WORLD NUCLEAR ASSOCIATION

Methodology to Manage Material and Waste from Nuclear Decommissioning

Waste Management & Decommissioning Working Group

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Waste Management & Decommissioning Working Group,
World Nuclear Association

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of industry experts but does not
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With more nuclear facilities reaching the end of their operating lifetimes – or being prematurely closed due to market forces or national policies – decommissioning and related material and waste management have become global challenges.

This report by the Waste Management & Decommissioning Working Group of World Nuclear Association presents and analyses the full range of international knowledge and expertise, which is based on actual decommissioning experience worldwide.

Despite some specific differences in national policies, a number of common principles have been identified:

- The end state and future use of the site should be defined at the beginning of the life-cycle of the plant, *i.e.* during the planning phase.
- Radiological, physical and chemical inventories should be established as early as possible and updated throughout the operational phase right up to plant shutdown. This information is needed to select the most suitable decommissioning strategy and waste management processes.
- Decommissioning and waste management techniques, operator training, as well as public engagement, should be continuously assessed, and improved where necessary.
- Material from decommissioning should be sorted and segregated in order to maximise the quantity of material to be recycled in a cost-effective and sustainable way. At the same time, the quantity of radioactive waste to be sent for disposal should be minimised in order to preserve waste storage capacity, which should be viewed as a valuable resource.

Although there are differences between countries (*e.g.* regulation, available resources and infrastructure) and/or the objectives of the operators, this report recommends a sequence to best manage decommissioning and waste management, encompassing decisions on: strategy and site end state (Chapter 2); characterisation and inventories (Chapter 3); waste routes (Chapter 4); and waste management (Chapter 5). Underpinning each stage are economic considerations and financial planning (Chapter 6).

Strategy and end state

The decisions on strategy and end state will have a direct and major impact on decommissioning planning and associated costs.

Decommissioning strategy selection requires a wide range of influences including national policy, space requirements, funding, waste disposal availability, fleet closure programmes, future use of the site (including re-use as a nuclear plant) to be taken into account.

End state objectives are not normally determined by the plant operator but according to national goals, policies and regulations that relate to a mix of political, economic and technical criteria. It is important that the plant operator defines the processes and validation approaches to be used prior to commencing decommissioning. This will ensure that resources and waste management are optimised.

Inventories

A materials inventory should be recorded and maintained, starting from the early design phase, continuing throughout operation, and regularly updated.

All information concerning modifications made to the equipment and systems in the course of the facility's operation, as well as about incidents and their consequences that have occurred during operation, should be promptly documented. Prior to the final shutdown of a facility, a decommissioning database should be developed and put in place.

Waste routing

A wide range of waste routes is used worldwide. However, for a given country, not all waste routes may be available for certain waste categories. The objective should be to select waste route alternatives that achieve the site end state efficiently at an acceptable cost.

Following the 'waste hierarchy' principle will increase the effectiveness of existing and planned waste facilities. This means that during design, construction, operation and decommissioning, significant effort should be made to: reduce contamination of structures, equipment and materials; reduce the volume, packaging and transport of resulting waste; re-use or recycle structures, equipment and material whenever possible; and dispose of conditioned waste in a manner that minimises future exposure, repackaging and transport, as well as preserves natural resources.

Treatment and processes

The volume of radioactive waste arising during decommissioning activities and the related treatment are main factors affecting the costs and schedule. Processing and clearance leads to the reduction of radioactive waste volumes and conditioning of the remaining waste makes it suitable for transport, storage and disposal.

The application of the 'waste hierarchy' principle encourages recycling and thus minimises the amount of waste for final disposal.

Decommissioning economics

The cost of decommissioning is influenced by several drivers, in particular waste management, which must be carefully handled to avoid cost escalation and schedule overruns.

Taking into account long-term responsibilities and capabilities, the nuclear plant operator must decide which decommissioning activities to carry out within the company (*e.g.* material inventories) and which ones to contract out to third parties.

Although the costs of waste treatment, conditioning, packaging and transport are not a major part of the overall decommissioning cost, these activities have a strong influence on the schedule and disposal. Avoiding schedule overrun reduces the time-related costs (*e.g.* project management and site operation) and volume reduction lowers the overall disposal costs.

Preface

The nuclear industry has acquired considerable experience, as well as developed good practices, in the decommissioning of nuclear facilities. In 2015, the Waste Management & Decommissioning Working Group of World Nuclear Association decided to produce a report that would bring together this knowledge and expertise, to provide guidance to those facing new decommissioning challenges.

During the plenary sessions of the Waste Management & Decommissioning Working Group and the Annual Symposium of World Nuclear Association, the status of the report was regularly presented to the nuclear community. This allowed the authors to continuously develop and update the report by taking into account new processes, improvements and events. In addition, the authors cooperated with other international organisations (such as the International Atomic Energy Agency, OECD Nuclear Energy Agency and the European Commission) to ensure that the report would complement the findings and objectives of these organisations.

It is intended that *Methodology to Manage Material and Waste from Nuclear Decommissioning* will serve as a practical guide to decommissioning nuclear plants, allowing both established nuclear stakeholders and those new to the industry to learn from past experience. It outlines international good practice and gives details on potential methodologies for decommissioning and dismantling waste management programmes. Where appropriate, the report attempts to summarise the wealth of decommissioning experience and include guidance on the deployment of proven tools, techniques and processes. The report is intended for policy makers, utilities, regulators and other relevant industry participants, especially where there is little developed capability, long-term track record or experience.

World Nuclear Association is the international organisation that represents the global nuclear industry. Its mission is to promote a wider understanding of nuclear energy among key international influencers by producing authoritative information, developing common industry positions, and contributing to the energy debate.

The Association's Waste Management & Decommissioning Working Group contains experts from nuclear operators, vendors, contractors, scientists, analysts and observers. The Working Group monitors developments and shapes industry positions with a view to improving the system of waste management and decommissioning. It promotes the appropriate re-use and recycling of material – and safe disposal of waste – from nuclear sites.

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Terms and definitions

Given that terminology is not always harmonised across the international nuclear community, the authors have attempted to be consistent with internationally accepted definitions where these are available. Definitions of key terms used in the report can be found in: International Atomic Energy Agency (IAEA) Safety Glossary, *Terminology Used in Nuclear Safety and Radiation Protection*, 2007 Edition (STI/PUB/1290); and IAEA *Radioactive Waste Management Glossary*, 2003 Edition (STI/PUB/1155).

