of the phases being delivered by a number of projects, the combined delivery of which will achieve the desired outcome.

I–8.1.1. Pond preparation

Before any remediation work could start, the condition of the pond had to be transformed from a passive store to a plant capable of complex retrieval operations. This work included plant and equipment upgrades, removal of redundant structures and the provision of an effluent treatment plant for removing particulates and dissolved activity from the pond water.

I–8.1.2. Canned fuel retrieval

Canned fuels, including oxide and carbide fuels, represent the most significant inventory in the pond and are therefore the highest priority within the programme. The project associated with this stream has provided handling and export equipment required to remove the canned fuel from the pond. It has also developed treatment routes utilizing existing site facilities to allow the fuel to be reprocessed or conditioned for long term storage.

I–8.1.3. Sludge retrieval

In excess of 300 m^3 of sludge has accumulated in the pond over many years and is made up of debris arising from fuel and metallic corrosion, windblown debris and bio-organic materials. The sludge retrieval project has provided the equipment necessary to retrieve the bulk of the sludge. This includes skip washer and tipper machines for clearing sludge from the pond skips, equipment for clearing sludge from the pond floor and bays, along with an 'in-pond' corral for interim storage of retrieved sludge.

Two further projects are providing new plant and equipment, which will allow the sludge to be temporarily stored before being passivated for long term storage by treatment in existing site treatment plants.

I–8.1.4. Metal fuel retrieval

Metal fuel from various sources is stored within the pond. The fuel varies considerably in both form and condition. The metal fuel retrieval project provides the fuel handling, conditioning, sentencing and export equipment required to remove the metal fuel from the pond for export to on-site facilities for interim storage and disposal.

I–8.1.5. Solid waste retrieval

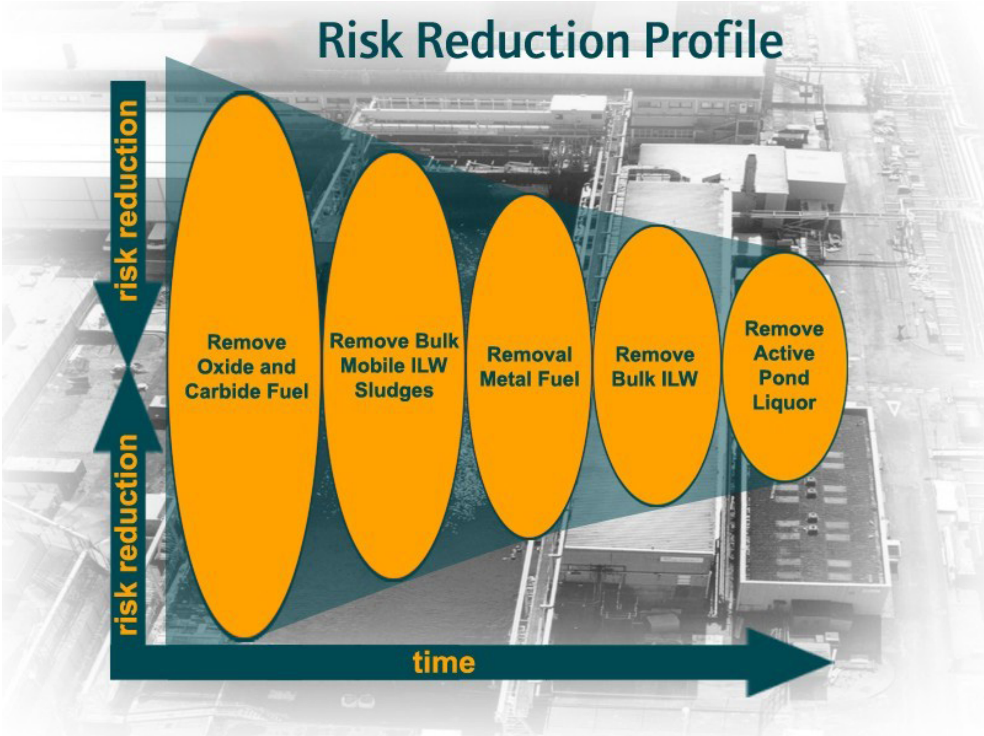
A final retrieval project will provide methods for handling, retrieval, packaging and export of the remaining solid ILW within the pond. This includes residual metal fuel pieces, fuel cladding (Magnox, aluminium and zircaloy), isotope cartridges, ion exchange media, reactor furniture, and miscellaneous activated and contaminated items. Each of the waste streams requires conditioning to allow it to be disposed of via one of the site treatment plants.

I–8.1.6. Pond dewatering and dismantling

Delivery of the above projects will allow operations to progressively remove the radiological inventory, thereby reducing the hazard and risk posed by the plant. This will then allow subsequent dewatering of the pond and dismantling of the structure. Strategies for these phases of work are currently being developed. A graphical illustration of the programme structure is shown in Fig. I–52.

I–8.2. Pond preparation

The PFSP is situated on a very congested part of the Sellafield site. It is surrounded on all sides by buildings that originate back to the earliest history of nuclear operations on the site. The operating areas are generally small, and the building infrastructure reflects the smaller scale of the early nuclear operations. Much of this infrastructure had reached the end of its design life. It was recognized early in the programme that if efficient retrieval operations were to be established, significant improvements to the building infrastructure and working environment would be required.



Note: ILW — intermediate level waste.

FIG. I–52. Graphical representation of the pile fuel storage pond remediation strategy (courtesy of Sellafield Ltd).

I–8.2.1. General refurbishment

A series of building refurbishment projects were initiated, with the first priority being the replacement of the skip handler, which had not operated since 1972. The skip handler is essential to operations, as it not only enables skips to be moved in the pond but also provides a general lifting capability above the pond and provides the only operator access over the pond. The first project completed replaced the original skip handler with a modern system capable not only of moving skips but also of providing a general lifting capacity of up to 20 t over the pond, which was essential to enable future work. Figure I–53 shows the skip handler before and after refurbishment. In addition to this work, hydraulic isolation barriers were installed to separate the pond from the ducts through which fuel was originally transferred underwater from the Windscale piles. Installation of these barriers considerably simplified interactions within the pond as it enabled the pond to be considered as an independent water retaining structure.

Other building refurbishment work included the provision of a new radiological protection system, a new ventilation system, improved piped services, an upgrade of main electrical supplies, improved lighting, a replacement decanner and withdrawal bay cranes. This refurbishment work was accompanied by a general cleanup of the facility to remove historically contaminated areas. With these improvements, work then commenced on removing some of the items stored in and around the pond to reduce congestion. In these campaigns, 21 m^3 of zircaloy hulls was retrieved and exported, and 25 redundant fuel flasks stored in and around the pond were sent for disposal.

To allow space for working and for construction of new facilities, a number of redundant structures were demolished. This included the demolition of the winch house shown in Fig. I–54, which was used to pull skips of fuel from one of the Windscale piles into the pond. The area where the winch house used to stand has been transformed into a general purpose work and decontamination area where items removed from the pond can be worked on. To the north of the pond, a redundant change room and office building were demolished, opening up access for the project work and freeing space for construction of new facilities.

FIG. I–53. Pile fuel storage pond skip handler (courtesy of Sellafield Ltd).

FIG. I–54. East winch house (courtesy of Sellafield Ltd).

I–8.2.2. Local effluent treatment plant

The provision of a local effluent treatment plant (LETP) for the pond was an essential prerequisite for the programme. The levels of activity in the pond water have been gradually increasing over the years owing to the corrosion of the fuel held within the pond. These rising activity levels pose difficulties, as they increase the dose to operators working around the pond and increase the activity in the pond overflow, which is discharged down the site's low active drain to the segregated effluent treatment plant prior to discharge to the sea. It is expected that the retrievals processes will cause further increases in the activity burden in the pond. It was therefore considered essential that a means of controlling the pond discharge was available to ensure that future retrieval techniques were not limited by environmental discharge constraints.

The principles of the LETP are to reduce the potential for any solids to discharge to the drain by introducing a sand bed filter designed to capture solids down to a few micrometres in size, and to reduce the activity of the pond liquid discharge using an ion exchange process to extract caesium and strontium. These nuclides together contribute over 99% of the soluble activity within the pond liquid. The LETP unit designed can process up to 125 m^3 of pond water per day, of which typically 100 m^3 is returned to the pond, with the remainder discharged to the low active drain.

The sand bed filter and ion exchange system, along with the associated pumping equipment and pipework, are all mounted on a single skid unit that has been installed into the pond (see Fig. I–55). Auxiliary control and services systems were provided on skids located to the side of the pond structure. The plant was designed in this way to allow all of the key processing equipment to be assembled and tested off-site, with minimal dismantling prior to installation. This minimized the work required over the pond and the risk of installation errors affecting the plant. Clearing the site to the north of the pond offered the opportunity to lift the LETP module, weighing in excess

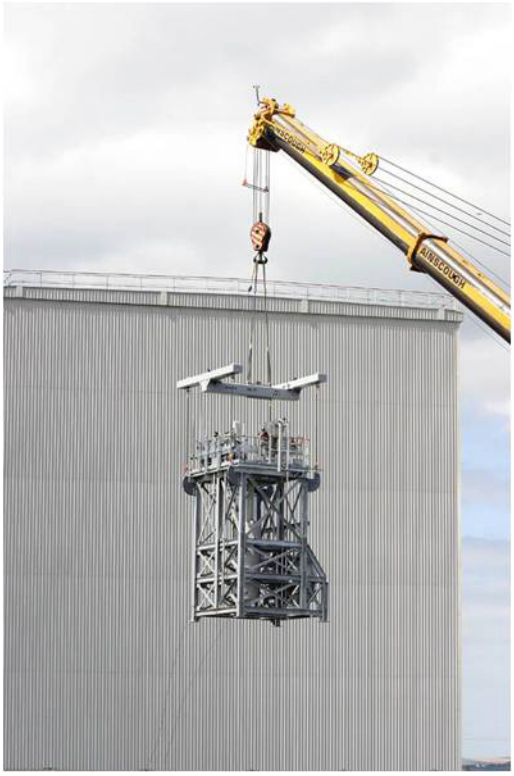


FIG. I–55. Local effluent treatment plant module undergoing testing and installation (courtesy of Sellafield Ltd).

of 20 t, in a single lift using a mobile crane. Owing to the weight of the module and the reach required to lift the LETP over the PFSP crane gantry, the lift required one of the largest mobile cranes in Europe, with a capacity of 800 t and use of a 60 m long boom.

Preparation for the lift required four fuel skips to be removed from the pond and the pond floor under the module to be cleaned; this not only created space for the LETP but also provided valuable data for the future programme of skip recovery and sludge retrieval. The ground under the mobile crane also had to be prepared, to take the large imposed loads from the lift. With this preparatory work complete, the lift was undertaken and the module placed into the pond within a few millimetres of its designed location.

The LETP has been successfully brought into service and has reduced the activity in the pond liquid discharges by a factor of 100. This has not only enabled further retrieval activities to be undertaken, but has also led to a significant reduction in the Sellafield site discharges.

I–8.2.3. Surveying, sampling and characterization

In addition to this work to improve the building itself, extensive surveying, sampling and characterization work has been completed to understand both the inventory of the pond and the physical condition of the pond structure itself. These studies provide all of the underpinning data for the programme, not only for the projects to retrieve the waste but also to justify the extended life of the facility while retrievals are undertaken.

The completion of this extensive preparatory work has significantly improved the working environment and capability of the PFSP and enables the retrievals elements of the programme to be effectively deployed.

I–8.2.4. Asset care, maintenance and safety justification

The final step in ensuring the pond can be decommissioned efficiently was to ensure that a suitable asset care programme was in place. This was essential as the retrievals programme lasts over 20 years and, given the age of the plant, it is likely further major refurbishment will be required to ensure nuclear safety functions and plant operability is maintained throughout this period. A key element of this work was the establishment of key asset integrity committees, where subject matter experts are charged with reviewing condition data from critical assets and recommending future programmes of maintenance and refurbishment.

While the existing plant safety case was adequate for passive care of the facility, it was recognized that additional justification would be required for any new equipment and each new retrieval operation. To provide a more usable and easy to understand safety case for the plant operators, the decision was taken to revise and restructure the existing case. This provided a case based on the latest inventory characterization data and safety assessment methodologies that would also be used for forthcoming projects. It was also written so new activities and plant modification could be incorporated without the overall case becoming disjointed, overly complicated or confusing.

I–8.3. Canned fuel retrieval

The PFSP contains canned oxide fuels from a number of sources, including research reactors, the Windscale advanced cooled gas reactor and the Winfrith steam generating heavy water reactor. The first priority for the programme was to establish inventory data for these fuels and to determine whether any of the fuel was suitable for reprocessing. Extensive research of industry records established sufficient evidence to confirm that the oxide fuels could be treated within the site Thermal Oxide Reprocessing Plant (THORP) or were suitable for storage with other orphan fuels within the various THORP pond facilities. Unfortunately, the cans that contain the fuel cannot be handled in those facilities, and no infrastructure existed to export or recan the fuel.

The canned fuel project was initiated to establish a waste route for the fuel. This project has provided retrievals and export equipment within the pond to allow the fuel to be retrieved from the pond skips and placed into a new fuel flask (see Fig. I–56). Using the new fuel flask, the fuel can be transferred to an existing fuel handling facility that has been modified by the project to recan the fuel in packages suitable for handling at the THORP ponds. This fuel route is now operational and PFSP defuelling is under way.

I–8.4. Sludge retrieval

Operation of the pond, which is open to the environment, has led to the gradual accumulation of in excess of 300 m^3 of sludge at the bottom of the pond. The sludge generally consists of debris from fuel and metal corrosion, windblown debris and bio-organic materials such as decayed algae and bird guano.

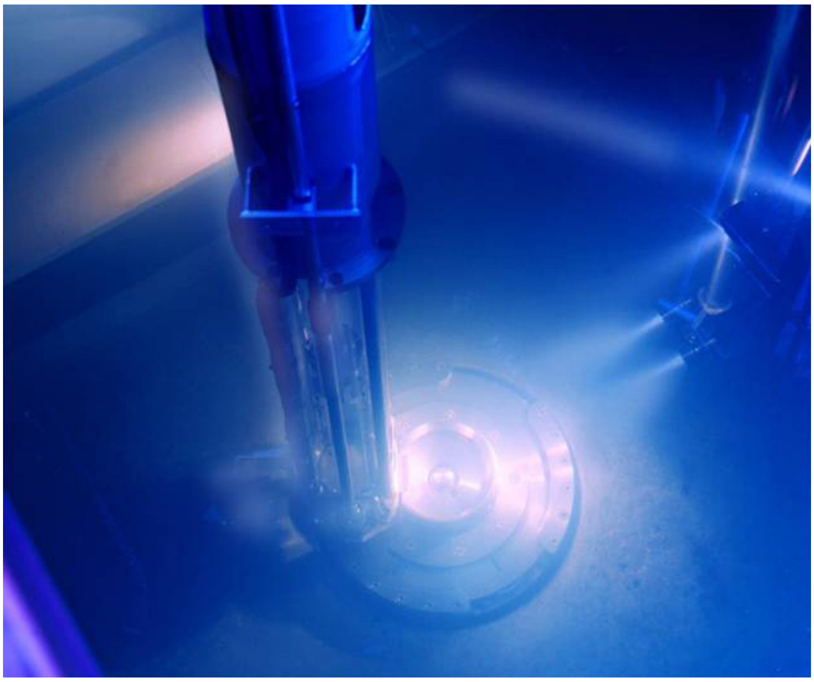


FIG. I–56. Canned fuel as stored in the pond and retrieval tool during a work test (courtesy of Sellafield Ltd).

The pond floor is covered with a blanket of sludge, which has been observed to be piling up in the pond corners. Quantities of sludge have also accumulated in fuel skips and within the bays originally used for decanning and withdrawing fuel. To complicate matters further, in addition to the sludge, there is a large quantity of pond floor debris that includes pieces of concrete, graphite, wire, cladding, spent fuel and other metals present as oxides. Removal of the accumulated sludge is a high priority for cleaning up the PFSP as it is one of the most mobile waste forms, increasing the hazards associated with loss of containment. The sludge also prevents effective characterization and retrieval of the other waste forms.

To enable the sludge to be removed, three interconnected projects have been undertaken: these provide the sludge retrieval equipment (sludge retrievals project), interim safe storage for the retrieved sludge (local sludge treatment plant storage project) and a scheme for passivation and packaging of the sludge for long term storage (local sludge treatment plant export project).

I–8.4.1. Sludge retrieval project

The general principle of the sludge retrieval project is to retrieve sludge from all the pond areas and collect it in an in-pond corral. The concept of the in-pond corral is to disconnect the time consuming and labour intensive process of sludge retrieval from the construction of the sludge storage plant. This parallel work will save several years in the overall retrieval programme.

The sludge in the pond has collected in three distinct areas: within the decanning bays, within the pond skips, where there is a higher concentration of corrosion product, and on the pond floor, where the sludge is generally organic material and windblown debris. Retrieval of sludge from each of these areas required different retrieval technology to be developed and implemented.

I–8.4.2. Bay desludging

The plant has 12 wet bays, in which fuel was decanned and exported for reprocessing. The bays are generally very congested with redundant machinery from these operations. The bays contain various quantities of sludge, which is relatively rich in corrosion products from the debris left behind from the decanning operations.

To clean the bays, a process has been deployed that takes advantage of the hydraulic linking of these bays in pairs, and creates a current within each pair of bays into which the sludge can be mobilized and carried out of the bay into the main pond, from where it can be retrieved, to the corral, with other pond floor sludge. This is achieved by placing a pump (shown in Fig. I–57) at the entrance to one of the bays and drawing water from the pond through the U shaped pair of bays and forcing it back into the pond. Once the through current is established, the sludge bed is disturbed using water lances forcing the sludge into the flow and out of the bay.

FIG. I–57. Flowmaker and bay desludging operations (courtesy of Sellafield Ltd).

Operations to remove the bulk sludge from 6 of the 12 pond bays were completed by 2011, and these bays have been isolated from the main pond by the installation of a blanking plate on the bay door. The methodology has been very successful, removing the bulk of the sludge and enabling solid removal from the bay to commence. This phase will concentrate on the segregation and removal of potentially LLW.

I–8.4.3. Pond skip desludging

The pond contained around 180 fuel skips, which are arranged in a matrix on the pond floor. The skips contain a variety of miscellaneous ILW and fuel. Sludge has accumulated in the skips by a combination of corrosion of the skip contents and through organic material and windblown debris falling into the skips. Sludge has to be removed from the pond skips for three reasons. First, the skips contain a significant proportion of the sludge inventory, which needs to be captured. Second, desludging of the 30 nominally empty fuel skips allows these to be cleaned and exported from the plant; exporting these skips creates space on the pond floor, enabling the sludge to be retrieved from there more easily. Finally, washing the sludge out of the full pond skips creates the opportunity to inspect and, where possible, consolidate skip contents to underpin future ILW and fuel retrievals work.

To enable skip desludging, a skip washing machine and a skip tipping machine have been developed and installed into the pond (see Fig. I–58). Each of the empty skips, measuring 1.8 m × 2.1 m × 1.5 m, is transported to the skip washing machine. Sludge is then washed from the internals of the skip and transferred to the corral using a hydraulic resuspension technique. Recirculating pond water is jetted onto the sludge bed within the skip, gradually entraining the sludge, which is recovered by taking a side stream off to an in-pond corral. The washed skip is then transferred to the skip tipping machine where any solid debris is removed and consolidated into a single skip. The externals of the skip are then washed and the skip exported (see Fig. I–59).

By 2013, this process had been undertaken on over 40 identified nominally empty skips that had been decontaminated to levels that were acceptable for disposal as LLW. Export of these skips has created sufficient space to commence pond floor desludging. Work has continued to wash the remaining skips in the pond, and further removal includes other types of contaminated equipment and redundant metal structures above and below the water line in the pond bays [I–23].

I–8.4.4. Pond floor desludging

Pond floor desludging is again achieved mainly using hydraulic resuspension. A large desludging hood (see Fig. I–60) is deployed in the area of the pond cleared of pond skips and recovers the sludge by a similar method to that used by the skip washer. The desludging hood is transported around the pond by the skip handler and transfers sludge to the corral via a tensioned umbilical system that prevents the skip handler becoming entangled with the sludge transfer lines.

FIG. I–58. Skip tipping machine (courtesy of Sellafield Ltd).

FIG. I–59. Skip export (courtesy of Sellafield Ltd).

FIG. I–60. Sludge hood installation (courtesy of Sellafield Ltd).

While the pond floor desludging hood is ideal for clearing large open areas of pond, a number of other devices have been provided to collect sludge from more inaccessible areas; these include a remotely operated vehicle with a plough and eductor to retrieve the sludge. Lances, pumps and eductors, which can be used from the skip handler mast or from the pond wall, have been provided to move sludge into areas where it can be collected by the sludge hood.

Early operation of the remotely operated vehicle, which was originally fitted with a simple suction eductor, was not as effective as hoped owing to matting of the organic component of the sludge. This matting resulted in blockage of the inlet filter after a very short period of operation. To resolve this issue, the eductor head was changed to an eductor with an integral cleaning and agitation system, which significantly improved the recovery of sludge with the remotely operated vehicle, the two heads of which are shown in Fig. I–61.

I–8.4.5. Operation of the corral

The sludge that has accumulated on the pond floor has generally settled in situ to an average density of approximately 10 wt% solids. The hydraulic retrieval techniques employed to collect the sludge from the pond have the effect of reducing the sludge concentration by at least an order of magnitude. Transferring retrieved sludge to an in-pond corral (shown in Fig. I–62) provides two benefits. It divorces the sludge retrieval programme from the provision of the storage plant, and the corral also has a function in reducing the size and complexity of that plant by concentrating sludge, allowing transfer at higher average solid content.

FIG. I–61. Original remotely operated vehicle during installation and with amended suction head (courtesy of Sellafield Ltd).

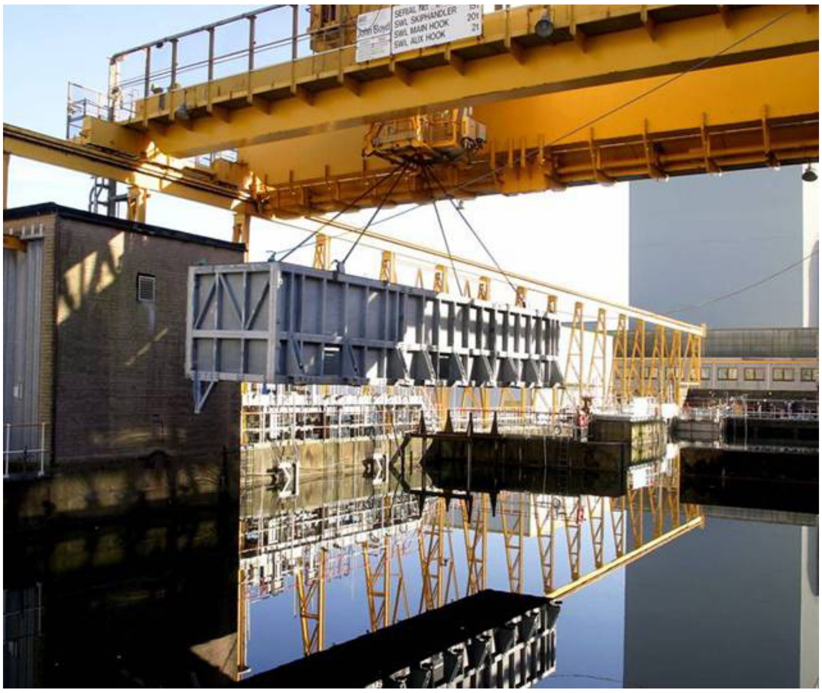


FIG. I–62. Corral installation (courtesy of Sellafield Ltd).

The sludge retrieved from the pond is discharged into the in-pond corral from the skip washing machine, the pond floor hood or the remotely operated vehicle in a very dilute form. The intention is for solids in the sludge to settle in the corral as the retrieved liquid slowly passes through before overflowing back into the pond via a weir. The corral is over 17 m long, which gives sufficient residence time for most of the sludge solids to settle out. The aims are to settle sludge in the corral to provide a bed with 10 wt% solids and to transfer this to the local sludge treatment plant at an average of 5 wt% solids. This initial thickening massively reduces the volumes of liquid that need to be handled by the storage plant and therefore dramatically reduce the size. The corral itself has a capacity of nearly 100 m^3, which allows a significant volume of sludge to be collected from the pond before transfers to the storage plant begin. Initial operation of the corral identified variations in the sludge behaviour and overall corral performance. To address this further, sludge characterization, additional retrieval trials and corral flow regime modelling work have been undertaken. A baffle plate within the corral is also being introduced to improve performance.

I–8.4.6. Local sludge treatment plant storage project

The PFSP local sludge treatment projects provide the facilities to store and eventually passivate the sludge by encapsulation. The plant is being delivered in two phases: the first phase, the local sludge treatment plant (storage) (LSTP(S)), provides the modern stainless steel storage tanks for containment of the sludge retrieved from the pond; the second phase, the local sludge treatment project (export), will provide the capability to passivate and export the sludge for long term storage. The development of two separate projects has enabled work to progress on the facilities to store sludge from the pond earlier than would have been possible for a combined project owing to site constraints, hence accelerating hazard reduction.

The storage plant is built to the north of the pond (see Fig. I–63), on the area cleared earlier in the programme, and contains settling and storage tanks along with facilities to enable future export to the second phase where the sludge will be treated.

FIG. I–63. Construction of the local sludge treatment plant (storage) (courtesy of Sellafield Ltd).

Sludge will be transferred to the LSTP(S) from the in-pond corral, via a dedicated pipe bridge to a settling vessel where the sludge is concentrated from an average of 5 wt% solids to 10 wt% solids. Gravity settling has been selected as the means of carrying out this concentration, as it proved more effective than active thickening processes in trials and generally leads to a simpler plant design. A batch of concentrated sludge accumulates in the settler before it is transferred to one of three bulk storage tanks, each with a capacity of over 100 m^3. The stored sludge is circulated every few days to prevent buildup of flammable gases and to ensure the sludge remains mobile. The plant is also fitted with a sentencing vessel and sampling system that allows the stored sludge to be sampled and eventually discharged to an export facility that will be used to ship the sludge to an encapsulation plant for treatment to enable long term storage.

I–8.5. Metal fuel retrieval

Metal fuel in the form of rods, flat bars, pennies and bits is present throughout the pond and originates from many areas of the UK national nuclear programme. An extensive study of industry records and plant surveys has been undertaken, which has confirmed that where fuel cladding is present, it is either aluminium or Magnox clad and that very little of the fuel is suitable for reprocessing in existing site facilities.

The inventory of fuel in the PFSP is not significant in comparison to the overall site inventory, and will not drive the overall solution to this waste problem. Therefore, the objective for the PFSP programme is to ensure that sufficient infrastructure exists to retrieve the fuel and to export it to the site fuel handling plant, which is to be used to hold the fuel pending the development of the disposal programme. To enable this, the metal fuel retrieval project has been initiated to modify the canned fuel equipment to export metal fuel to the fuel inspection facility where aluminium cladding will be removed and the fuel packaged for transfer to the fuel handling plant.

In parallel to the baseline project work, the programme has successfully undertaken a pilot project to open a direct route from the PFSP to the fuel handling plant for unclad fuel. The incompatibility of flasking capability at each facility required innovative technology and work practices to open this route. The pilot project transferred fuel out of the facility for the first time in 40 years, without the need for significant changes to plant infrastructure. While not being suitable for the entire metal fuel inventory, opening this route still provides significant potential acceleration benefits for the programme.

I–8.6. Solid waste retrieval

Over 700 t of activated and contaminated ILW are present in the pond and will be dealt with as part of the final retrievals phase of the programme. Good records of skip contents were maintained when the pond was undergoing early operations. However, these were not maintained as thoroughly when plant operations ramped down. This has led to significant difficulties in defining the inventory to be dealt with by this project. This is further complicated by the size of the skips and the presence of closed boxes and tins that limits the value of simple visual inspection for inventory determination. Figure I–64 shows typical skips as stored in the pond.

Despite the limitations in records, reviews and surveys have been undertaken and identified around 1000 separate waste types to be dealt with by this project. These include, but are not limited to:

- Fuel cladding (Magnox, aluminium and zircaloy);
- Isotope cartridges, irradiated within the piles and Magnox reactors;
- Reactor furniture, from Calder Hall, Chapelcross and the Windscale piles, in the United Kingdom;
- Residual items of sludge, larger than the sludge recovered during sludge retrieval operations, and original process equipment, such as fuel skips, flasks, decanners, guide rails and trolleys;
- Debris that has fallen into the pond;
- Scrap items that have been stored in the pond as no other waste route was available at the time;
- Ion exchange media.

The baseline strategy for dealing with this waste is to export it to a new purpose built pond solid treatment plant, which is to be built on the site, where it will be treated along with waste from other site facilities. However, to accelerate the decommissioning of the PFSP, the plant operators are striving to decontaminate and segregate material that can be exported as LLW and develop a buffer store where the material can be held in a segregated area while other decommissioning activities take place. Figures I–65 and I–66 shows some of this work in progress (see also Ref. [I–23] for further details).

I–8.7. Pond dewatering and dismantling

Pond dewatering will be the final stage of the retrievals programme. All non-fixed plant and equipment will have been removed in previous phases, and therefore the first operation will be to fix or remove activity from surfaces and remove the pond water. As these activities remain for some time in the future and technology is being developed in similar facilities worldwide, no firm plans for achieving this step are being developed. However, it is critically important for the success of the programme that infrastructure provided for earlier phases will support this work. For example, the LETP provided at the beginning of the programme has been designed to allow modification to empty the pond if required. Dismantling of the fixed structures will then take place as a final phase of work.

FIG. I–64. Video survey image of a fuel cladding and isotope skip (courtesy of Sellafield Ltd).

FIG. I–65. Solid waste retrieval and size reducing (courtesy of Sellafield Ltd).

FIG. I–66. Example of removal of redundant underwater steelwork (courtesy of Sellafield Ltd).

I–8.8. Conclusions

The programme developed for remediation of the PFSP has proved to be effective, with significant inroads having been made in the improvement in infrastructure, provision of retrieval equipment and commencement of retrieval. The programme has also proven to be very robust, having seen limited changes to the technical or logical baseline, despite some of the biggest changes in the history of the UK nuclear industry environment, which has seen the number of stakeholders in the programme expand and diversify.

Excellent progress has been made in transforming the facility and commencing retrievals operations. However, significant progress is still required to remediate the facility. The unknown nature of the remaining inventory and the interactions with the wider Sellafield site remediation programme are likely to remain the greatest challenges. However, the robust work completed to date has ensured that both the facility and the projects to support its remediation have sufficient flexibility to handle these changes.

I–9. MAGNOX PONDS DECOMMISSIONING PROGRAMME, UNITED KINGDOM

I–9.1. Introduction

Magnox operates ten nuclear power plants and one hydroelectric plant in the United Kingdom on behalf of the UK Nuclear Decommissioning Authority (NDA). The ten nuclear sites are located around the United Kingdom in England, Scotland and Wales (see Fig. I–67). A hydroelectric plant is located in Wales on Lake Trawsfynydd, near the Trawsfynydd site. Wet fuel ponds have been used at all sites other than Wylfa, where the used fuel route is dry.

FIG. I–67. Map of Magnox sites and research centres (Harwell, Winfrith) with timescales for entering care and maintenance (courtesy of Magnox Ltd).

Sites are divided into: operating units (only one reactor at Wylfa in mid-2015), accelerated sites, decommissioning sites and fuelled sites. As accelerated sites, Bradwell and Trawsfynydd are being prioritized for entry into care and maintenance by 2015 and 2016, respectively.

Decommissioning of the Magnox fleet is being delivered in accordance with an overarching plan called the Magnox optimized decommissioning programme. This optimizes the order in which sites are decommissioned and the sequence of decommissioning activities at the sites. Delivery of decommissioning activities takes place under the four strategic programmes:

(1) Intermediate level waste programme;
(2) Ponds programme;
(3) Fuel element debris treatment programme;
(4) Plant and structures programme.

These programmes are focused on bringing consistency to activities and maximizing the benefits of learning between sites by transfer of both people and processes. The scope of the ponds programme is:

— Pond decontamination and decommissioning;
— Waste vault decontamination;
— Provision of modular active effluent treatment plants (AETPs);
— Various site specific plant decommissioning activities.

It is notable that no two ponds are alike across the Magnox fleet, although all are of reinforced concrete construction. Key differences include:

— Number of pond chambers and physical configuration;
— Proportion of ponds above and below ground;
— Pondwater treatment provision;
— Proximity to other major structures (e.g. reactor buildings).

It is notable that Hunterston is the largest single pond in the fleet and is partially below ground. By contrast, Chapelcross has two ponds, both of which are predominantly above ground. Figures I–68 and I–69 show the Chapelcross pond before and after draining.

I–9.2. Ponds programme strategy and approach

I–9.2.1. Strategy

The stated Magnox strategy for pond decommissioning is given in the decommissioning and radioactive waste management strategy [I–24]. Generally, this strategy involves decontamination and removal and backfill of the ponds prior to the site entering the care and maintenance phase. However, experience gained at the Bradwell and Trawsfynydd sites is informing a re-evaluation of this strategy. Indeed, it is recognized that consideration of the pond in isolation from the rest of the site is not appropriate and that it may not be practicable or cost effective to try and deliver ‘finality’ before care and maintenance.

Figure I–70 presents a view of the relationship between cost and hazard reduction, although it should be noted that this is just a visual model.

FIG. I–68. Chapelcross pond before draining and decommissioning (courtesy of Magnox Ltd).

FIG. I–69. Chapelcross pond after draining (courtesy of Magnox Ltd).