1 | Introduction

There are over 450 operable nuclear power reactors around the world, as well as 156 that have already been shut down. In addition there are many enrichment, fuel manufacturing, reprocessing, waste and effluent treatment plants, and other research and ancillary facilities.

In recent years, the question of decommissioning has gained more importance as an increasing number of facilities around the world approach final shutdown. More than 250 operating reactors are older than 30 years, and most of the current commercial nuclear power plants are expected to begin decommissioning by 2040.

Some countries have been decommissioning nuclear power plants and other facilities since the 1960s (*e.g.* UK, USA and Russia). Other countries have relatively young nuclear programmes and are now preparing to commence major decommissioning projects for their nuclear reactors and facilities, for which they might have limited capability.

Although decommissioning is often only considered to be a part of the final stage of a nuclear facility's life-cycle, it has a role in all three phases (*i.e.* design and construction; operation; and post-shutdown phase). Given that many maintenance tasks carried out over the several decades of a plant's operational lifetime are very extensive (*e.g.* replacement of large components), the decommissioning process should be planned not only during the design and construction phase, but also throughout the operational phase. In other words, right from the very start of a facility's life-cycle, economic and operational decisions should take future decommissioning activities into account.

Radioactive waste is generated not only during decommissioning but also throughout the operational phase of a nuclear facility. The management of this operational waste, along with the eventual waste from decommissioning, plays a vital role in both the success of the particular facility and of nuclear power in general. This report focuses on the management of material arising from decommissioning (coming from controlled areas of a power plant or research reactor), which takes place during the post-operational phase.

The scope of the report covers commercial nuclear plants and nuclear research facilities, as well as legacy military facilities, being decommissioned after normal operation. Although light water and graphite reactor types – *i.e.* the most common nuclear technologies – are mainly considered, the methods described can be applied to other nuclear reactor technologies (*e.g.* fast neutron reactors and heavy water reactors).

This report highlights the key principles and stages of efficient waste management processes and good practices. Guidance is provided on:

- Stakeholder engagement to define end states and associated strategies.
- Characterisation and inventories.
- Material classification, acceptance criteria for waste disposal, and establishment of clearly defined waste routes.
- Treatment and optimisation techniques.
- Economics and financial planning, including managing uncertainties and unexpected challenges during dismantling.

Although there are differences between countries (*e.g.* regulation, available resources and infrastructure) and/or the objectives of the operators, this report recommends a sequence to best manage decommissioning and waste management, encompassing decisions on: strategy and site end state (Chapter 2); material characterisation and inventories (Chapter 3); waste routes (Chapter 4); and material management (Chapter 5). Underpinning each stage are economic considerations and financial planning (Chapter 6).

By sharing the methods and lessons learned so that decommissioning becomes increasingly more efficient and economical, public trust and stakeholder confidence in the worldwide nuclear industry will be strengthened.

2 | Decommissioning Strategies

Summary

Decommissioning strategy

- Decommissioning strategy selection requires a wide range of influences including national policy, space requirements, funding, waste disposal availability, fleet closure programmes, future use (including re-use as a nuclear plant) to be taken into account. Hence the selection of the strategy may not be based on technical attributes or operational priorities. Currently, the main considerations are the availability of funding and waste management capabilities, which normally support the option of deferred decommissioning.
- The selection and application of a decommissioning strategy will influence the quantity and category of radioactive waste generated during decommissioning. This in turn affects the complexity of processing methodologies and the provision of suitable handling, transport and storage facilities.
- The selection of a particular decommissioning strategy has a more significant impact on the methodologies for waste processing than the end state criteria, in particular managing hazards associated with the low- and intermediate-level radioactive waste inventory.
- Strategies requiring immediate decommissioning will produce more radioactive waste of a higher category than deferred or entombment strategies, as the benefits of radioactive decay will not be realised.

End state

- End state objectives are not normally determined by the plant operator but according to national goals, policies and regulations that relate to a mix of political, economic and technical criteria. As a consequence, any decommissioning plan will need to take account of both the goal (end point) and how achieving that goal will be validated.
- National approaches to end states normally have stated goals but are not prescriptive on how these are demonstrated or achieved. It is important that the plant operator defines the processes and validation approaches to be used prior to commencing decommissioning. This will ensure that resources and waste management are optimised.
- End state selection will mainly influence the quantity of lower categories of radioactive waste (*i.e.* low- and very low-level waste) created during decommissioning. Scenario planning to significantly reduce or remove requirements for post-decommissioning regulatory controls will require the removal of increased quantities of these lower categories of waste.
- If the selected end state is brownfield, the site will require ongoing management and control to mitigate any residual risks. This is a common scenario for sites to be re-used for future nuclear plant construction.
- The choice of strategy and end state have a direct impact on decommissioning planning. The earlier in the plant life-cycle that the decommissioning requirements and objectives are identified, the earlier the strategy and end state can be defined, allowing the associated finances to be structured in line with the proposed project schedule and activities.

2.1 Introduction

All decommissioning activities create radioactive waste. The categories, quantities and management requirements of the radioactive waste generated are significantly influenced by the decommissioning strategy employed and the end state objective.