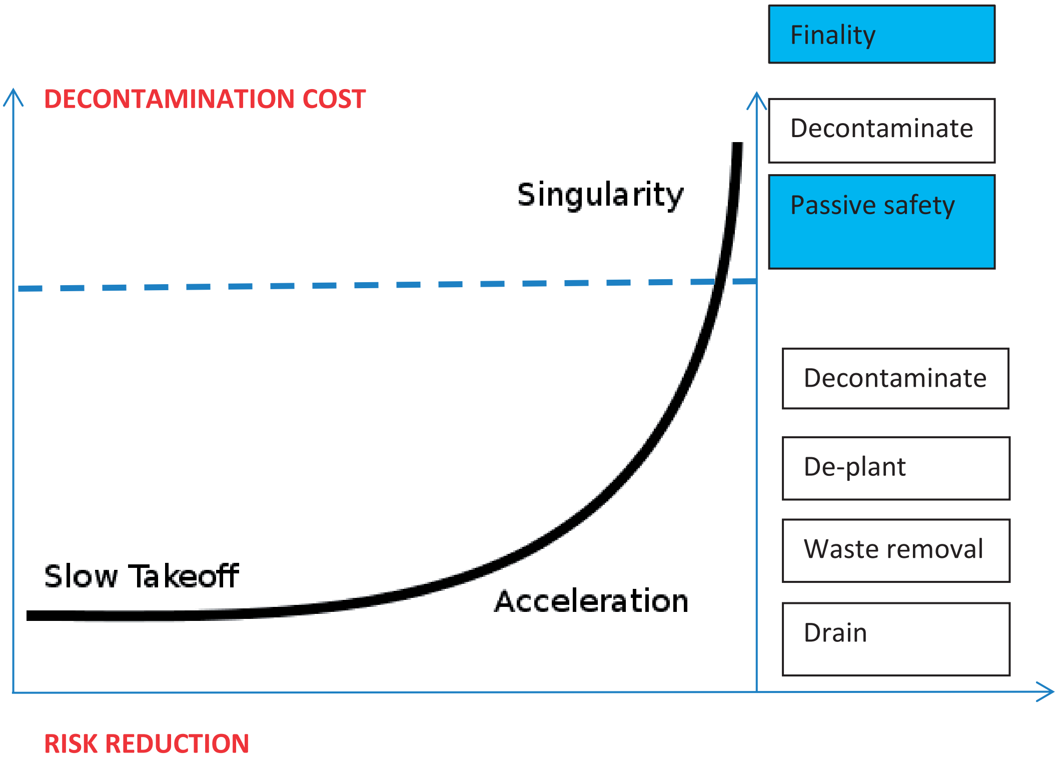
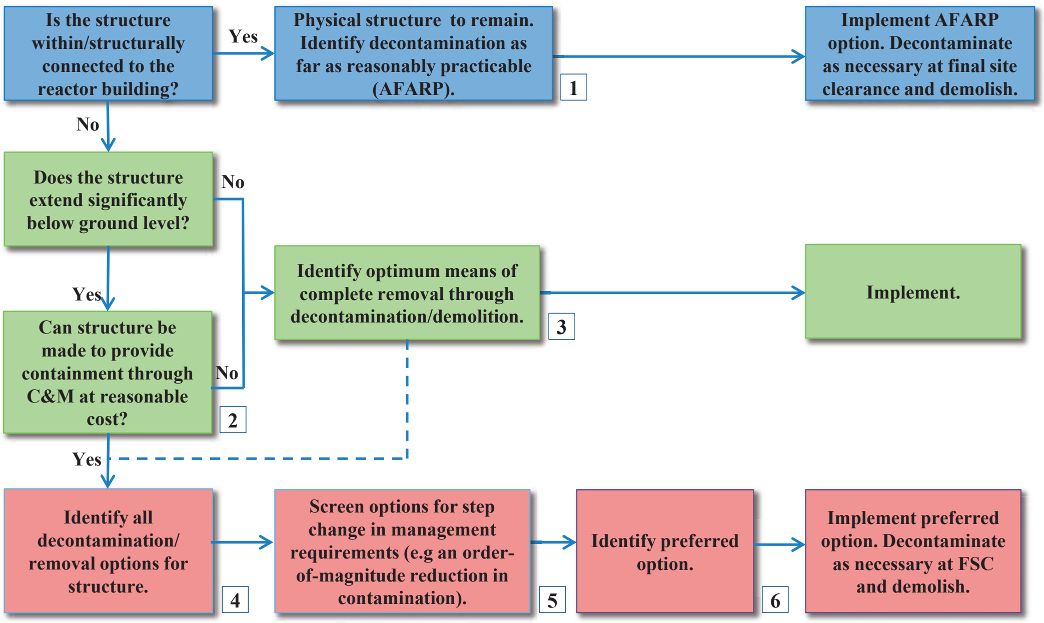


FIG. I–70. Cost versus risk reduction relationship (courtesy of Magnox Ltd).



Note: AFARP — as far as reasonably practical; C&M — care and maintenance; FSC: final site clearance.

FIG. I–71. Contaminated structure care and maintenance entry process chart (courtesy of Magnox Ltd).

The ponds programme team are currently focused on identifying the most practicable and economic care and maintenance entry conditions for each pond. A decision making framework has been developed as a planning tool to enable the care and maintenance entry state for each pond to be identified, see Fig. I–71 and the following explanatory notes:

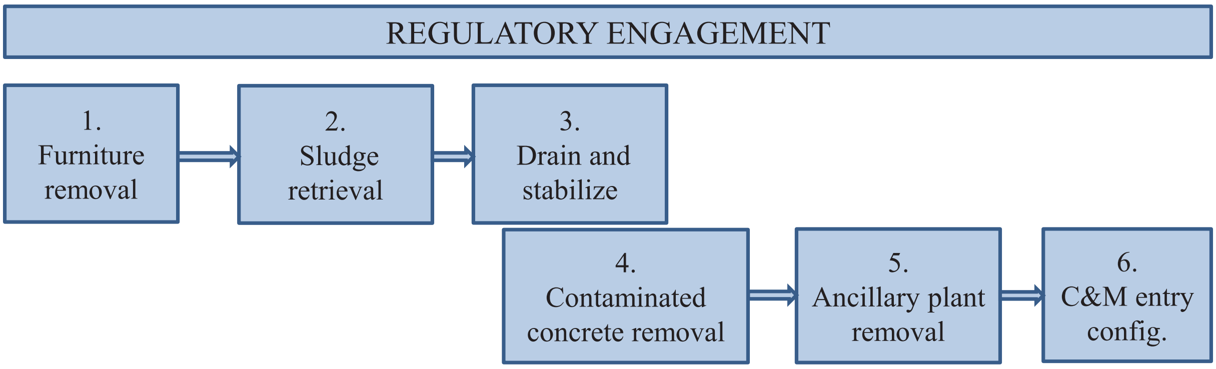
(1) Box 1: Identify the as far as reasonably practicable decontamination option for structures within/structurally connected to the reactor building. Include 'no decontamination' and 'full decontamination' options. The following factors should be considered:
   (a) Short term and life cycle worker dose;
   (b) Short term and life cycle cost;
   (c) Long term maintenance requirements;
   (d) Depth of contamination penetration;
   (e) Presence of double containment or liners;
   (f) Difficulty of structure, or aspects of structure, to decontaminate;
   (g) Benefits of radioactive decay;
   (h) Waste volumes and types;
   (i) Site decommissioning strategy (effect on schedule);
   (j) Other factors as identified in the safety assessment principles.
(2) Box 2: Consider the practicability of ensuring long term containment of the contamination within the structure as influenced by:
   (a) Short term and life cycle worker dose;
   (b) Short term and life cycle cost;
   (c) Long term maintenance requirements;
   (d) Potential ingress and egress of water (interaction of the structure with the water table, transmissivity and hydraulic permeability of the surrounding land);
   (e) Requirement for active control measures (e.g. automatic pump systems) during care and maintenance;
   (f) Timescales for intervention in care and maintenance under fault conditions.
(3) Box 3: If complete removal is inconsistent with the established strategy for surrounding land or structures, consider all management options via (4).
(4) Box 4: 'No decontamination' and 'complete removal' options need to be included in the option assessment.
(5) Box 5: The following screening criteria should be applied to identify a step change in management requirements:
   (a) An order of magnitude reduction in contamination or ambient dose rate levels, or a reduction in the area classification;
   (b) The elimination of a requirement for active control systems or prompt response to faults;
   (c) A significant reduction in future inspection and maintenance requirements;
   (d) A significant reduction in life cycle waste volumes.
(6) Box 6: In addition to the factors outlined in (1), the following should be considered:
   (a) Is there an economic case for removal during care and maintenance preparations?
   (b) Would the benefits of radioactive decay be significant if complete decontamination is deferred?
   (c) Would the complete decontamination or removal of the structure be inconsistent with strategies for adjacent buildings, structures or land?
   (d) Would complete decontamination or removal be inconsistent with strategies for other facilities on-site?
   (e) The ability to produce a case for the strategy considering remaining contamination, the potential for water ingress and any associated authorized discharges from the site (discharge doses relative to 10 μSv/year).

It should be noted that this process is just to enable forward planning. Actual care and maintenance entry states will be determined from physical characterization of the ponds and the decontamination techniques that are most applicable.

Preliminary evaluation using this framework suggests that a care and maintenance entry state of partial decontamination and decay storage is appropriate for most sites.

I–9.2.2. Approach

The Magnox ponds programmes has configured delivery plans to a six step approach that has been determined to optimize early hazard reduction and pond cleanup (see Fig. I–72).



Note: C&M — care and maintenance.

FIG. I–72. Magnox ponds decommissioning: A structured approach (courtesy of Magnox Ltd).

These steps are:

(1) Furniture removal: Plant and equipment stored in the ponds is removed and disposed and sent for recycling. Typically, this will involve the removal of redundant fuel skips, caesium management equipment, pipework and other fixed items within the pond.

(2) Sludge retrieval: Removal of any legacy sludge from the pond.

(3) Drain and stabilize: The pond is drained of liquid via an appropriate water treatment system. The empty pond may then be cleaned and, if deemed necessary, surfaces may be stabilized through the application of a fixative to prevent the production of airborne contamination. Prior to pond draining, assessment of the pond wall and floor radiological and chemical characteristics takes place, which enables determination of whether an aggressive clean is required during draindown to control likely dose and contamination levels. Generally, if the pond is heavily contaminated, the walls will be cleaned using a technique such as hydrolasing as the pond liquid level is dropped. This 'aggressive' clean removes up to 10 mm of material from the wall surface and reduces contamination and dose levels significantly as the liquid is removed from the pond. A by-product of aggressive cleaning is that some level of decontamination through concrete removal is achieved during the drain of the pond. This may negate the need for significant additional concrete removal during step 4. However, this is not the preferred approach if it is not necessary for dose control, as a wet sludge of concrete and paint is generated, which need to be retrieved and managed thereafter.

(4) Contaminated concrete removal: Core samples are taken from the pond walls and floor to enable characterization. This characterization enables determination of how much material removal is necessary from surfaces and joints to establish an appropriate care and maintenance entry condition. Concrete removal may be achieved using a variety of techniques including hydrolasing or dry scabbling.

(5) Auxiliary plant removal: Any remaining pond complex plant is removed, including cranes, heating and ventilation and redundant pipework, to minimize maintenance burdens during the care and maintenance phase.

(6) Care and maintenance entry configuration: During this stage, the physical configuration of the pond required by the care and maintenance safety case will be established. This may involve such activities as full removal of the pond structure, removal of above ground elements of the structure, installation of an overbuilding or capping of voids. It is notable that the degree of demolition prior to care and maintenance may vary from site to site depending on the proportion of the pond above ground level and the site access arrangements for inspection and maintenance during the care and maintenance phase.

The tools for performing each of these steps are generally off the shelf and subject to minimal modification or development. Where a tool does not readily exist in the nuclear industry, potential products are developed from similar industries. For example, the development of freeze plate technology for mixed waste recovery at Bradwell, which is a system that was originally proven commercially in cleaning up sediments in waterways and in chemical plants.

Examples of tools used include:

— Submersible filters;
— Submersible remotely operated vehicles;
— Modular floating platforms (pontoons);
— A submersible mini digger (see Fig. I–73);
— Vortex pumps;
— Hydrocyclone separators;
— Electrocoagulation units;
— A freeze plate system;
— Ultra high pressure (UHP) water jet equipment (hydrolasing).

A standard remote controlled digger, specially adapted for underwater use by removing electrical drives and converting the hydraulics to run with water instead of oil. It is used to consolidate and retrieve sludge at the bottom of ponds, and was developed and used at Hinkley Point A and later Bradwell. Because it was an off-the-shelf product adapted by Magnox staff, it saved thousands of pounds (see Fig. I–73).

I–9.3. Implementation experience

I–9.3.1. Furniture removal: Pond skip disposal

Pond skips have been disposed from Hinkley Point A, Bradwell and Hunterston. Disposal of skips is currently being planned at Chapelcross. The general approach to skip disposal is to clean or decontaminate to a UK LLW category and to send to the UK LLW repository for processing or disposal. It is the preference of the NDA that the disposition of low level metals be managed through the LLW repository, as they have established framework contracts with all leading waste processing organizations and are able to find the most appropriate route for materials in alignment with the waste hierarchy.

At Hinkley Point A, the skips were decontaminated using UHP water removal of paint from their surfaces and were sent directly from Magnox to the EnergySolutions facility at Bear Creek, in the United States of America, where they were combined with metals from other organizations, melted and cast into shield blocks for beneficial reuse in the nuclear industry. The contaminant by-products were disposed of at the Clive facility, in the United States of America.

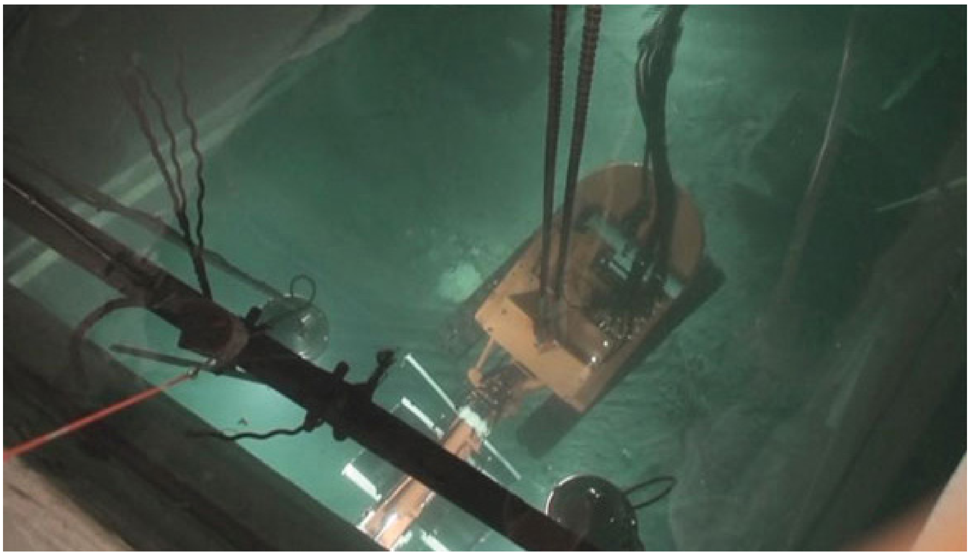


FIG. I–73. Submersible mini digger (courtesy of Magnox Ltd).

At Bradwell, the radiochemical fingerprint of the skips prevented these items being shipped to EnergySolutions as had been performed at Hinkley Point. The strontium component was much higher than at Hinkley Point. Decontamination of the skips through paint removal demonstrated that the contaminants were ‘engrained’ in the parent metal. In this instance, a route was agreed with the LLW repository through Inutec and EnergySolutions, enabling the skips to be used as an interim waste package for British Energy advanced gas cooled reactor desiccant waste. Bradwell was left with four ILW skips that could not be transported. These have been cut up and will be stored along with other ILW pending the availability of a UK repository.

At Hunterston, the skips were site specific and manufactured from aluminium. Pondwater chemistry had created a resilient contamination layer on the skip that necessitated decontamination through pickling in nitric acid. The skips were disposed of to the LLW repository, while the nitric acid will be neutralized and used as part of the grout formulation for the encapsulation of other wastes on-site. Figure I–74 shows a detail of skip disposal activities at Hunterston A. Figure I–75 shows the last of nearly 1200 metal skips being removed from the Hinkley Point A cooling ponds to begin a process which will eventually see it smelted at the Bear Creek facility, in the United States of America.

Fuel skip disposal is currently being considered at the Chapelcross site. Underwater dose surveys suggest that a significant part of the skip inventory may be ILW and that this may be representative of the general situation at many of our sites that share the Sellafield fuel route. Hence, dry decontamination techniques are currently being trialled and evaluated by the Magnox ponds programme team. The lead option currently being trialled is mechanical decontamination using a computer numeric controlled milling machine with simple modifications to ease manual interaction and ensure effective swarf collection. Full scale tests will follow small scale trials performed on coupons from the ILW skips at Bradwell that have demonstrated the potential for very high decontamination factors (>120) with minimal material removal. The full scale trials will enable ‘process’ and dose modelling and optimization of material removal levels to ensure the correct ILW and LLW mix of bulk material and arisings. Magnox are working with and sharing the development trials with Sellafield, which has similar challenges in the storage ponds.

FIG. I–74. Hunterston A skip disposal (courtesy of Magnox Ltd).

FIG. I–75. Hinkley Point A Site, the last of nearly 1200 metal skips is removed from the cooling ponds (courtesy of Magnox Ltd).

I–9.3.2. Sludge retrieval

Two types of sludge have so far been retrieved and managed in the Magnox pond decommissioning activities:

(a) Legacy sludge: Primarily magnesium corrosion products containing caesium and strontium contamination;
(b) Decontamination sludge: A combination of legacy sludge and a concrete or paint based sludge generated through UHP jetting of the pond walls — primarily caesium and strontium contaminants.

Figure I–76 shows a detail of underwater inspection at the Sizewell A pond.

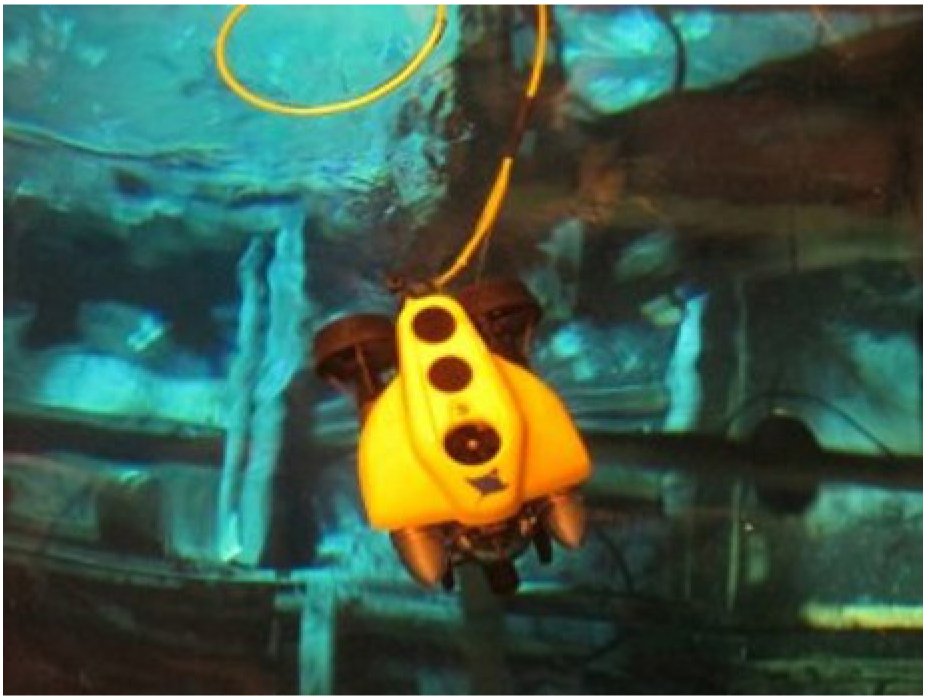


FIG. I–76. Underwater inspections confirm that Sizewell A ponds are empty of nuclear fuel (courtesy of Magnox Ltd).

Sludge is characterized by taking multiple samples and generating a composite fingerprint in reflection of the fact that the sludge will be consolidated for retrieval and disposal. Two phases of sludge retrieval may be performed:

— Bulk sludge retrieval: Prior to drain operations;
— Final cleanup: Following drain (and UHP operations, where applicable).

To achieve bulk sludge retrieval, a number of techniques and combinations of techniques have been applied:

— Use of a modified mini digger underwater to consolidate the sludge into piles on the pond floor (Bradwell and Hinkley Point A) (see Fig. I–73);
— Direct pumping by placing a vortex pump on the sludge pile, which has varied results owing to the presence of particulates (Bradwell, Hinkley Point A and Hunterston);
— Diaphragm pumps passing sludge through a rock basket to separate solids (Bradwell);
— Use of a freeze plate and drumming up the sludge for interim storage pending the ILW retrieval campaign (Bradwell).

The sludge has been accumulated in a variety of ways depending on the site and the available options:

— Passing through sand pressure filters and backwashing to sludge tanks (Hinkley Point);
— Pumping straight to accumulation tanks, settling and decanting water (Hunterston);
— Accumulating and settling in the centre bay (Bradwell);
— Initial dewatering using a hydrocyclone was tested at Bradwell, but gave variable results owing to the presence of particulates.

A key challenge has been the effective separation of the sludge from particulates and miscellaneous items (e.g. residual fuel element debris from past operations). Methods include:

— Passing the sludge through a rock basket in a Tri-Nuc filter housing;
— Passing the sludge through a perforated skip (5 mm pore size);
— Hand picking of the ‘big bits’.

Final cleanup has been achieved using a combination of a modified mini digger and Brokk machines with fitted squeegees and blades.

I–9.3.3. Drain and stabilize

In addition to the Berkeley and Trawsfynydd ponds that were drained some years ago, more recently the ponds have been drained at Bradwell and pond 1 has been drained at Chapelcross. Pond drain commenced at Hunterston in December 2011 and draining of R1 and R2 ponds was conducted at Hinkley Point A.

As described above, it may be beneficial to perform a degree of decontamination during the draindown of the pond. This may ease dose and contamination control and enable the water in the pond to be used as a shield during drainage operations. Hence, before draindown begins, the extent of decontamination is determined from measurements and characterization before pond draining takes place.

Magnox characterize their ponds using underwater core boring and underwater dose mapping, and develop dose models that are developed and tested through drainage of the first 1 m depth of water or through draining a small part of the pond (e.g. dispatch bays at Hinkley Point A). These models inform decisions of whether a light or aggressive decontamination method will be required during draindown.

At Bradwell, the ponds were decontaminated in parallel with draindown using UHP water jetting (hydrolasing). This was performed manually by workers operating from floating platforms on the pond surface (pontoons) (see Fig. I–77). It should be noted that UHP water jet cleaning of the floor was tried, but decontamination factors were found to be low, owing to the liquid effluent recontaminating the cleaned concrete. Hence, this was ceased as the results were not considered to merit the operator dose uptake.

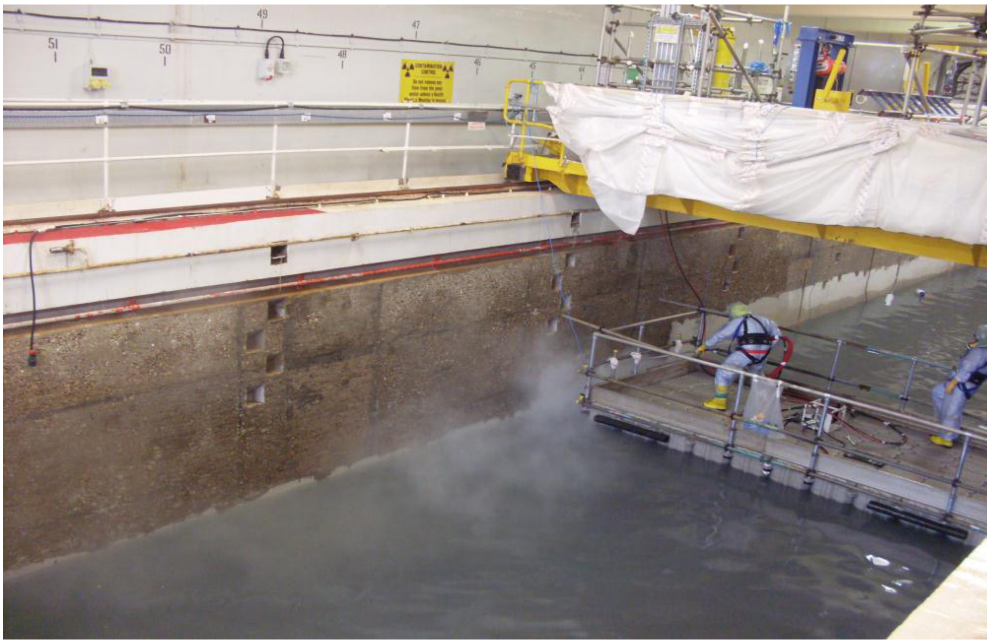


FIG. I–77. Manual hydrolasing of pond walls from pontoon platforms (courtesy of Magnox Ltd).

A challenge experienced during the drain and clean of the Bradwell pond was maintaining water clarity. In an attempt to improve water clarity, an electrocoagulation unit was trialled. However, results were inconsistent. Additionally, vortex separation pumps were used and were more effective. The pond centre bay was used as an accumulation and settling tank. The pond water was discharged via the site's active effluent treatment system.

It is estimated that the decontamination performed during the drain at Bradwell removed upwards of 90% of the radioactive inventory from the pond. Hence, discussions are currently taking place with UK regulatory bodies, the Office of Nuclear Regulation and the Environment Agency, to agree how the pond will enter the care and maintenance phase. The focus is on sealing the floor and lower walls with a robust sealant to minimize the potential for mobilization of actinides from the original paint that has not been removed, rather than further concrete removal. Figure I–78 shows a detail of Bradwell pond drain.

At Chapelcross, pond assessments indicated that it would not be necessary to aggressively clean the pond during draindown. Moreover, water quality assessments indicated that significant treatment would not be necessary prior to discharge. Therefore, the pond was drained using a submersible filter unit (Tri-Nuc) and without a need for further processing (see Fig. I–79).

At Hunterston, it was determined that an aggressive cleanup will be necessary during draindown. Pontoons have been installed across the entire surface of the pond to maximize access to the pond walls, and decontamination was performed using hydrolasing. Characterization indicated that removal of around 6 mm of material from the wall surfaces would achieve in excess of 95% decontamination; hence, this has been set as the target level. Figure I–80 shows decontamination activities in the Hunterston nuclear power plant pond.

In addition, Hunterston has had to install a large AETP to process the pond water before discharge to satisfy discharge authorizations. Commissioning and early operation of this plant was troublesome because the system had been designed to operate with high pH pondwater chemistry, but it is also being used for 'miscellaneous' discharges from active drains that have a more neutral pH. Hence, a bypass filtration arrangement has been installed that enables both streams to be processed.

FIG. I–78. Bradwell pond drained (courtesy of Magnox Ltd).

I–9.3.4. Concrete removal

Other than the concrete removal performed using the UHP water jetting discussed in Section I–9.3.3, significant concrete removal has taken place at Trawsfynydd. Because the site is located next to a lake in the Snowdonia National Park, a dry scabbling approach has been adopted to prevent wet waste production that may have to be discharged into the lake.

Scabbling is performed remotely using rotating heads connected to Brokk machines (see Fig. I–81) and ‘peckers’ for corners, construction joints and cracks. Waste material is vacuumed straight from the scabbling head to waste containers that are double lined with bags and designed to maximize the loading capacity of a half height ISO container. Wastes are sent to the LLW repository for burial.

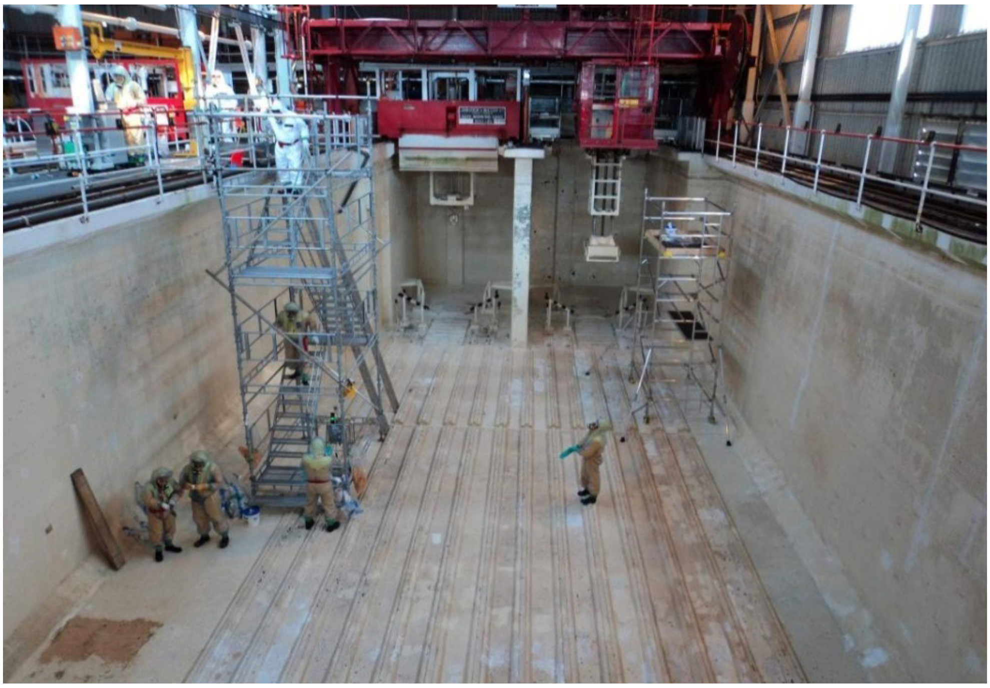


FIG. I–79. Chapelcross pond drained (courtesy of Magnox Ltd).

FIG. I–80. Hunterston pond hydrolasing (courtesy of Magnox Ltd).

Significant improvements have been made in process performance since this work commenced in 2006, and a redesign to the scabbling head has improved reliability and increased the single pass cut depth from 16 mm to 30 mm.

FIG. I–81. Dry scabbling of Trawsfynydd pond lanes (courtesy of Magnox Ltd).

It has been estimated that 40 mm of material removal from the walls will reduce the ponds to UK clearance levels (free release). However, significant difficulties have been experienced decontaminating the construction joints and any cracks in the pond, owing to the degree of contaminant penetration. Moreover, the pond is predominantly below ground, and there is known to be contamination in the land surrounding the pond and in the drains beneath the pond. Hence, a review is currently taking place to identify alternatives to full remediation and an acceptable care and maintenance entry condition.

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Annex II

SPECIFIC EPISODES AND LESSONS LEARNED

The following examples of lessons learned comprise an outline of the problems and challenges encountered at the nuclear pool facilities involved. The situations are typical examples of the difficulties that can arise when planning or implementing the decommissioning of a nuclear pool facility. The information is not intended to be exhaustive, and readers are encouraged to evaluate the applicability of the lessons learned project of their interest.

Readers may also find useful an overview in Table II–1 of the specific episodes and lessons learned to be found in Annex II.

TABLE II–1. OVERVIEW OF SPECIFIC EPISODES AND LESSONS LEARNED

Event	Annex II section numbers
Radiation protection, internal or external exposures	1, 3, 8, 11, 15, 16, 20, 21
Working conditions	1, 11, 17, 21
Technical requirements	2, 12, 14, 18, 19–23
Loss of knowledge, unexpected findings	4, 9, 24
Waste characterization and management	5, 6, 13, 21
Working tools and systems	3, 7, 10, 11, 19, 21, 22
Effluents	2, 20, 23

II–1. REMOVAL OF BERYLLIUM MATERIAL DURING DECOMMISSIONING OF A SLOWPOKE REACTOR, TORONTO, CANADA

II–1.1. Challenges encountered

The Slowpoke (acronym for Safe LOW-POwer Kritical Experiment) is a low energy, tank-in-pool type nuclear research reactor designed by the Atomic Energy of Canada Limited in the late 1960s. The fuel cage is surrounded by a beryllium assembly at the bottom of a water pool about 6 m deep. The beryllium reflects neutrons back into the core. Basically, the reactor is a subcritical mass of fuel, which the surrounding beryllium makes critical. The rate of reaction is controlled by inserting a neutron absorbing cadmium rod. Slowpokes have a maximum power of 100 kW and normally operate at about 20 kW.

The University of Toronto SLOWPOKE-2 Reactor research services ended in December 1998, and the reactor was finally defuelled in June 2000. On 10 November 2000, the Canadian Nuclear Safety Commission (CNSC) issued the decommissioning licence to the University of Toronto for its SLOWPOKE-2 Nuclear Reactor Facility. The reactor decommissioning was completed in January 2001. The beryllium material was to have been shipped under the operating licence, but actually it was shipped under the decommissioning licence.

The CNSC revoked the decommissioning licence for the University of Toronto SLOWPOKE-2 Reactor Facility on 24 February 2012, and the site was returned to the university for unrestricted site use. The following is a description of the incident involving the beryllium material management [II–1].

When the University operators removed the beryllium from the reactor and placed into its container, they found that while the exposure rate at the surface of the container met the regulatory requirements (it was about 1 mSv/h), the exposure rate at 1 m was in excess of the prescribed transport index.

The excess radiation was basically due to the large size of the beryllium sources. Estimates had been based on assuming a point source. The difference in size is probably the reason why the estimates were wrong. This denotes a characterization inadequacy. Subsequently, the operator applied a lead shield to control the radiation field.