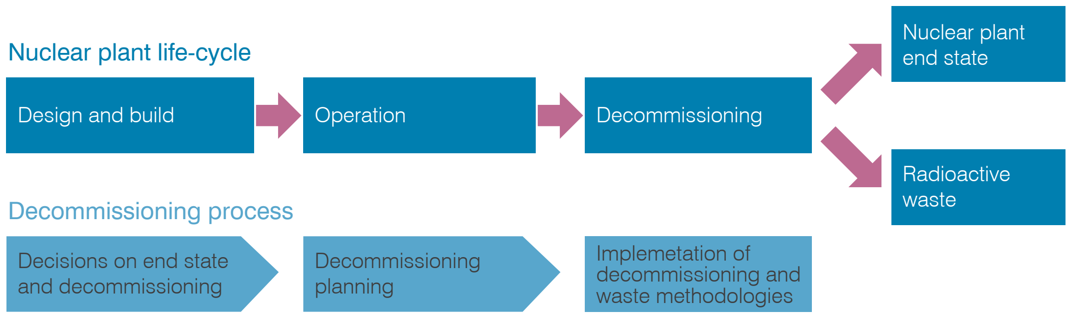


Figure 2.1. Relationship between decommissioning strategy, end state and radioactive waste generation resulting from decommissioning a nuclear plant

Figure 2.1 shows the timing of the decommissioning process in relation to the life-cycle of the nuclear plant. The particular decommissioning strategy and plant end state directly affect the generation of radioactive waste. For example:

- The selection of the decommissioning strategy determines the overall timing and ultimately affects the radioactive waste inventories that need to be managed (see Chapter 3). This in turn affects the methodologies (see Chapter 5) that can be used to generate, process, transport and dispose of (see Chapter 4) the radioactive waste from decommissioning and dismantling.
- The end state affects the proportion of the radioactive inventory remaining onsite after decommissioning, with the balance processed as radioactive waste material for offsite disposal. This has a significant impact on the quantities of waste to be considered for processing and for disposal, as well as on any residual risk requiring ongoing monitoring and control.

2.2 External influences

Decisions on large-scale decommissioning and waste management projects have potentially far-reaching consequences on the local, regional and even national level. As a result, there should be extensive engagement programmes for all the affected parties in order to agree on the decommissioning approach, obtain funding (see Chapter 6) and regulatory approval, define the decommissioning end points, identify waste routes, and plan for future site use. Although stakeholder engagement may require additional time to reach a consensus on the decommissioning plan, the associated clarity in the future can save significant time and money, particularly if agreed early in the life-cycle of the plant.

The major influences on determining the decommissioning strategy and the end states are normally outside the control of the plant operator. The requirements ultimately adopted by the body responsible for decommissioning the plant are driven by the following external factors:

- National, regional and local regulations.
- Policy and socioeconomic factors.
- Future use (including future use for nuclear).
- Available funding for decommissioning.
- Waste route/disposal maturity and availability.
- Waste acceptance criteria.
- External stakeholder influence.

Appendices 1 and 2 provide a summary of national decommissioning strategies and end state requirements (respectively).

Appendix 1 shows that there is often some flexibility on the decommissioning strategy that can be adopted by nuclear plant operators, with the decision criteria normally being heavily influenced by economic factors (see Chapter 6) and waste route availability (see Chapter 4). Due to social, political and land scarcity concerns, national policies on decommissioning civil nuclear plants do not normally support entombment. For an organisation with a fleet of nuclear plants, the timing of reactor closures may result in a peak of decommissioning activity for which the infrastructure and available funding might be insufficient. In such instances, immediate decommissioning may be delayed or consideration given to deferred decommissioning.

The end state describes the accepted completion point of the decommissioning process where the associated limits on radioactive (and chemical) material permitted to remain onsite post decommissioning are defined. Appendix 2 shows that there are national variations on end state goals and associated regulatory requirements. The decision on the end state is influenced by a range of stakeholder influences outside the control of the plant operator. Defining the levels of contamination that remain onsite after decommissioning affects the decommissioning processes used, the extent of remediation works carried out, the quantity of radioactive waste to be processed and transported offsite, as well as the requirements for ongoing monitoring and management.

As discussed in Chapter 4, the radioactive waste infrastructure required for decommissioning is very different from that required for operations. Waste acceptance criteria, processing facilities, export routes, interim storage and disposal capabilities should all be identified and, where needed, established. Recognising that available waste infrastructure is subject to change over time, the availability of waste routes and capacity may influence the timing (strategy) and extent (end state) to which sites are cleared.

2.3 Operator influences

A prerequisite in preparing for an efficient decommissioning project is to clearly define the decommissioning and site remediation objectives (the project end point), which are primarily determined by the selected decommissioning strategy and end state options.

The release of funding for decommissioning projects is dependent on the acceptance of a decommissioning plan with a robust business case demonstrating the ability to achieve the

The 185 MWe Yankee Rowe PWR operated from 1960 to 1992. Decommissioning started in 1992 and was completed in 2007 (image courtesy US Nuclear Regulatory Commission)

desired end state within the funding available (see Chapter 6). The strategy and end state options are influenced by the availability of both the annual and overall funding.

- Where the overall decommissioning funding is required to be focused on the removal of higher-risk waste from the site, leaving low-risk waste onsite, the end state could be affected.
- The availability of funding in any given year will influence the scheduling of decommissioning activities, an issue that can become more acute for national or fleet programmes where a number of plants become available for decommissioning within the same time frame. This scenario normally results in prioritisation and deferment of decommissioning to optimise the annually available budgets, which will affect the choice of decommissioning strategy.

The time elapsed between the end of power generation and the achievement of the decommissioning end point is defined by both the strategy and end state. For example, deferment could introduce a 50- to 100-year extension on an overall decommissioning programme. This raises a number of considerations related to the workforce requirements during decommissioning.

For immediate (near-term) decommissioning:

- Re-skill and refocus existing workforce into decommissioning roles.
- Restructure the decommissioning organisation to efficiently execute decommissioning.
- Prepare external infrastructure and organisations to support radioactive waste generation, *e.g.* regulators, waste recipients, transport, laboratories.

An interim spent fuel storage installation remains on the Yankee Rowe site, with 15 dry storage casks containing 533 spent nuclear fuel assemblies and one cask containing sections of the reactor vessel internals (image courtesy Yankee Atomic Electric Company)

For deferred (longer-term) decommissioning:

- Transfer knowledge of physical and inventory information to the decommissioning workforce.
- Re-engage with external infrastructure and organisations to support radioactive waste generation.
- Re-establish workplace environments and safe operational systems necessary for decommissioning and waste preparation.

These two strategies demonstrate quite different issues to be addressed when preparing a workforce for decommissioning and associated waste processing. The successful implementation of the requirements and approaches discussed in this report requires an engaged and suitably qualified and experienced workforce to deliver a financially sound decommissioning project.

The planned future use of the site to be decommissioned has a significant influence on its end state. Options range from unrestricted future use requiring total clearance, through to accepted restrictions on future use, for example further nuclear development by the operator. If the site or facility is not completely cleared and retains residual radioactivity and contamination, *i.e.* to brownfield status, then stakeholders will need to be consulted on this and agreed ongoing management controls implemented. However, the acceptability of brownfield status may change over time, leading to a risk of intervention in the future.

Table 2.1. Summary of decommissioning strategy options

Strategy Option	Cost Factors	Risk Factors	Regulatory Factors
Immediate dismantling The radioactive inventory associated with the plant at shutdown constitutes the basis of the resultant radioactive waste inventory to be processed during immediate decommissioning. Waste volumes for each category of waste are determined by the volume of material, the distribution of the radioactive inventory, creation of secondary waste and the conditioning factors during decommissioning and waste processing.	High initial cost resulting from controls due to the radioactive inventory and the associated cost of waste processing. Shorter lifetime costs and minimal care and maintenance costs. Cost benefits may be achieved if there is limited alternative construction space for new build.	Increased radiological risks during dismantling and waste processing. Funding requirements forecast over a shorter term with increased predictability. Availability of known waste routes/ requirements with inventory quickly processed to lower-risk forms/storage.	Regulator and stakeholder interface and approach is known and planned for during decommissioning. Reduced risk of escalation of regulatory requirements for waste or end state conditions.
Deferred dismantling As shown in Table 3.1 (on page 24), a nuclear plant reduces the magnitude of the radioactive inventory due to natural decay of short-lived isotopes. As a consequence of this reduction in inventory, there is a reduction in the categorisation and volume of waste to be removed, processed and disposed of.	Some initial costs to prepare the facility for deferment care and maintenance and ongoing site management. Some reduction in costs will be realised during dismantling due to the influence of decay on the radioactive inventory. The acceptance of this approach is reliant upon there being no significant loss of value associated with the plant footprint.	The condition of the plant may deteriorate during the deferment period. Loss of knowledge and skills. Closure of waste routes, increase in waste processing requirements. Difficulty in forecasting future economic conditions, influencing the availability of funding.	Regulator and stakeholder requirements may change in future years to impose more stringent controls over the range of decommissioning activities.
Entombment Not normally recognised as a potential strategy for civil nuclear plants. Uses the existing structure to contain the decommissioning waste *in situ*. The resultant entombed structure effectively becomes radioactive waste within its own disposal site requiring ongoing institutional controls commensurate with the associated categories of waste [1].	Moderate initial costs preparing and implementing the entombment option. Will be followed by long-term, possibly indefinite, site management and monitoring. The financial justification of this approach is reliant upon there being little future value of the site.	If adopted, future changes in national policy may backtrack on authorising this option, requiring subsequent site clearance.	Regulator and stakeholder requirements may change in future years to impose more stringent controls over the long-term management and monitoring requirements.

As discussed later in this Chapter, the strategy and end state selection has a direct impact on the eventual radioactive waste quantities, categories and timing. This in turn affects the associated removal, processing methodologies and disposal/storage requirements that account for a significant portion of the decommissioning budget.

2.4 Decommissioning strategy options

The successful planning and delivery of any decommissioning project requires the agreement and adherence to a fully considered and robust decommissioning strategy. Once selected, the execution of a particular strategy will significantly influence the categories and quantities of waste to be managed. The resulting radioactive inventories and associated processing requirements will in turn affect the decommissioning scheduling and waste disposal approaches needed. Whilst delay may reduce the radiological risks associated with the decaying radioactive inventory, it increases other risks, for example political change, facility degradation, loss of direct knowledge, or implementation of more demanding regulations or waste acceptance criteria.

The decommissioning strategies considered within this report are summarised in Table 2.1.

The decommissioning strategy to be adopted should be established very early in the life-cycle of the nuclear power plant, ideally during design. This allows for:

- An appropriate decommissioning funding model to be established.
- An associated 'design for decommissioning' [2, 3] to be reflected in the eventual plant construction, infrastructure and layout.
- The timing and phasing of decommissioning activities to be determined, *i.e.* the extent of full system decontamination (FSD) post shutdown.
- Determining the proportions of different waste categories affected by the timing of decommissioning and waste reductions accrued through the decay of short-lived radioactive isotopes in order to allow the inventories of radioactive material to be assessed and planned for.
- Assessing the secondary waste volumes to be generated in addition to existing waste.
- Interim and final end state objectives to be defined.

To demonstrate the influence of immediate and deferred decommissioning, reference should be made to Table 3.1 (on page 24) of the mass of activated radioactive waste from decommissioning a VVER-1200 reactor. This Table shows a relationship between deferment period and the quantities of radioactive waste.

From Table 3.1 it is evident that the activity associated with the total waste quantities of the VVER-1200 reduces appreciably over the time frames normally considered for deferment, *i.e.* by 17%. In addition there is an overall reduction in radioactive inventory, which reduces the radiation levels encountered during decommissioning. It should be noted that the influence of deferment decay varies according to reactor type and/or operating history.

Indian Point 1 (pictured centre between units 2&3) was shut down in October 1974 and has been in SAFSTOR since January 1996 (image courtesy Entergy)*

The decommissioning strategy selected influences the approaches to be adopted for the radioactive waste processing. For example, as discussed in Chapter 4, immediate decommissioning will require approaches which promote the prompt removal and processing of higher activity waste whereas deferred decommissioning permits a greater flexibility of approaches such as staged decommissioning, segregation of lower activity waste, and interim storage options.

2.5 Influence of plant end state on decommissioning strategy

The identification of the plant end state is fundamental to defining and planning decommissioning activities throughout the plant's life-cycle. It significantly influences the approach to the later stages of decommissioning and in particular the characterisation requirements and the associated quantities of material to be removed, processed and disposed of as radioactive waste.

Plant end states are frequently determined by national policy (see Appendix 2), but it is not uncommon for a plant end state to be imposed or defined by the regulator. In these instances the operator should define its future plans at an early stage. The determination of an end state objective during the plant's design stage provides valuable direction on the acceptable operating parameters for the site and future planning for decommissioning and waste management [2, 3]. Waste end states (as opposed to plant end states) are discussed in Chapter 4.