The contract the university had with Transportation Logistics Incorporated called for removal of the container from the campus within 24 hours after loading. The destination of the transport was the Savannah River site, in the United States of America. There would have been no incident if there had not been the excess radiation field of about 0.25 mSv/h at 1 m, whereas it needed to be 0.1 mSv or below.

This particular shipment could have been categorized as "exclusive use" and allowed to take place in its current radiation conditions, except that to obtain approval for this in the United States of America may have taken six months or more and leaving this container on campus for any extensive period of time was unacceptable. There was a contingency action in the detailed decommissioning plan, which consisted of applying a lead shield to the container. Incidentally, an exclusive use approach could have been possible in Canada, but this alternative was not at hand.

Another part of the problem was the potential exposure of workers in other parts of the university, especially the mechanical engineering department. The container was in a lane between two buildings and the lane was blocked at one end (like a blind alley); and at the other end, the university established an exclusion zone. Having taken some measurements, the operators did not expect that there would be any significant radiation fields above the university constraint of 2.5 μSv/h in any of the surrounding buildings. However, later on the CNSC inspector who was on-site noted to the university operators that they had made an error in the readings and the actual field at the exclusion barrier was about 17.8 μSv/h. So the operators began surveying within the nearby buildings, particularly the mechanical engineering department, which was the closest to the container. They found that the radiation field exceeded 2.5 μSv in one lecture room. It was about 4.0 μSv. They also found that the field exceeded 2.5 μSv in a lunchroom that belonged to machinists. Fields in excess of 2.5 μSv were also detected at the windows of the building which overlooked the container. The university posted these areas, put up notices that the field exceeded 2.5 μSv/h, and excluded access to those places. A police barrier was erected in a large lecture room and large classes were rescheduled. Smaller classes were relocated away from the exclusion zone. In the meantime, the lead shield had been ordered. It arrived and was applied the following day. The data show that no worker or member of the public was exposed to recordable levels of radiation.

II–1.2. Lessons learned

Radiological characterization (e.g. exposure rates) of materials resulting from nuclear decommissioning is subject to uncertainties. This is especially relevant to the subsequent phases of waste packaging, storage and transport because radioactive pieces can be arranged in different configurations. Exposure scenarios should include a reasonable conservatism.

A specially designed container with internal shielding should be used for shipping beryllium reflectors in order to meet the transport index criterion. The transport plans should include provisions for interim storage of containers. In this case, the university had applied for interim storage at the Chalk River Laboratory (CRL) site. CRL had eventually agreed to take the container with the beryllium shipment, and the university would have probably received approval to do this from the CNSC. But by that time, the university had alternative arrangements in place, as they could ship the container to the United States of America with no need for interim storage.

A contingency plan was available in case of an excess radiation field (which indeed occurred). However, it would have been advisable for the university to have had lead shields on site and to have not had to wait for lead availability. In addition, it would have been advisable to have a contingency plan which provided for alternative storage in the event that a force majeure such as actually occurred would not restrict the transport, as it was foreseen and as the University had a mandatory contract.

II–2. SPENT FUEL BAY CONTAMINATION IN A CANADIAN NUCLEAR REACTOR

II–2.1. Challenges encountered

The large stainless steel liner of the spent fuel bay at a nuclear reactor in Canada [II–2] had been contaminated as a result of storing 23 000 fuel bundles and a number of broken bundles from post-irradiation handling. The contaminated products, including fission products, had to be removed.

II–2.2. Solution found

The stainless steel walls above the water surface were cleaned by hand (with mild abrasive cleaners) and below the surface by means of a swimming pool cleaner. This slowly allowed all the particulates to enter the water. When circulation was complete, the particulates were removed by filters and ion exchange columns until the water quality was better than drinking water standard. After regulatory approval, the contents were then discharged into Lake Huron. The complete process took around six months.

II–2.3. Lessons learned

The decontamination operations required significant time. Any future spent fuel bay should be lined with stainless steel that has an extremely high quality polish finish, including the welds. Experience indicates that biological growth actually concentrated the activity.

II–3. LESSONS LEARNED FROM PREVIOUS WORK IN A GAS COOLED REACTOR FUEL POOL BEFORE DECOMMISSIONING, VANDELLOS NUCLEAR POWER PLANT, SPAIN

II–3.1. Challenges encountered

In the initial phase of the decommissioning of Vandellos I gas cooled reactor in Spain, work was started on the spent fuel pool in 1996 [II–3]. The work included the complete dewatering of the fuel pool, the removal of the pool's contents and the decontamination of pool surfaces and the building. Precautions to mitigate airborne contamination included routine monitoring by a particle filter and worker protection using particle filter masks.

In February 1996, a significant increase of airborne contamination was measured that was mostly ^{241}Am. This was assumed to have been caused by work to decontaminate a large component. After this event, precautions for cutting and decontamination of material required work to be completed inside a confinement, with the workers protected by bubble suits. In addition, surface contamination monitoring upon exiting the building was introduced, and the workers were instructed to take a nasal smear to confirm the absence of alpha contamination.

As more material was retrieved from the pool and the water level decreased, airborne contamination rose once more. Therefore, the use of bubble suits had to be extended to all workers entering the building.

In August 1996, nasal smears indicated contamination by ^{241}Am. This event occurred when a radiation protection worker was assisting other workers taking off their protective clothing. This resulted in the introduction of procedures requiring all radiation protection staff to wear protective masks when helping workers undress after active controlled working.

In April 1997, after a positive nasal smear of several workers, personnel were instructed that, when exiting the building, the bubble suit should not be reused and a protective mask should be retained until thorough skin monitoring was completed at the area boundary. The bioassay analysis associated with the event indicated no internal contamination.

To mitigate the increased airborne activity, the ventilation system was also modified. The building was initially designed to work in overpressure condition. During decontamination operations, environmental surveys did not indicate any contamination outside the building. However, it was considered prudent to reverse the flow of air to mitigate the increased airborne contamination. Preliminary dose estimates for this work were 60 man mSv, but the actual doses were 240 man mSv.

II–3.2. Lessons learned

The relevant lessons learned are as follows:

- Actinides are very toxic, a 200 Bq intake results in a 50 mSv legal annual dose being accrued by the worker.
- Airborne actinides require the use of assisted respiratory protection equipment.
- The undressing process can cause internal contamination if it is not managed properly.
- To aid early detection, nasal smears are an effective tool on exiting the radiation area.
- Monitoring low air concentrations can be difficult owing to interference by radon and other naturally occurring radionuclides.

II–4. CIVIL ENGINEERING KNOWLEDGE, SELLAFIELD, UNITED KINGDOM

II–4.1. Challenges encountered

During preparation for decommissioning of the Sellafield pile fuel storage pond (PFSP), it became apparent that there was limited knowledge of the condition and likely performance of the pond civil structure and that this would significantly reduce the efficiency with which retrievals work could be delivered.

The drawings showing the pond design were over 50 years old, and, in some cases, were in poor condition, with the detail being very difficult or impossible to read. Much of the original civil engineering design analysis was lost. The detailed properties of the original materials of construction were not accurately known in all cases. The performance of the materials over time and any degradation in performance was not accurately known. This impacted on the ability of the civil engineering team to support safety assessments for the facility and future decommissioning projects.

As an example, the pond construction includes an asphalt membrane. The exact construction records and drawings were not easy to interpret. The original bitumen properties are not accurately known. The degradation of the membrane material over time is not known (including ageing effects and radiation degradation effects). These factors make predictions of the performance of the membrane during decommissioning activities and fault scenarios considered in safety cases difficult to predict.

II–4.2. Solution found and analysis

A structured approach was taken to understand what civil engineering information was required to support future projects and safety assessments. Then, a gap analysis was undertaken, and specific work packages undertaken to fill the gaps. To help the team understand this, a ‘knowledge pyramid’, indicating how each level of information would be used to support the overarching assessments, was constructed (see Fig. II–1).

Examples of the types of tasks undertaken to fill the knowledge gaps included:

- Engaging consultants to research and prepare specific material property investigative reports for materials on topics such as the ageing and radiation degradation of asphalt materials that were understood to have been used in the ponds construction;
- Redrawing all key pond drawings to improve legibility and conduct surveys to confirm accuracy where possible;
- Undertaking surveys to identify any signs of degradation of defects.

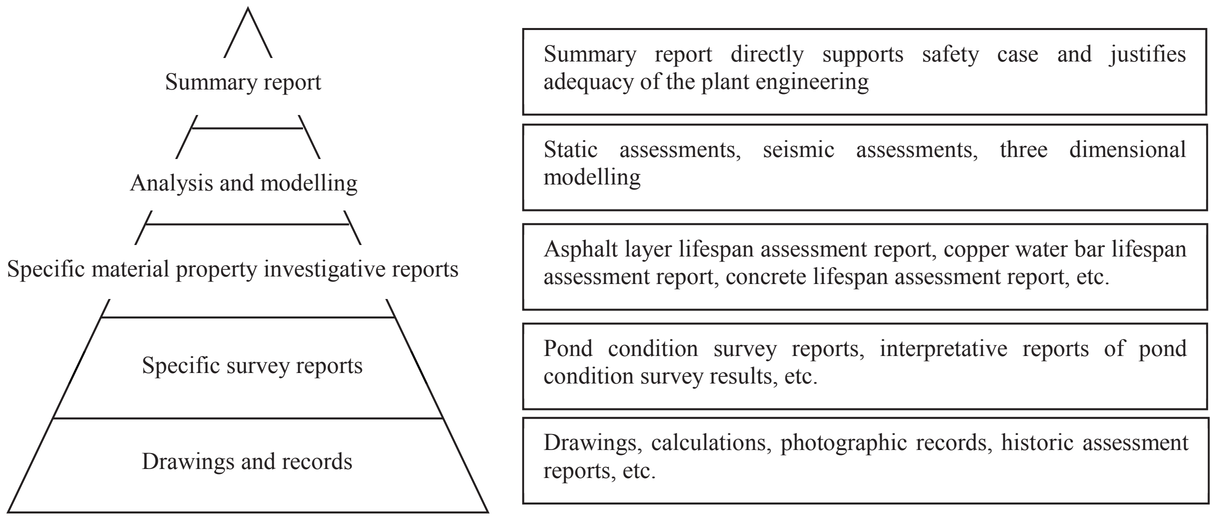

FIG. II–1. Knowledge pyramid.

II–4.3. Lessons learned

As part of the preparation for decommissioning pond facilities, it will be necessary to thoroughly review the extent of available engineering information and to assess whether this is likely to be adequate to support the anticipated projects and safety assessments.

A structured approach to this will allow a gap analysis to be undertaken and to identify areas requiring early efforts. For ageing facilities, it should be anticipated that efforts will be required to restore plant engineering records and undertake assessments of ageing and degradation effects on key structural and containment systems and components. During the preparation of programme and project schedules, allowance should be made for these activities.

II–5. SLUDGE PROPERTIES, SELLAFIELD, UNITED KINGDOM

II–5.1. Challenges encountered

The Sellafield PFSP is an uncovered external pond. In the 50 year period prior to decommissioning, considerable quantities of sludge have accumulated: estimates suggest in excess of 300 m^3. The sludge is dispersed across the pond floor, in around 180 skips located on the pond floor and within 12 bays link to the pond that had previously been used for decanning and withdrawal operations. The sludge is a mixture of fuel and metallic corrosion products, windblown sand and debris, and bio-organic material from both bird guano and algae that grows in the pond. As part of decommissioning the pond, the sludge inventory needs to be removed. Some limited sampling and characterization has been undertaken in the past.

To support the development of sludge retrieval and treatment processes, additional information was required on specific sludge properties, particularly those related to sludge handling (i.e. settling behaviour, rheology and density). In addition, the dispersed nature of the sludge introduced uncertainties about the degree of variation in the sludge properties in different locations, for example sludge within skips and bays was known to have higher proportions of corrosion products, whereas sludge on the pond floor was known to be predominantly degraded organic material. Early sampling campaigns provided limited data, with lack of consistency in how it had been collected. Given the variation in the inventory, the wide range of characteristics of interest to designers and the wide variety of design tasks necessary to complete the work, the available data were inadequate to provide the required project underpinning.

II–5.2. Solution found and analysis

A further programme of sludge sampling and characterization was undertaken, along with trials to improve the understanding of specific properties. For example, 'bell jar' trials were undertaken to understand the sludge settling properties. Importantly, the output from these and all the previous characterization campaigns were collated into a single overview report. This was used as an underpinning reference for design and safety case development. The use of a single approved reference removed the opportunity for inconsistence use of data or protracted debate about which data sources to use.

Further understanding of the sludge has been gained from early retrievals tasks. These found that the sludge properties varied more than expected. In some locations, the sludge was more gritty than expected. In other areas, the sludge was more fibrous in nature and mats together, behaving more like a carpet. The difficulty in accurately predicting sludge properties has resulted in the development of robust retrieval and treatment processes, for example ensuring sludge is screened at source, ensuring sludge transfer devices blend sludge prior to transfer and introducing dual inlets to pumps at different depths to prevent inlet blockages.

Flammable gases, such as hydrogen from radiolysis and corrosion, were anticipated. The bio-organic nature of sludge also introduces the possibility of methane gas generation should the material decay anaerobically. Water industry and university experts were engaged to advise on potential generation rates. Inactive and active trials were also undertaken to fully understand the issues. Provisions to manage flammable gases were included in the design of treatment facilities, with contingencies if trials demonstrated higher flammable gas rates than expected.

II–5.3. Lessons learned

As part of the preparation for decommissioning pond facilities, it will be necessary to characterize wastes. However, it should be recognized that it is difficult to fully characterize wastes that are dispersed over large areas. The design of retrievals and treatment techniques needs to include provisions to make the techniques robust to variations in properties.

It may be necessary to engage experts with specific experience to help understand sludge wastes (e.g. rheologists, microbiologists and experts from other industries that handle sludge). The output of all characterization work should be compiled into a single point of reference that is used to underpin all work on the project. During the preparation of project schedules, allowance should be made for these activities. This approach will be beneficial in removing the opportunity for inconsistence use of data or protracted debate about which data sources to use.

II–6. SOLID WASTE INVENTORY IDENTIFICATION, SELLAFIELD, UNITED KINGDOM

II–6.1. Challenges encountered

The Sellafield PFSP ceased operation in the mid-1960s. Since then, various types of solid wastes have been stored in the pond. The inventory essentially falls into two categories:

(a) Solid waste that is part of the pond infrastructure, such as redundant decanning machines and bogie and rail systems, which need to be decontaminated, dismantled, size reduced and exported from the pond. This includes 'new' equipment provided to assist with effluent treatment and decommissioning activities.
(b) The residual inventory is held predominantly within the pond skips, but some is on the pond floor. This includes residual fuel, miscellaneous wastes from reactor operations and radioactive materials.

The quantities and nature of these solid wastes and items need to be documented to help to plan decommissioning activities. However, for much of the waste, the base design information was not available, and the current condition was unknown. This reflects the age of the pool and its use for storing miscellaneous waste. Many of the wastes had particular characteristics that made them unsuitable for processing when they were first introduced into the pool, and it was recognized that this could be significant for the design of the treatment process.

This problem is compounded with the difficulties in recovering the waste for characterization, which can be as challenging as the main retrieval project work.

II–6.2. Solution found and analysis

Original inventory records were reviewed, along with more recent survey results, project records, drawings and photographs, to help establish a complete listing of all solid wastes. This was supported, where practical, with knowledge capture exercises from the workers who had operated the plant in the 1950s and 1960s.

The details were included in a database that records location, description, origin, dimensions, weight, activity, and dose estimate and condition. All this information was judged to be necessary to help to define how the inventory could be handled in the pond, define the scope of size reduction equipment requirements, define retrieval techniques, establish the most appropriate treatment route for the material, as well as support dose assessment and safety case development. The data also allow retrievals to be planned and realistic timescales to be established.

Responsibility for maintaining the database has been defined so that it can be updated as items are removed, when any newly identified items are identified and when more data about the items in the database become available.

II–6.3. Lessons learned

There is a requirement to define the solid wastes that need to be removed prior to decontamination and dismantling of pool structures. As well as the residual active inventory, consideration needs to be given to installed plant, equipment and support structures within the pool, as these items may contribute to a significant proportion of the inventory.

The data can be used to support definition of retrieval and treatment techniques, as well as to support safety case development and project planning. Plans should also include campaigns of further data gathering, taking advantage of opportunities for improved characterization, which will come from advancements in the pond cleanup programme. For example, removal of sludge provides an opportunity to gain greater understanding of the inventory that may be partially obscured. Similarly, sorting or handling specific wastes may provide information about the condition and degree of corrosion of other wastes.

II–7. BUY IT AND TRY IT APPROACH, SELLAFIELD, UNITED KINGDOM

II–7.1. Challenges encountered

During the decommissioning of the Sellafield PFSP, a number of tools were required for the retrieval of sludge from the pond wet bays. The nature of the sludge and the general environment in the bays, which were very congested with redundant equipment, made it very difficult to fully specify the tools for the work. A particular issue was specifying water lances for mobilizing the sludge.