* The US Nuclear Regulatory Commission defines 'SAFSTOR' as: "*A method of decommissioning in which a nuclear facility is placed and maintained in a condition that allows the facility to be safely stored and subsequently decontaminated (deferred decontamination) to levels that permit release for unrestricted use.*"

Definition of 'end state'

The International Atomic Energy Agency (IAEA) defines an end state as follows [4]:

1. *The state of radioactive waste in the final stage of radioactive waste management, in which the waste is passively safe and does not depend on institutional control.*
   - *In the context of radioactive waste management, the end state includes both disposal and, if an adequate safety case can be made, indefinite storage.*
2. *A predetermined criterion defining the point at which a specific task or process is to be considered completed.*
   - *Used in relation to decommissioning activities as the final state of decommissioning.*

The UK's Nuclear Decommissioning Authority (NDA) has a similar definition [5]:
The 'end state' of a site is the physical condition of the site at the point at which the NDA has finished its business.

The NDA suggests that this definition does not necessarily require that all radiological material be removed from the site (or facility), since it is possible for the site to remain under long-term institutional control even after the NDA has finished its work.

At the ultimate end of the plant's life, there is a choice of two end state objectives:

- The first option results in the retention of a certain amount of regulatory control (brownfield), *i.e.* the site is re-used with some restrictions, the nuclear plant is removed and the associated radioactive inventory is removed as radioactive waste. Any remaining inventory is normally associated with subsurface structures and low levels of ground contamination. An entombment strategy will have an end state where regulatory controls need to be retained.
- The second option results in the removal of all regulatory control (greenfield), where the site is released from all regulatory monitoring with no restrictions on its future use. The site is cleared of all of its radioactive inventory.

The extent of land contamination may be an important issue in determining the feasibility of specific end states as it can be a major factor in identifying the amount of remediation required and hence waste to be managed in achieving the decommissioning project completion.

It is not uncommon for an operator to identify an alternative route to achieving an end state where an 'interim end state' is proposed. This can entail:

- Decommissioning/decontamination for re-use of the facility (whole or part).
- Preparing for deferred decommissioning.

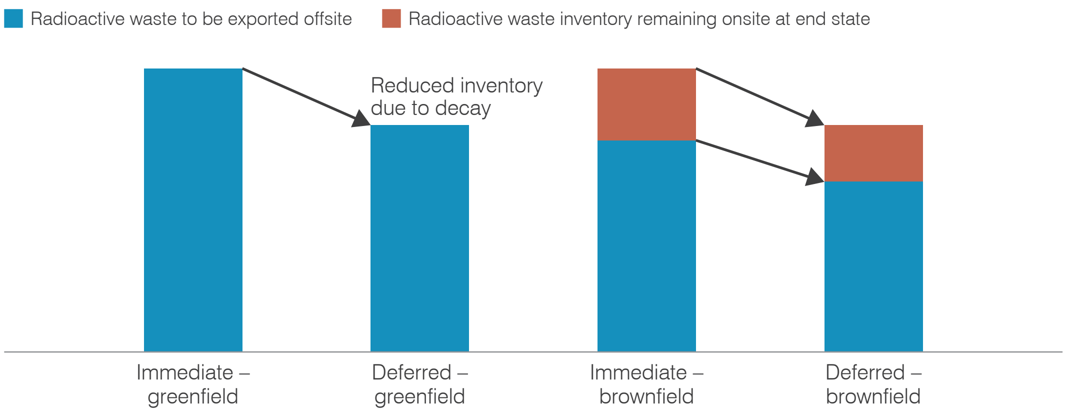


Figure 2.2. Relationship between end state and quantity of radioactive waste exported to offsite disposal/ storage and radioactive waste remaining onsite requiring ongoing regulatory control

For the re-use interim end state scenario, it may be possible to design a reactor system where all the major components (including the pressure vessel) can be removed and replaced periodically. Whilst the removed components will enter the waste stream, the large biological shield and associated buildings are re-used. This approach will provide an effective reduction in the eventual radioactive waste volumes generated compared with the benefit achieved (*i.e.* MWh/m^3 of radioactive waste).

When preparing for deferred decommissioning, the achievement of the interim end state will coincide with a significant change in residual hazard, resulting in reduced regulatory status, monitoring and care and maintenance requirements.

The particular end state that is selected will influence the quantity of radioactive waste generated [6]. Figure 5.1 (on page 44) shows the range of influences on the requirements to process, export and manage the associated radioactive inventory. To summarise:

- The quantity of radioactive waste to be managed offsite reduces in line with that which is to be retained onsite after decommissioning.
- The greater the quantity of radioactive material retained onsite post decommissioning, the greater the potential residual risk, which will require commensurate controls, monitoring, and management arrangements.

The greenfield option, which allows unrestricted future use, requires all radioactive waste to be removed from the site. This can include significant quantities of very low-level radioactive waste (VLLW) or lower category associated with ground contamination, resulting in an increase in the overall volume of radioactive waste to be processed offsite. As illustrated in Figure 2.3, this results in increased waste transport, treatment and disposition costs during the decommissioning period. However, the greenfield option also removes the site from any future regulatory control and as a consequence no future financial provisions are required.

The brownfield option, which results in there being restrictions on future use, normally reflects an approach that aims to optimise the use of capacity and resources over the full life-cycle

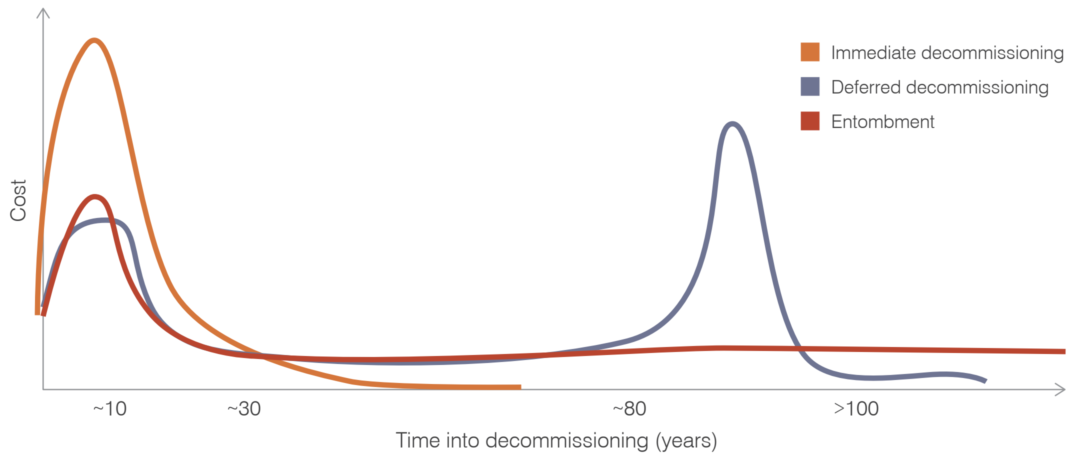


Figure 2.3. Strategy effects on cost and schedule

of a nuclear plant. The small dispersed inventories of radioactive material remaining onsite are normally justified by risk-based arguments recognising potential exposure and future use scenarios. This optimises the quantity of radioactive waste to be processed and exported offsite whilst limiting future management and control requirements. Whilst this approach will reduce waste processing and disposition costs during decommissioning, liabilities and regulatory obligations may remain, requiring financial provision to be made for future years.

Although not normally applicable to commercial nuclear plant decommissioning scenarios, an entombment end state would result in low-level radioactive waste (LLW) and intermediate-level radioactive waste (ILW) being incorporated into the overall inventory of waste remaining onsite. Furthermore, as this waste incorporates the remaining very low-level radioactive waste (VLLW) and clean or exempt waste, this results in an overall increase in the volume of material classified as radioactive waste to be managed onsite. Both the volume and inventory of the remaining waste will influence future controls, monitoring and management arrangements.

As previously discussed, the removal of regulatory controls will involve increased transport, processing and disposal of radioactively (or chemically) contaminated material, which will lead to higher decommissioning project costs. Partial clearance may not be the most suitable economic option, given the potential for the remaining inventory to incur ongoing monitoring and management costs. There is also the underlying risk that public acceptance and regulations might change over time, requiring further remediation of the site with corresponding costs.

2.6 Decommissioning planning

The selection of the decommissioning strategy and end state has a significant influence on which decommissioning activities are required to be carried out and when they should be implemented. This in turn drives the selection of the most appropriate decommissioning approaches and methodologies to achieve the desired objectives. Different technological approaches and sequencing of dismantling, clean-up and remediation tasks are then structured to transform the facility and/or site to its intended end state. A well-developed decommissioning management plan would describe clearly how to achieve the end state in line with the decommissioning strategy.

Successful decommissioning planning requires clear direction (decommissioning strategy), a defined end point (end state definition), planning time, upfront resources, investment and communication. This will facilitate and smooth the process as decommissioning proceeds through the various stages of the project. The best technical and engineering solution can be worthless if it does not provide a financially, socially and politically acceptable solution to delivering the selected decommissioning strategy whilst achieving the selected end state. The following aspects of managing decommissioning waste are developed further throughout this report:

Inventories

The radiological inventory and conditions encountered during decommissioning will influence the approaches and methodologies that can be selected, as discussed in Chapter 3. The removal of regulatory control is normally determined on risk-based arguments, which are based on radioactive inventory and future use considerations. For example, an end state where the site does not require ongoing regulatory control will entail an associated decommissioning plan in which the radioactive inventory associated with the nuclear plant is removed from the site.

Waste routes

The footprint of, and structures/equipment within, a nuclear plant and its associated facilities may constrain what is physically achievable when processing radioactive waste. The ability to process waste is further influenced by offsite waste capacity where, due to non-availability or bottlenecks in offsite storage/disposal capacity, it may only be possible to achieve an interim state or use interim storage solutions until the required waste routes are available (see Chapter 4).

Waste treatment

The treatment, storage and disposal of waste onsite is another potential area of decommissioning risk. As discussed in Chapter 5, the definition of agreed end states and waste acceptance criteria will affect how all categories of radioactive and other waste (*e.g.* mixed waste, heavy metals, organics) are processed. The methodology options will be assessed according to several criteria (such as suitability, feasibility, public acceptance, cost, benefit and risk), resulting in the selection of a preferred approach, thereby also influencing decommissioning and remediation planning.

Planning and economics

As discussed in this Chapter, the strategy and end state have a significant impact on how and when decommissioning activities are carried out, *i.e.* timing, full system decontamination (FSD) requirements, and the quantity and nature of radioactive waste generated. Chapter 6 assesses how these considerations combined with economic constraints will influence the development of a viable decommissioning management plan.

Table 2.2 provides a summary of some of the effects on schedule and cost to be considered when developing a decommissioning management plan.

Table 2.2. Influence of decommissioning strategy and end state on planning

Planning and Estimating Criteria	Decommissioning Strategy Influence	End State Influence
Time schedule	Decommissioning strategy has a direct impact on the scheduling of decommissioning projects due to the defined timing and overall project duration. As discussed in Chapter 6, the duration of decommissioning activities has a significant impact on cost.	More demanding end state requirements will extend the duration of latter stage activities and consequently schedule due to additional remediation and characterisation activities.
Number of stages	Selection of an entombment strategy will reduce decommissioning stages. Deferred decommissioning may introduce interim states.	An end state requiring the removal of regulatory control will require additional stages to be completed and demonstration of remaining conditions.
Quantity and classification of waste	As discussed in Section 2.4, deferral reduces both the quantity and category of radioactive waste to be processed.	As discussed in Section 2.5, delivering an end state leading to the removal of regulatory control will result in increased quantities of waste (of a lower category).
Degree of decommissioning complexity	Immediate decommissioning will involve dealing with the radioactive inventory at the time of shutdown with no decay benefits, resulting in more complex activities associated with increased waste volumes of a higher category.	Whilst the main decommissioning tasks are not affected, there may be some complexities in measuring and demonstrating end state compliance.
Influence of decommissioning strategy on full system decontamination (FSD)	FSD may be integrated with early decommissioning activities for immediate decommissioning. For deferred decommissioning and entombment there may be more reliance on time-based decay to manage radioactive hazards.	The end state has very limited impact on FSD unless the nuclear plant has some external systems which will be removed during FSD. The end point status of these systems should therefore be taken into account when planning these activities.
End state requirements and associated demonstration	The entombment strategy is the only strategy which directly influences the end state due to the associated radioactive waste material remaining onsite – effectively creating a waste disposal site.	The delivery of more demanding end state criteria (*e.g.* removal of regulatory control) will require more challenging remediation and measurement activities. The extent of remaining regulatory control will be determined by risk-based analysis.