II–7.2. Solution found and analysis

Typically, pond equipment would be extensively developed and trialled, involving considerable cost and time. As the likely cost of water lances was low and the chances that the equipment would be at least partially successful, it was judged that it was more appropriate to use a ‘buy it and try it’ approach. There was a risk that some of the equipment would be found to be unsuitable and would need to be discarded and disposed of. However, the risks would be offset against the benefits of savings in development trial costs, gaining experience of doing the task (helping to specify the future equipment better, including ergonomics), and whether the equipment proved successful, or partially successful, and some sludge retrieval were achieved.

Three different lengths of lances were deployed initially: two of fixed length and one telescopic length. Initial use showed that the telescopic lance was too heavy and ergonomically awkward and that lances of additional intermediate lengths were required. The other lances were adequate and continued to be used.

II–7.3. Lessons learned

Pool decommissioning activities are likely to require a range of new tools and techniques. Some of these may be expensive and complex, while others may be simple and of low cost. For the latter, it may be better to use a buy it and try it approach, rather than undertaking inactive development trials prior to deployment. Considering this approach for low value equipment may save money and time and increase learning.

Because of the uncertainties associated with decommissioning tasks, project plans should make allowance for some equipment and operations not being fully successful. Some flexibility should be allowed for deployment of alternative approaches, particularly if minimum upfront development has been done.

II–8. WORKER ALPHA CONTAMINATION KEEPS TRAWSFYNYDD POND WORK SUSPENDED, TRAWSFYNYDD, UNITED KINGDOM

II–8.1. Challenges encountered

Decommissioning of the Trawsfynydd nuclear power plant cooling pond was suspended in May 1999, after workers in respirators scraping down contaminated concrete surfaces were found to have inhaled alpha contaminated dust. Whole body monitoring was carried out for those workers involved, and the use of old and possibly lightly contaminated respirators banned. The results of biological samples from the two most affected workers showed that they had received a dose equivalent of around 4 mSv, less than 10% of the annual legal dose limit. There was no release of radioactive material beyond the pond building [II–4].

II–8.2. Analysis

The regulator, Nuclear Inspection Inspectorate (NII), issued an enforcement notice on the licensee, British Nuclear Fuels Limited (BNFL), because of procedural errors and concern that the contravention was otherwise likely to be repeated. The BNFL informed the NII that contamination had been discovered on respirators after they had been cleaned in the laundry. Arrangements were made to provide only brand new respirators pending further investigations. The BNFL attributed the respirator contamination to poor barrier procedures and cross-contamination within the laundry. The NII did not consider enforcement action at this point because the licensee had responded in an appropriate manner.

II–8.3. Lessons learned

This case highlights that the spent fuel environment is likely to generate airborne contamination, particularly during decontamination work, and protective measures should be ensured and regularly checked at all times.

II–9. TUBE DISCOVERED DURING DECOMMISSIONING OF POND, DOUNREAY, UNITED KINGDOM

II–9.1. Challenges encountered

An underwater survey was conducted as part of preparations to decommission the pond adjacent to the Dounreay Materials Test Reactor (MTR) [II–5]. Investigation of a higher than expected radiation reading identified a hollow metal tube on the floor of the pond. The tube measured approximately 45 cm in length and 4.5 cm in diameter. It posed no risk to the workers in its position because it was beneath 4 m of water.

II–9.2. Analysis

Plans were made to remove the tube for further examination.

II–9.3. Lessons learned

The presence of unexpected, undocumented items in spent fuel ponds is a definite possibility, especially in old reactors.

II–10. USE OF PREFORMED POLYVINYL CHLORIDE PACKING AT SELLAFIELD AND MAGNOX SITES, UNITED KINGDOM

II–10.1. Challenges encountered

Removal of the contaminated and radioactive waste from a pool often generated a high volume of bulky waste requiring wrapping for contamination control and disposal. While individually the activity associated with any of these items does not warrant automated solutions, the radiation dose accrued by workers handling the large number of packages can become a problem.

II–10.2. Analysis

Pond furniture and general waste stored within pools can often be disposed of by simple decontamination techniques that enable the items to be disposed of as low level waste (LLW). In most cases, the disposal conditions for acceptance require that the item is wrapped in PVC sheeting, or something similar, to prevent the spread of contamination from the item during handling and disposal operations. The large bulky nature and large number of items to be handled can lead to significant dose uptake for the workers undertaking these tasks, even if the absolute activity associated with any specific item is relatively low. The best means of controlling and reducing this exposure is to reduce the time spent by the workers doing the task, particularly those activities requiring close proximity working.

Significant success has been achieved by utilizing bags, either specifically made for each item or bought with generic features to reduce handling time, such as Velcro fastenings or inbuilt lifting slings. Utilization of these bags often has a secondary benefit of improving the manual handling risk associated with the wrapping operation.

II–10.3. Lessons learned

Utilization of purpose designed wrapping bags or proprietary bags with generic fastening and lifting features significantly reduces the handling time associated with preparing solid waste from the pool. Doing this reduced both the chronic dose uptake to the worker, associated with the large number of operations required, and the manual handling risk of undertaking the work.

II–11. RADIATION PROTECTION IN THE MAGNOX PONDS PROGRAMME, UNITED KINGDOM

II–11.1. Challenges encountered

The Magnox ponds programme is faced with significant and changeable radiation conditions during its decommissioning activities at each of its sites. The ponds programme is typically a people based self-performing group, meaning real time, appropriate radiation advice is critical for effective delivery.

Historically within Magnox, radiation protection has been a compliance group providing advice at arm’s length to its delivery projects. It was seen more as a policing agent than an enabler for work. Both the changing radiation conditions and project demands have proven very difficult to keep up with. This model has been demonstrated to be largely ineffective in the past, resulting in either overly prescriptive advice or a lack of it. In the worst cases, this can result in event or strategy changes, potentially meaning long project delays.

II–11.2. Analysis

The Magnox ponds programme has a different approach to radiation protection. It is now seen as a key part of the delivery side in a project. It is embedded within the project, working permanently alongside the other members of the team. Typically, more resources have been provided to keep up with the changing conditions. The understanding of problems from a radiation protection standpoint is much greater, meaning solutions can be fully considered. Here are two examples of technologies implemented by radiation protection to help aid delivery:

(a) Teledosimetry is used in high radiation environments for tasks such as pond floor cleanup. It uses wireless transmitters and receivers to transmit dose information to a remote computer, where it is monitored constantly. This means workers no longer need constant workface monitoring support. They can also focus on the task in hand and not worry about the dose they are accruing. It also reduces the potential for miscommunication between the work party and those monitoring dosages. A single clear instruction (a siren) is given to the workers when they are approaching their dose limit, indicating for them to leave the area. Using teledosimetry reduces total dosage by 33–50% and improves the efficiency of the workforce.

(b) Historically, within Magnox, work in high radiation airborne environments would have been conducted in airline suits, owing to limited company tolerance for potential internal doses to the workforce. This method of working has a number of disadvantages such as increased time and cost and additional conventional safety issues. Work in such areas wearing respirators is much more effective, but has the potential to incur internal dosages. This is unlikely if managed properly. The ponds programme uses a method of derived air concentration hours (DACh) tracking to assess potential internal doses. This effectively assigns a potential dose to each worker based on air sample results from their location and occupancy time. DACh tracking allows the use of respirators as opposed to airline suits. Studies have shown that this increases the effectiveness of the workforce by two to three times.

II–11.3. Lessons learned

By integrating radiation protection within projects of this type, compliance and delivery can actually be improved. Close radiation protection interaction can result in a more informative and consequently less conservative approach to a solution, meaning less time, cost and effort involved. This relationship results in radiation protection also taking responsibility for delivery of the project and looking at ways in which it can help overcome challenges.

II–12. FOLLOWING THE DATA, MAGNOX, UNITED KINGDOM

II–12.1. Challenges encountered

In pond decommissioning, it may not always be possible to know what to expect. Answering all the questions, or trying to come up with an ultimate solution for the problem at the outset, is almost impossible. As a result, work is very slow to get going. Trying to outline a strategy based on assumptions can be very costly and ultimately unsuccessful. It may be found that the strategy is either far too conservative in its approach, costing more time, money and effort than is required, or that the problem has not been understood well enough, usually leading to a change in strategy, costing more time, money and effort.

II–12.2. Analysis

The key to providing appropriate solutions to challenges in dynamic radiological environments is to understand the actual conditions faced, both conventionally and radiologically, not the assumed or perceived ones. To do this, it is important to try to obtain real data, such as dose rate measurements, physical samples and replication of scenarios, that are likely to be encountered. Typically, the ponds programme has attempted to take small steps to gain real information to allow the next step in a process to be made, for example ‘Do a bit, review. Do a bit more, review. Do a bit more, review’, and so on.

Wherever possible, mini-trials have been conducted to gain real data to inform future decision making. An example of this is draining a small isolated bay within a cooling pond to gain information to help to plan the methodology for draining the entire pond.

A small scale trial such as this is much easier to undertake and can be bounded more simply. The information gained, such as levels of contamination within the concrete walls and floors, and the effectiveness of techniques that can be used for decontamination of these surfaces can all be understood in this type of trial. Radiation protection data (dose rate, loose contamination and airborne contamination) can also be confirmed, thus allowing for appropriate controls to be put in place. Experience has shown data gained through these trials have been very transferable to larger scale work.

All of these data feed into future decision making, with facts being known rather than using a set of assumptions. The small scale trial also has a secondary effect on a delivery base project in that it allows physical work to be delivered. This builds confidence within the team, and also confidence from the stakeholders, in the ability to deliver work in such radiological environments.

II–12.3. Lessons learned

Key points are as follows:

- Do not make too many assumptions about the effectiveness of a technique or the radiological conditions that will be encountered at the outset of a project;
- Try to obtain real data as soon as possible to confirm assumptions;
- Small scale trials are typically easier to get started, and the information they give is essential;
- Getting a project to start physical work in a dynamic radiological environment is important for building confidence and understanding its strengths and weaknesses.

II–13. METAL DECONTAMINATION, MAGNOX, UNITED KINGDOM

II–13.1. Challenges encountered

Ultra high pressure (UHP) water blasting was a successful technique deployed at Hinkley Point A, in the United Kingdom, for an isolated population of pond skips. UHP blasting achieved levels that allowed the skips to be routed via metal melt to the Energy Solutions Bear Creek facility, in the United States of America, which allowed the beneficial reuse of metal in accordance with the waste hierarchy. However, owing to higher levels of ^{90}Sr in the remaining Magnox skips, metal melt was not an acceptable option for the skips.

Decontamination trials were conducted on a representative population of remaining Magnox skips using UHP blasting and UHP blasting with abrasive. The trials demonstrated that for the remaining population of Magnox skips, and skips shared between sites via Sellafield and existing fuel routes, UHP blasting (and other techniques) could not deliver a consistent decontamination factor, or a high enough decontamination factor to significantly and reliably reduce intermediate level waste (ILW) skips to LLW or LLW skips to metal melt acceptance criteria.

Based on the trial results, there was a significant risk that many ILW skips would remain ILW after decontamination with UHP blasting, along with the creation of a secondary wet ILW arising. This, coupled with a significant amount of worker dose expended for no apparent benefit, made direct disposal of the skips as LLW the only viable option. It also demonstrated that a significant amount of the radioactivity was in the base metal, or driven into the base metal by the decontamination processes.

This left disposal as the only remaining option. The skips were combined with other low activity waste streams and disposed of as LLW, using averaging techniques. This technique was viable until recent restrictive guidance was received from the LLW repository regarding methods of averaging the activity of discrete waste items over a waste consignment. The added restrictions from the guidance eliminated the programme’s ability to optimize the number of skips that could be disposed of as LLW, resulting in a further increase in the projected number of ILW skips. This large unexpected rise in ILW skips represented a significant cost increase to processing, storing and disposing of the skips.

This necessitated an investigation into alternative methods of decontaminating ponds skips with the goal of reducing the number of skips that would have to be disposed of as ILW.

II–13.2. Analysis

To address this unexpected cost increase, the programme embarked on an investigation of new technologies that may allow the ILW skips to be reliably reduced to LLW, and the LLW skips reduced to contamination levels that would allow reuse and recycle techniques such as metal melt to once again be employed.

Previous trials, optioneering studies and actual experience on active skips have documented the use of high pressure water jetting, UHP water jetting, UHP water jetting with abrasive, carbon dioxide blasting, metal shot blasting, chemical decontamination, liquid nitrogen blasting and sponge blasting for decontaminating skips. Inadequate or inconsistent decontamination factors, difficult to process or high volume secondary arisings, and inappropriate technology for the local conditions (i.e. wet processes deployed where there is no infrastructure to treat the liquid arisings in a cost effective manner) have so far ruled out these technologies for the remaining skip population.

The most promising technology that emerged was the milling of metal with standard industrial computer numeric controlled (CNC) milling machines. The milling technology appeared to consistently achieve decontamination factors of 10 or greater on ILW skips, without generating secondary arisings beyond the actual material being removed.

II–13.2.1. Milling trials

An investigation into the technology used in modern industrial machine shops revealed that CNC milling machines are robust, highly versatile and extremely accurate machines that can remove metal from surfaces in passes that are less than 100 μm thick.

The technology allows for advanced programming that adjusts for the contour of surfaces and varied geometries, allowing quick set-up times and remote operation of the machine. The machines are completely enclosed and self-contained, providing good confinement of potential airborne hazards and spread of contamination.

The milling trials are being conducted in three steps, with the first two steps being run concurrently. The first step was to size reduce a clean Magnox skip down to five flat pieces (i.e. four side pieces and one bottom piece) at an industrial machine shop. The clean skip pieces were machined on a large milling machine to demonstrate the viability of the process, identify potential problems and develop the procedure for efficiently removing material from the skips.

The second step that ran in parallel with the first step was the milling of ILW coupons from Bradwell, in the United Kingdom, skips using a small bench top CNC milling machine. The small scale active coupon trial demonstrated that 99% of the activity was removed in 14% of the mass. This achieved the goal of taking ILW to LLW using the benchtop milling process.

Based on the success of the first two steps, the third step was taken to procure an off the shelf milling machine that was large enough to machine the size reduced Magnox skips. The full scale trial of radioactive skips will provide data and information to optioneering and best practicable environmental option workshops to determine the path forwards for the company with regard to skip processing.

II–13.3. Lessons learned

The ILW skip problem has shown that the rapid improvement of technologies being developed and used in other industries can provide off the shelf answers for difficult problems within the nuclear decommissioning industry. The philosophy of decommissioning by trial has also proved to be a very efficient way to minimize the safety, nuclear and economic risks of deploying new technologies by breaking down a complicated problem into several smaller problems that can be solved through a series of inexpensive small scale trials.

II–14. INTERIM AND END STATES, SELLAFIELD, UNITED KINGDOM

II–14.1. Challenges encountered

The Sellafield PFSP is an uncovered external pond, currently in the pre-decommissioning waste retrieval phase. Further consideration is now being given to the next phases of decommissioning, including defining interim states and the end state for the facility.

II–14.2. Solution found and analysis

The pond is a substantial structure, including the main pond and a number of connected bays. Historically, there were interconnecting water ducts to adjoining facilities, which are now isolated. The structure is constructed partially below normal ground level. The facility is one of many on a major reprocessing site. Therefore, there are numerous factors to be taken into consideration when evaluating potential interim states and the final end state.

The IAEA publication Redevelopment and Reuse of Nuclear Facilities and Sites: Case Histories and Lesson Learned [II–6] states (footnote omitted):

> "The initial concept of decommissioning management was that of a closed life cycle for nuclear facilities, which entailed the final disposal of waste and the restoration of a site to its original condition. This concept is no longer the only option. Decommissioning should not be an endpoint of a facility or site, but should provide an opportunity for redevelopment and reuse. Total demolition of a facility or site should be only one decommissioning option under consideration, and various redevelopment and reuse options should be explored in the decommissioning strategy."

For this facility, the project team identified a list of potential interim states and end states that included:

— Dark and dry: Interim state (i.e. no services required, all water removed, consideration of how to manage rainwater accumulation in this outdoor facility);
— Dark and wet: Interim state (i.e. no services required, but water not removed and weather protection not required);
— Reuse as a wet store: Interim state;
— Use of the pond as a site water store: Interim state;
— Use the facility to support other site operations: Interim state;
— Interim dry store for wastes: Interim state;
— Interim store for equipment and materials: Interim state;
— Delicensing and reuse for nuclear purposes: Interim state;
— Putting into care and maintenance without waste retrieval: Interim state;
— Removing high hazard items only, then care and maintenance: Interim state;
— Demolish to ground level (leave underground structure and surrounding ground undisturbed): End state;
— Leave complete or partial structure in situ: End state;
— Delicense and release footprint for non-nuclear use: End state.

This list was generated following a literature review and wider consultation. It included evaluation of relevant IAEA publications [II–6, II–7], combined with consultation with others known to be undertaking analogous decommissioning work, both within the United Kingdom and worldwide. The list of projects considered drew experience from Austria, Canada, the Czech Republic, Estonia, France, Germany, Italy, Norway, Slovakia and the United States of America. This included a review of projects involving pools, reactors and non-reactor buildings to help understand wider opportunities.