Continued on the next page

Regulation	Immediate decommissioning provides the most rapid route to reducing and ultimately removing regulatory control. Deferred decommissioning extends the duration of regulator interaction until decommissioning is completed. Entombment will require ongoing regulatory controls commensurate with the remaining radioactive inventory.	In line with the end state description, retention of regulatory control may be the end state objective requiring ongoing management and monitoring, whereas removal of regulatory control requires no future regulatory constraints.
Condition of the facility after final shutdown (material and radiological)	Regardless of strategy, other obligations on the plant operator should aim to achieve a known minimised contained inventory.	The specific end state has no influence. The plant operator should aim to achieve a minimised contained inventory.
Available waste management infrastructure	Immediate decommissioning may require the provision of interim waste management arrangements if the final waste export routes are not available. Deferred decommissioning can delay the timing until these routes are available.	The quantity of waste material removed to achieve the desired end state may require extensive characterisation, transport and disposal capacity.
Available financing	Immediate decommissioning imposes a definitive date when decommissioning funding is required. Deferral can introduce a degree of flexibility as well as uncertainty, and can also increase the overall schedule. As discussed in Chapter 6, the duration of decommissioning activities has a significant impact on cost.	More demanding end state criteria may impose a degree of risk to the funding due to uncertainties in subsoil conditions and demonstrating clearance. Retention of regulatory control requires funding to be made available for post-decommissioning management.

3 | Inventories

Summary

- A materials inventory should be recorded and maintained, starting from the early design phase, continuing throughout operation, and regularly updated. A correctly performed inventory eases maintenance during the several decades of operation and will reduce uncertainties during decommissioning. Accurate inventory preparation will reduce costs, help to remain on schedule, and avoid changing technical solutions.
- A complete inventory needed to perform efficient decommissioning is based on three components – physical, radiological, and chemical/biological. This involves considering what information is needed and the means to provide it.
- Since every reactor facility has its own specific properties, operation history, layout, chemical composition of materials, *etc.*, each individual facility would normally require an independent calculation of the induced activity levels in its construction and shielding materials at the time of its decommissioning.
- There are two principal sources of ionising radiation during decommissioning: equipment and structures that have been activated by neutron irradiation; and radioactive contamination by radioactive isotope-containing material. Despite the variety of nuclear plant types, there are common patterns in the processes of formation of radiation fields due to residual radioactivity, although the specific quantities of radioactive contaminants can vary greatly.
- Chemical components arise from the original construction materials, chemicals used in operational processes and chemical spills and incidents associated with the facility. Understanding this is particularly important for worker safety and meeting the specific acceptance criteria of candidate waste treatment and disposal routes.
- It is presumed that all information concerning modifications made to the equipment and systems in the course of the facility's operation, as well as about incidents and their consequences that have occurred during operation, will be promptly logged, documented, and stored in an operations database. Prior to the final shutdown of a facility, it is necessary to develop and put in place a facility decommissioning database.
- The volume of material arising during decommissioning activities is one of the factors that could significantly affect the costs involved in a decommissioning project. Processing and conditioning reduces the volume of the radioactive waste, and makes it suitable for transport, storage and disposal.

3.1 Introduction

Nuclear plant operation and decommissioning activities give rise to large amounts of material. In order to optimise and reduce the volume of the material generated during decommissioning, the facility should be designed and operated with decommissioning in mind. This material should be sorted according to a variety of parameters (*e.g.* nature, type, volume) to take advantage of all available waste routes: free release, direct re-use or processing for recycling; disposal in appropriate radioactive or hazardous waste disposal facilities; or decay storage or interim storage awaiting final disposal or release (see Chapter 4). It is important to minimise the volume of material generated within each classification through selective segmentation of contaminated/activated components and careful segregation.

As the characteristics (*e.g.* type, nature, quantity, composition, activity) of the material arising from decommissioning activities influence the nuclear facility's decommissioning strategy, an accurate inventory must be started at the planning stage of the facility, and maintained throughout the operational phase. Prior to final shutdown of a facility, it is necessary to develop and put in place a facility decommissioning database. It is presumed that all information about inventories will be recorded and stored in this database. It should contain not only electronic document archives required to prepare the reactor facility for decommissioning, but also a corresponding 3D model, which can be used to train personnel to perform specific dismantling operations of the installation's equipment and reactor (see Section A3.3 in Appendix 3). This database should be frequently updated.

Although there are additional costs associated with building and maintaining an accurate inventory, this will result in lower uncertainties while performing decommissioning. A reliable, comprehensive and accurate inventory will help to optimise key parameters (*e.g.* number and type of packages required, capacities of treatment/recycling facilities, availability of disposal, avoidance of waste for which there is no outlet). Maintaining information on the radiological, physical, biological and chemical properties of the plant will enhance the operator's credibility with key stakeholders, such as officials and the public.

X-ray examination of waste drum (images courtesy SVAFO)

The preparation of the inventory should include:

- Investment in measurement, sampling, and characterisation for decommissioning from the beginning of the plant design phase.
- Updating data (type, nature, dimensions, chemical composition, radiological categorisation, *etc.*) throughout the life-cycle of the plant.
- Maintainance of records of all operations and incidents occurring during the lifetime of the plant.
- Accounting for all modifications and other changes.

An up-to-date and complete inventory comprises three different components, which affect the management of the materials generated from decommissioning:

- Physical – *i.e.* the quantity, type and nature of the materials – which affects treatment and handling.
- Radiological, which is crucial for the sorting and routing of material and waste.
- Chemical and biological, which may affect dismantling, routing and disposal.

If the inventory is prepared in a timely manner, it will underpin the development of a reliable, efficient and cost-effective decommissioning plan.

3.2 Influence of inventory on materials management

The objective of an accurate materials inventory is to sort material into categories in order to identify the most suitable routes and decommissioning methodologies (see Chapters 4 and 5). A materials inventory should make allowances for the characteristics of a facility (*e.g.* physical dimensions, volumes, activities, historical operation). The conventional chemical characteristics of a nuclear facility (*e.g.* surface coating*) and associated materials should be taken into account, as this can significantly affect the decommissioning plan, in particular the plans for optimising segregation and disposal. Secondary waste generated from decontamination and waste treatment should also be included in the inventory.