These options were carried forwards to an initial screening process, with the outcome being a shorter list for more detailed evaluation. The initial screening criteria included technical feasibility, financial consideration, stakeholder and regulator acceptability, alignment with site strategy, benefits and potential negative impacts.

II–14.3. Lessons learned

The experience describes an approach that may be useful to others who are developing their own pool decommissioning strategy. The list of possible interim and final end states should ideally be developed for the specific facility because each situation will be different. Analogous experience from elsewhere should be used to help to inform the definition of feasible interim states and final end states. Consideration needs to be given to the overall site context within which the facility is located.

This section has indicated the range of possible interim and final end states that may be applicable, but this range should not be regarded as an exhaustive list (see also Sections 3.1.2 and I–7.5).

II–15. FUEL POOL DECONTAMINATION PROJECT, UNPLANNED EXPOSURE, WEST VALLEY, UNITED STATES OF AMERICA

II–15.1. Challenges encountered

Operators received unplanned exposures from the uptake of airborne contamination while working on decontamination and decommissioning of fuel receiving and storage (FRS) pool equipment [II–8]. The use of utility water to spray sediment off components that were lifted from the pool likely caused the spread of the airborne contamination. On 10 May 2002, as a lift rack was being removed from the fuel pool, a layer of loose sediment was noted in the bottom channel of the lift rack. Similar to the work previously performed on the bottom section of the weir gate (24 April 2002), an operator used the utility hose to spray out sediment discovered in the channel. The spray was in the direction of the bridge crane operator, who was lifting the rack. A radiation protection technician and other operators were in various locations in the facility. By reviewing the strip chart, it was noted that there was an increase of 200 counts/min in all three continuous air monitors (CAMs) at the approximate time that the spraying was recorded. However, this increase was not high enough to challenge the low CAM set points. No CAMs alarmed, and no personnel contamination was detected while using the personnel contamination monitor.

On 24 May 2002, during a routine annual whole body count, the radiation protection technician who worked in the FRS facility during the aforementioned evolution was discovered to have detectable ^{137}Cs. In addition, on 17 June 2002, an operator who had worked in the FRS during this period was also discovered to have detectable ^{137}Cs, again during a routine annual whole body count. On 2 July 2002, West Valley Nuclear Services Company received confirmatory data, indicating that two decommissioning operators had received a single dose in excess of 1 mSv from the uptake of airborne contamination, which was below the site's annual administrative control level. Preliminary calculations indicated an exposure of around 2 mSv and 1.65 mSv. Although the exposure triggered an off-normal occurrence report, it was well below the West Valley Demonstration Project conservative annual administrative limit of 5 mSv for radiation workers.

II–15.2. Analysis

Because of the unique aspects of the occurrence and the difficulties in isolating the specific cause of the exposures, an independent review was performed to establish direct, contributing and root causes. The review focused on the activities in the FRS facility (the location where the individuals worked) during the period when an upward trend in airborne readings was recorded by CAMs and during which personnel had received detectable doses as measured through annual whole body monitoring. It was concluded that the exposures most likely occurred during the removal of the lift rack (10 May 2002) or during decontamination of the pool gate (24 April 2002), which both involved similar work activities. It is believed that the exposures could have occurred while other activities were introducing energy into the pool (e.g. sparging) or as other components were lifted from the pool and sprayed using the utility hose to remove sediment. This was further supported by an evaluation of the physical and radiological conditions of the pool water.

II–15.3. Lessons learned

For the specific case in question, the following actions were carried out:

— Strengthened hazard evaluation and monitoring to ensure that hazards were adequately re-evaluated when changes in anticipated conditions were encountered (e.g. changes in pool water clarity, and discovery of components with design features that accumulated pool sediments);
— Only allowed use of low pressure spray to rinse (not decontaminate) components to minimize modes for transport of contaminated water;
— Ensured that all decontamination was performed underwater;
— Specified the use of respiratory protection for activities where pool water was disturbed (e.g. sparging, spraying and equipment removal), unless a thorough review was conducted prior to the activity, which indicated that such respiratory protection was not necessary.

In general, changes in environmental conditions that may change the associated hazards were not always readily recognized. In this case, historical data from sample results, previous work performed and expected working conditions were relied upon to prepare the work document. Consideration was not given to the changing water chemistry and the likelihood of contamination in suspension from sediments on components being lifted from the pool. As a result, there was no clear requirement included in the work document mandating that equipment requiring decontamination or the removal of sediment be performed only underwater. Performing this activity underwater would have minimized the spread of airborne contamination.

In addition to performing characterization of environmental conditions where there is potential for the spread of airborne contamination, identifying specific criteria and directions for performing activities in these areas should prevent such an occurrence.

II–16. INADEQUATE WORK PACKAGE DEFINITION RESULTS IN RADIOLOGICAL UPTAKE, HANFORD, UNITED STATES OF AMERICA

II–16.1. Challenges encountered

The majority of a fuel storage basin superstructure was demolished using a generic demolition work package [II–9]. The basin water chiller system, a tube heat exchanger and associated piping, among other things, were known to have internal radiological contamination. A decision to crush the chiller piping resulted in radioactive contamination spread and airborne radiological contamination. Three workers in the area at the time that the crushing took place received low level radiological uptakes.

II–16.2. Analysis

The chiller piping was wet when initially sheared from the chiller unit, and this wetness minimized the release of the internal radioactive contamination during the shearing operation. However, the piping internal contamination dried through a week long exposure to the summer sun and temperatures. Consequently, by the time the pipe was crushed, the contamination had become far more dispersible. While the radiological control organization recognized that there was an increased risk, the project management did not fully understand the magnitude of that risk.

The top level radiological planning documentation specifically identified the chiller piping and other equipment within the demolition area as unsuitable for aggressive void space removal techniques such as crushing. However, this restriction was not effectively carried forwards into the generic demolition work package used.

There was an unwritten intent to create a separate work package for disposition of the chiller and associated chiller piping. However, preparation of such a work package had not been completed at the time that the chiller piping was removed.

The generic work package did not explicitly define the mechanism by which the chiller piping would be dispositioned, nor did it explicitly prohibit disposition via crushing of the pipe to eliminate void space. The project management perceived that various disposition methods could be applied, while also believing that internal contamination could be controlled through application of water sprays. As such, the project management directed that the piping be crushed to eliminate void space so that the piping could be disposed of by use of environmental restoration disposal facility containers.

A nuance in the work package allowed in-field supervisory decisions for demolition and contamination control, and allowed certain decisions of this sort to be made without requiring radiological review. This deficiency resulted in performing work that was not analysed by the ALARA process.

Upon discovery of the contamination, the radiological control technician who found the contamination called a supervisor by radio, and the supervisor and another radiological control technicians responded in street clothing to the area in which the contamination was found. An assumption was made that radon was the likely cause of the instrument readings. This may have led to two additional personnel receiving uptakes, whereas the appropriate response should have been to back out of the suspect area, put on appropriate protective clothing and respiratory protection, and survey in from a known safe area to determine the extent of the problem.

II–16.3. Lessons learned

While the nature of deactivation and decommissioning projects requires that work packages afford some level of latitude for a variety of expected conditions, the project management need to ensure that appropriate scope definition, precautions, limitations and restrictions are well defined and applied to prevent decisions that could result in unanalysed activities or situations.

All involved in work procedure preparation need to conduct a systematic evaluation of upper tier analyses and planning documentation to ensure explicit identification and application of controls, radiological and otherwise.

Sufficient communication among field management, work planners and functional organizations can never be assumed. Project and functional management need to ensure that all assumptions and requirements are documented and understood by all involved in work package preparation and execution.

Project management should validate work planning assumptions during actual in-field execution to ensure that field conditions reflect those analysed. In-field monitoring to measure radiological conditions and validate analysis assumptions could aid early identification of problems.

All personnel need to understand that all indications of radiological or chemical contamination should be considered and acted upon as authentic, and that appropriate response actions always need to be carried out.

Inadequate work scope definition in generic demolition work packages can result in activities being performed for which hazards have not been adequately analysed and appropriate controls established. Appropriate responses upon identification of radiological contamination are imperative. All indications of radiological contamination need to be treated as real.

II–17. EQUIPMENT USED PRIOR TO TURNOVER TO OPERATIONS: LESSONS LEARNED ON COMMUNICATION AND MATERIAL SEGREGATION, SAVANNAH RIVER NUCLEAR SOLUTIONS, UNITED STATES OF AMERICA

II–17.1. Challenges encountered

In late 2013, the procurement of 200 new L-Area bundles was initiated as part of a project to install new storage racks in the L-Area basin. The L-Area bundles are safety significant (SS) aluminum tubes used to contain spent fuel assemblies within the storage racks. Following initiation of rack and bundle procurement, the rack installation project was cancelled with the agreement to fund receipt of the racks and bundles but stop short of rack installation.

During fabrication of the bundles by an offsite vendor, a supplier deviation disposition request (SDDR) was initiated to allow an additional alloy of aluminum and a different fabrication method to be used for fabrication of the bundle lids.

Incorporation of the associated design changes into site drawings was to be performed at a later date due to competing priorities. Fabrication of the L-Area bundles was completed and the bundles were delivered to the L-Area in January 2013. Because the SDDR driven design change had not been incorporated into the site drawing, a decision was made to segregate the bundles to prevent inadvertent use. Operators receiving the bundles were told to barricade the bundles, but the reason for the barricade was not adequately communicated. As a result, the bundles were stored near previously accepted bundles with a barricade that specified only property, plant and equipment (PPE) required to enter. The reason for the segregation was later verbally communicated during weekly safety focus meetings.

In May 2013, during preparations for unloading of an offsite spent fuel shipment, operators were sent to obtain two L-Area bundles. Bundles were selected from the accepted batch. However, owing to issues regarding the fit, lids were selected from the batch of new bundles within the barricade. The bundles were then loaded with spent fuel and stored in the L-Basin racks.

Days later, during a facility walk-down, an L-Area shift operations manager (SOM) noticed that two of the new bundle lids were missing from the barricaded storage area. The on-duty SOM was notified and the facility entered an LCO owing to spent fuel being stored in bundles that were not per the current SS design. The issue was later reported as an ORPS 10(2) Management Concern [II–10].

II–17.2. Analysis

A fact finding meeting was conducted on 20 May 2013 to identify the primary cause and error precursors for the event. The following were identified:

(a) Primary cause: The reason for the segregation of the bundles was poorly communicated to the personnel receiving and storing the bundles. As a consequence, the barricade posting did not include the reason for the segregation, but only PPE required to enter the barricade.
(b) Contributing cause: Follow-up was not performed by operations management/supervision to ensure that the bundles had been properly segregated and the reason for the segregation adequately communicated. The barricade was observed to have been placed but the barricade posting was not checked.
(c) Error precursors:
    — Assumption that the reason for bundle segregation had been adequately communicated;
    — Segregated bundles were stored near bundles authorized for use;
    — Inaccurate perception of risk that bundles would be used prior to final acceptance.

II–17.3. Lessons learned

The following recommendations were given by the operator to prevent re-occurrence:

— Ensure that intent is communicated clearly and confirm intent was implemented.
— Avoid co-locating materials/equipment that has not been accepted for use with approved materials/equipment.

Organization/facility operating experience programme coordinators should share this information with their organization as appropriate, including:

— Management;
— Supervision;
— Others as applicable.

Equipment that has been procured or modified and is pending turnover to operations should be segregated from equipment that has been accepted and approved for use. Segregation should be properly communicated via reliable means such as labelling, signage or procedures, as well as verbally.

II–18. TECHNICAL SAFETY REQUIREMENT VIOLATION AT THE HIGH FLUX BEAM REACTOR DECOMMISSIONING PROJECT, BROOKHAVEN, UNITED STATES OF AMERICA

II–18.1. Challenges encountered

At Brookhaven National Laboratory (BNL) on 6 July 2009, a technical safety requirement (TSR) violation was declared at the high flux beam reactor (HFBR) project, which was a limited scope decontamination and decommissioning project associated with the permanently shutdown reactor [II–11]. The violation extended from performing decommissioning activities within the facility under the incorrect mode. The draining of the spent fuel pool was performed in the warm standby mode when it should have been in the operation mode.

The TSR was developed contrary to the United States Department of Energy (DOE) TSR guidance, which recommends that facility operations should only be carried out in the operation mode. The facility TSR allowed operations to be carried out in both modes. The HFBR operation mode focused on the removal of a small number of highly irradiated components with associated limited conditions of operation (LCO), while the warm standby mode focused on all other tasks in the facility and did not require entry into the LCO.

II–18.2. Analysis

The facility had viewed draining of the spent fuel pool as a low hazard task and that it did not require entering the operation mode because it did not involve highly irradiated components. This was an erroneous decision that could have been avoided if the HFBR mode definitions had been developed in accordance with the DOE guidance, with all facility operations to be performed only by entering the operation mode.

II–18.3. Lessons learned

The possibility of performing activities within a given hazard category (in DOE terminology, 2 or 3), having the non-reactor facility in the incorrect mode is significantly reduced by defining the modes in the TSRs following recommendations in the DOE TSR implementation guidance [II–12]. The DOE TSR guidance recommends that the operation mode should be used for conducting the mission of the facility, and the warm standby mode should be used for maintaining the facility inventory but not performing operations.

II–19. INSUFFICIENT FOREIGN MATERIAL EXCLUSION CONTROLS, HANFORD, UNITED STATES OF AMERICA

II–19.1. Challenges encountered

The Fluor Hanford sludge containerization and hose in hose (HIH) transfer projects were designed to containerize and pump radioactive sludge located in Hanford’s 100 area K east facility to containers located at the K west facility [II–13]. On several occasions, the HIH pumps lost suction, resulting in shutdowns to troubleshoot and backflush portions of the system. During the backflushing operations, material larger than 0.6 cm in diameter, the maximum size the system was designed to carry, was discovered. Items, such as a nut, tape and a ball point pen, were discovered in the HIH system.

II–19.2. Analysis

The sludge containerization system design included 0.6 cm strainers primarily to prevent fuel from entering the containers during vacuuming operations. Therefore, the sludge collected in the containers was assured to be less than 0.6 cm in diameter. However, measures were not taken to ensure foreign material could not enter the open containers, or if foreign material were able to enter the containers, that it would be prevented from entering the HIH system during subsequent transfer to the K west basin. The lack of adequate foreign material controls led to avoidable delays for the sludge containerization and transfer projects. The project failed to realize that settler tubes over the containers, and the container covers would not preclude entrance of foreign material into the sludge containers. in addition, some foreign material entered the containers during construction. Procedures and practices did not specifically address requirements for foreign material exclusion during design.

II–19.3. Lessons learned

Sound engineering, construction and operating practices were not applied with regard to foreign material exclusion during the design, construction and operation of the sludge containerization and sludge HIH transfer projects. Project personnel failed to recognize the need for foreign material exclusion controls to maintain the integrity of their nuclear facility systems.

II–20. DOCUMENTED SAFETY ANALYSIS DID NOT ANALYSE VARIATIONS ON ACCIDENT SCENARIOS, HANFORD SITE, UNITED STATES OF AMERICA

II–20.1. Challenges encountered

DOE-HQ HS-64 performed an independent review of the Waste Encapsulation and Storage Facility (WESF) documented safety analysis (DSA). The review identified a potential concern, which was determined to be a positive unreviewed safety question. The concern related to capsule failure due to drop impact accidents where a dropped load over pool cells could possibly damage a heat exchanger and then impact the capsules stored underwater. Under current DSA analysis, pool cell temperature is assumed at 50°C. If pool cell cooling was lost, temperature would eventually reach boiling (in approximately 11 hours). If capsules failed in the pool cell and water reached boiling, the release would be higher than the release currently assumed in the DSA (increase in consequence) [II–14].

II–20.2. Analysis

The WESF DSA considered an accident related to a dropped load into the pool cells damaging the stored capsules. In this case, the analysis did not factor in that if damage to a heat exchanger resulted in loss of pool cell cooling, temperature would eventually reach boiling, which would increase the consequence of a release. The analysis was part of the WESF Basis for Interim Operations from 1999 and had not been revised or re-analysed since it was originally approved. DOE approved the WESF DSA in 2003. The safety basis documents go through an annual review and approval cycle. However, the reviewers and approvers did not detect this aspect of the analysis during those reviews. Because many of the same people were involved throughout the life cycle of the document, they did not recognize this nuance until an external assessor with commercial nuclear experience raised a question. The WESF mission and associated hazards are unique on the Hanford Site. There was no specific guidance on development accident scenario related to these accident scenarios nor are there lessons learned available from other DOE facilities that might suggest a modification to the analysis.

II–20.3. Lessons learned

Collaborative in-depth reviews are essential in developing Safety Basis documents. Process changes to development and review of safety basis documents have since been implemented, which focus on a collaborative effort between the contractor and DOE in order to provide a more in-depth review. This change is anticipated to provide new perspectives, which may compensate for human error. A comprehensive description of spent fuel pool accident risks at decommissioning nuclear power plants including heavy load drops among others is given in [II–15].

II–21. FUEL POOL CLEANOUT DIFFICULTIES AFTER PLASMA ARC CUTTING, ARGONNE NATIONAL LABORATORY, UNITED STATES OF AMERICA

II–21.1. Challenges encountered

The experimental BWR core assembly was size reduced in the fuel pool; cutting debris subsequently had to be cleaned from the pool using a three part process that consisted of [II–16]:

> “ 1) grips attached to a long pole were used to remove large pieces of material, 2) a dustpan-like scoop was used to remove medium sized pieces and 3) a hydro vacuum was used to remove the fine tailings that remained. The entire operation was estimated to take eighty hours; however, many large pieces hidden by the finer tailings were difficult to maneuver when found. The dustpan scoop tended to ride at the surface of the slag rather than penetrating and gathering the slag. Also, the hydro vacuum became clogged due to the presence of the larger materials. The actual cleanup of the fuel pool took six times longer than expected.”

II–21.2. Lessons learned

A full account of the lessons learned is contained in Ref. [II–16].

II–22. DEGRADATION AND FAILURE OF STORED RADIOLOGICAL MATERIAL CONTAINERS AND PACKAGES, IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY, UNITED STATES OF AMERICA

II–22.1. Challenges encountered

On 3 December 2003, at the Naval Reactors Facility, Idaho National Engineering and Environmental Laboratory, in the United States of America, a canister containing an irradiated non-fuel test specimen failed catastrophically while stored in a water pool [II–17]. The failure made a large noise, dislodged the stainless steel canister made from 10 cm diameter schedule 40 pipe 45 cm long, ruptured its brass cap, and projected part of the cap 3 m away underwater. No injuries or other damage occurred and there was no measurable release of radioactivity to the environment. The brass cap screwed onto the canister, with two nitrile rubber O-rings providing a watertight seal. Investigators found evidence of water leakage inside the canister. Their preliminary conclusion is that during the 14 years the canister was stored in the water pool, the nitrile rubber seals degraded from exposure to high flux gamma radiation emitted from the test specimen. Water leaked into the canister and the canister subsequently resealed tightly as a result of the brass cap’s corrosion. Radiolysis caused the captured water to break down into hydrogen and oxygen gas, pressurizing the canister. (Decomposition of the nitrile rubber could also generate flammable gases.) The investigators concluded that the hydrogen detonated and caused the failure. Although the ignition source is still not clear, it could have been thermal energy from the specimen, reactions from radicals produced by the radiolysis, sparking from interaction of metallic components, or static electricity discharge.

II–22.2. Analysis

At the DOE, the causes and potential consequences from ageing and degradation of radiological material packages have been well known since at least the early 1990s. Then, many packaging configurations intended for only temporary storage became subjected to much longer storage periods. The increased frequencies and mechanisms of radioactive material packaging failures were analysed and disseminated in initiatives such as the plutonium and high enriched uranium vulnerability studies. A considerable effort was made to process or repackage the stored materials. Today, however, there are still radioactive material packages poorly designed for extended storage, as evidenced by recent events.

II–22.3. Lessons learned

Events demonstrate that long term storage of radioactive material containers and packages poses continuing hazards. Corrosion and other degradation of radioactive material packages and their contents, in combination with the buildup of pressurized flammable gases from radiolysis and decomposition, can create the potential for accidents unless such conditions are considered in design and maintenance, and for the actual storage lives of the packages. The following recommendations were issued by the operator:

(a) The design, evaluation, and maintenance of radioactive material packages need to address ageing and degradation of their contents and packaging components.
(b) The design, evaluation and maintenance of radioactive material packages should consider potential scenarios involving combinations of component failures, particularly ageing mechanisms that open and seal containment and vents in combination with those that generate flammable and pressurized gases.
(c) The packaging of radioactive materials in long term storage should be checked to see whether they have design specifications compatible with currently planned storage lives and conditions.
(d) If such design specifications are not met, or do not exist, then the packaging needs to be evaluated for currently planned storage lives and conditions.
(e) Near misses from packaging failures need to be recognized and addressed to prevent future accidents.
(f) When dealing with radioactive material packages that have not been designed to current standards (i.e. legacy materials), always assume that the package is unsafe until it is proven safe or repackaged to current standards.

II–23. DISCHARGE OF POOL WATER TO THE ENVIRONMENT FROM DECOMMISSIONING OF THE BROOKHAVEN NATIONAL LABORATORY BUILDING 830 GAMMA IRRADIATION FACILITY

II–23.1. Challenges encountered

At the end of pool inventory dismantling, water remaining in the pool contained low levels of radioactive and non-radioactive contaminants (^{60}Co: <3.7 Bq/L, Pb: ~12 μg/L, Zn: ~110 μg/L) [II–18]. To comply with site discharge permits, residual zinc content had to be reduced to less than 100 μg/L [II–18]. To achieve this reduction, a system was devised to pass the water through a high capacity (~400 L/min) diatomaceous earth pool filter [II–18]. This method quickly reduced zinc concentrations to below permissible discharge limits. According to Ref. [II–18]:

> "The discharge was delayed for six months because the established BNL procedure for evaluating discharges at BNL was revised shortly after the sources were shipped. While the GIF [Building 830 Gamma Irradiation Facility] pool water was dischargeable under the revised procedure, the procedure itself was not formally approved. The six-month delay occurred because the BNL's Environmental Policy calls for the involvement of stakeholders, including regulators and community groups. Presentations describing the procedure to the Community Advisory Council and the Brookhaven Executive Roundtable were given after the procedure had been reviewed and approved by the BNL Operations Council, the BNL Integration Council, the DOE Area Office, and federal and state regulators."

II–23.2. Lessons learned

Administrative and procedural aspects can play an important role in the decommissioning schedule and careful consideration should be given to the role of all stakeholders in the decommissioning plan.

II–24. LACK OF COMMUNICATION RESULTS IN ENTRY INTO AN UNPOSTED HIGH CONTAMINATION AREA, HANFORD SITE, UNITED STATES OF AMERICA

II–24.1. Challenges encountered

On Friday 11 April 2012, Washington Closure Hanford personnel working at the 100-N Area located on the Hanford Site were removing the concrete lids of the 1303N silos [II–19]. The area was posted as a contamination area (CA) and, due to the lid removal, access to the area was also posted to warn of the fall hazard. The boundary around the adjoining fuel storage basin (FSB) was posted as a high contamination area/high radiation area/airborne radiation area (HCA/HRA/ARA). A pre-evolution brief was held to relocate the HCA/HRA boundary by installing a new fence to demarcate the HRA and portions of the HCA for the FSB. The area between the fences was to be downposted to a CA. A radiological controls technician (RCT) performed a contamination survey in the area to allow the spaces between the fences to be downposted to a CA. During the survey, the RCT found a spot in the south-west corner of 1303N reading above HCA posting levels. No work was performed on or around the posted HCA on Monday 16 April. On Tuesday 17 April, relocation of the water cannons and the 'old' HCA fence were briefed. The work was performed on the radiological work permit for 1303N. Workers entered the CA and removed the water cannons, not knowing they traversed the unposted HCA discovered on Friday. The RCT supervisor and field work supervisor (FWS) assumed that the fall hazard boundary would prevent entry into the uncharacterized area, unaware that workers had already entered. At the pre-evolution brief on Wednesday 18 April, the FWS briefed work around the silos. The RCT covering 1303N stated that the RCT covering the FSB mentioned the unposted HCA by the silos. The RCT supervisor reviewed the survey data and determined there was an entry into an unposted HCA.

II–24.2. Analysis

The HCA information was not clearly communicated to the workers building the new HRA fence nor was it transferred to the Radiological Status Boards for either the FSB or 1303N. The footprint of the 100-N Area is shrinking as work is coming to an end in some of the areas. Because of this, there are overlapping work boundaries, different work groups in close proximity and personnel working in unfamiliar areas during overtime. All of these changes within the work area require extra vigilance by personnel to ensure that access controls and work controls are observed. Personnel need to resist the impulse to look ahead and instead focus on the work at hand. When anomalies and unusual conditions are identified, it is important for personnel making those discoveries to alert their fellow workers and supervision in a timely manner. In those instances where boundaries need to be modified, efforts need to be made to ensure all personnel in the affected work area are made aware of the new boundaries prior to entering impacted areas. Changes to boundaries and postings should be verified by the organization that controls the posting.

II–24.3. Lessons learned

Communication and coordination between work groups is always important, especially when groups are working in close proximity and transferring ownership of work areas.

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GLOSSARY

activation. Process of inducing radioactivity. Most commonly used to refer to the induction of radioactivity in moderators, coolants and the structures and shielding caused by irradiation with neutrons.

biological shielding. Large concrete shielding structure enclosing a reactor shield (bioshield).

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

decanning. Removing the outer cladding of a fuel pin or pellet.

decommissioning. Administrative and technical actions taken to allow the removal of some, or all, of the regulatory controls from a facility (except for a repository or for certain nuclear facilities used for the disposal of residues from the mining and processing of radioactive material, which are ‘closed’ and not ‘decommissioned’).

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

desludging. Process of removing sediments by draining and cleaning (a tank or a pool).

disposal. Emplacement of waste in an appropriate facility without the intention of retrieval.

eductor. Ejector like device for mixing two fluids.

entombment. Disposal of the nuclear facility where it is disposed wholly or partly at its existing location.

fingerprinting. Methodology of assigning an overall inventory including difficult to detect radionuclides by correlation with more easily detectable ones, for example ^{63}Ni by measurement of ^{60}Co.

furniture. Equipment installed within the pool.

hydrolasing. Water blasting at high pressure.

mixed waste. Radioactive waste that also contains non-radioactive, toxic or hazardous substances.

pool. Chamber for storing a research reactor, radiation sources, spent fuel or waste, underwater and usually constructed of mass concrete. Synonymous with ponds and basins.

robot. Automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications. The term ‘robot’ is currently used for systems that have ‘motion’ and ‘intelligence’ rather than being ‘multipurpose’. A teleoperated robot is a robot that can be remotely operated by a human operator.

safe enclosure. Condition of a nuclear facility during the decommissioning process in which only surveillance and maintenance of the facility take place.

scabbling. Mechanical process of removing a thin layer of concrete from a structure. A typical scabbler uses several heads, each with several carbide or steel tips that peck at the concrete. It operates by pounding a number of tipped rods down onto the concrete surface in rapid succession. It may take several passes with the machine to achieve the desired depth.

silo. Dry or wet storage chamber for nuclear waste usually constructed of concrete. Synonymous with vault and bunker. Different from pools and generally outside the scope of this publication.

sludge. Thick, soft, wet mud or a similar viscous mixture of liquid and solid components. The product of corrosion, deposition, amalgamation and partial or total solidification of particles in pools of nuclear facilities.

spalling. Mechanical process of breaking up (i.e. a piece of stone, rock or concrete) into chips or fragments.

spent fuel. Nuclear fuel, removed from a reactor following irradiation, which is no longer usable in its present form because of depletion of fissile material, buildup of poison or radiation damage.

storage. Holding of radioactive sources, spent fuel or radioactive waste in a facility that provides for their containment, with the intention of retrieval.

unrestricted. Use of an area or of material without any radiologically based restrictions.

zircaloy. Any of several zirconium alloys notable for corrosion resistance and stability over a wide range of radiation and temperature exposures, used to contain fuel in nuclear reactors.

ABBREVIATIONS

AETP	active effluent treatment plant
ALARA	as low as reasonably achievable
BNFL	British Nuclear Fuels Limited
BNL	Brookhaven National Laboratory
BWR	boiling water reactor
CAM	continuous air monitor
CIEMAT	Research Centre for Energy, Environment and Technology
CNC	computer numeric controlled
CNSC	Canadian Nuclear Safety Commission
CSN	Nuclear Safety Council (Consejo de Seguridad Nuclear)
DOE	United States Department of Energy
EPRI	Electric Power Research Institute
EUREX	enriched uranium extraction
FGMFSP	first generation Magnox fuel storage pond
FRS	fuel receiving and storage
HEPA filter	high efficiency particulate air filter
HFBR	high flux beam reactor
HIC	high integrity container
HIH	hose in hose
ILW	intermediate level waste
INL	Idaho National Laboratory
ISD	in situ decommissioning
ISFSI	independent spent fuel storage installation
LETP	local effluent treatment plant
LIBS	laser induced breakdown spectroscopy
LLW	low level waste
LOCA	loss of coolant accident
LSTP(S)	local sludge treatment plant (storage)
MTR	Materials Test Reactor
NDA	UK Nuclear Decommissioning Authority
NEA	OECD Nuclear Energy Agency
NRC	United States Nuclear Regulatory Commission
OECD	Organisation for Economic Co-operation and Development
PCB	polychlorinated biphenyl
PFSP	pile fuel storage pond
PVC	polyvinyl chloride
SCK•CEN	Belgian Nuclear Research Centre
SS	safety significant
TEPCO	Tokyo Electric Power Company
THORP	Thermal Oxide Reprocessing Plant
TSR	technical safety requirement
UHP	ultra high pressure
VLLW	very low level waste

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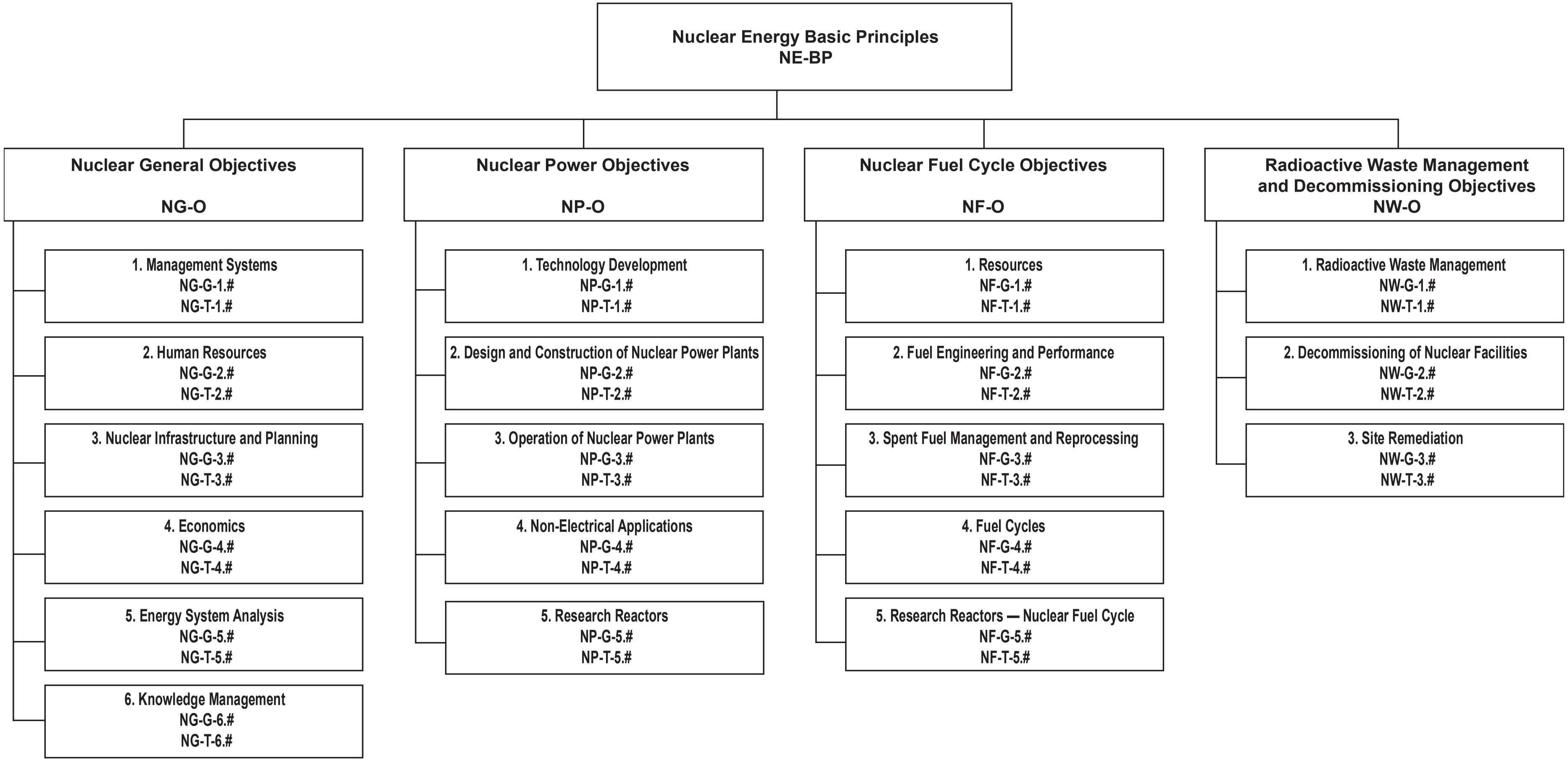

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