Several factors depend on the reliability of the inventory:

- Decommissioning schedule: planning of activities; social and environmental impacts; and negotiations with stakeholders (to obtain public acceptance) and regulators (to obtain authorisations on time).
- Associated operations: decontamination (or not); cutting and handling techniques; use of remote handling (or not); work conditions; safety measures; packaging; and transportation.
- Waste routes: availability of waste treatment facilities; compliance with shipment rules; compliance with acceptance criteria; storage capacities; and disposal availability.
- Corresponding costs (see Chapter 6).

* The surface coating may have a major impact on decontamination. In addition, certain coatings such as zinc may have implications for meeting the waste acceptance criteria for disposal facilities.

Once dismantling commences, the primary objective of the inventory is to manage the materials and their associated hazards, as many unexpected situations are likely to arise. This is particularly important for older plants where decommissioning may not have been considered during design.

3.3 Inventory types

New inventory requirements can be established from the existing inventory objectives and the information already available. This involves considering what radiological, physical, chemical and biological information is needed and how it can be provided. Key aspects are the contaminants concerned and the monitoring, sampling and analysis techniques that are required. This must be informed by an understanding of the quality of inventory information that the techniques can provide, for example, the accuracy/precision and limits of detection, and whether the inventory objectives can be met.

At this stage, it is worth checking whether an additional materials inventory is required, or whether the inventory information already available can be used to meet the inventory objectives. Where a materials inventory is needed, the best available techniques should be considered. In general, inventory information can be delivered through:

- Assessment through calculation or other means (*e.g.* calculated in the case of activation products or estimated indirectly from other information).
- Non-destructive (often *in-situ*) measurements.
- Destructive analysis, typically in a laboratory.

Often a combination of approaches will provide the most efficient and effective approach. For example, activation calculations to broadly assess the expected radionuclides present and their associated activity concentration must be validated and possibly refined through detailed sampling and laboratory analysis. This allows for the development of scaling factors for easy-to-measure radionuclides (typically abundant gamma emitters) relative to ones that are more difficult to measure. The scaling factors can be used with *in-situ* measurements (typically gamma spectrometry) to rapidly determine the inventory/activity concentrations of the radionuclides present.

More detailed consideration is also needed at this stage regarding what types of sample will be taken (*e.g.* metal, concrete), what analytical techniques will be used, how many samples are required, how long the analysis takes, how much it will cost and whether this can or will be undertaken within the organisation or be outsourced to an external supplier.

The evaluation of an inventory is typically based on understanding the characteristics from a ‘population’ of inventory results. This information can be interpolated/extrapolated to include all the material, but within defined boundaries which can be spatial, temporal or material specific. For example, zoning is often used to establish areas according to their radionuclide composition as this allows the use of scaling factors. Zoning takes into account factors such as different types of material and/or spatial areas that may become contaminated or activated in different ways. However, whilst factors such as radioactive decay can be compensated for, time boundaries can be important particularly where some of the contaminants are mobile and relative composition of contaminants/radionuclides can change. This means that the validation of inventory information with respect to time, space and material is very important, particularly when using indirect methods such as scaling factors.

There may be other considerations that can impact and/or influence the materials inventory, such as the timeline, funding, access to data or for sampling (*e.g.* due to inaccessible areas such as the internal surfaces of pipes and vessels), and national context, in particular the regulatory framework. It is important to define and record the boundaries, assumptions and constraints in order that the inventory information is understood and evaluated in the right context.

Since every reactor facility has its own specific properties, operation history, layout, chemical composition of materials, *etc.*, each facility would normally require an independent calculation of the induced activity levels in its construction and shielding materials at the time of its decommissioning. It is critical to obtain data on the radiation levels in the reactor's structural components through calculations and to forecast their changes over time as early as the facility's design phase. The total amount of radioactive waste generated during decommissioning will depend on the history of the plant operation and any accidents or disruption to normal operation that has occurred.

3.3.1 Physical inventory

Generation of materials during decommissioning follows a sequence based on removal and remediation of structures, systems and components. There will typically be some materials already present onsite that were generated or accumulated during the operation of the plant, such as spent resins and filters, asbestos, sludge, slurry, crystalline deposits in tanks, irradiated metals stored in the spent fuel pool and various mixed hazardous and radioactive waste. It is advantageous to manage these materials early in the decommissioning process to allow the components containing the waste materials to be treated in preparation for their removal.

Materials generated through decommissioning consist of:

- Solids resulting from the dismantling of equipment, buildings, and structures (their volume must be estimated when drafting a decommissioning plan for the facility).
- Liquids remaining in equipment systems (see Section A3.2 in Appendix 3).
- Secondary liquids and solids generated during decommissioning activities. These include material that needs further treatment (solidification, melting or storage).

Solid material from decommissioning includes a broad variety of items, the most significant of which are:

- Main process equipment (as assemblies or individual units), including reactor components, primary circuit piping, fittings, and valves.
- Metals resulting from the dismantling of auxiliary and support equipment and piping systems.
- Metal frames resulting from the dismantling of equipment in indoor areas.
- Cladding material (steel plates, plastic compounds), plaster and concrete fragments from the mechanical decontamination of indoor areas.

- Asbestos and thermal insulation.
- Ventilation and industrial filters, hot cell filters, filter fabric, thermal insulation, *etc.*
- Concrete from dismantling the biological shielding of the reactor and other premises.
- Construction and industrial waste (work clothes, cleaning material, *etc.*).

Volume, activity, nuclide composition and physical-chemical characteristics of the generated solid material depend on the performance of the decontamination and decommissioning works. Regardless of the amount of information available, provisions need to be made for unanticipated events, which may arise as a result of incorrect or missed information relating to potential radioactive waste. An accurate inventory will reduce overall radioactive waste management and disposal costs.

3.3.2 Radiological inventory

The radiological inventory represents the nature, location and concentration of radionuclides in a nuclear facility. It is one of the fundamental aspects of a decommissioning project.

There are several principal ionising radiation sources, which require safe handling during nuclear facility decommissioning. These can be classed as follows:

- Group 1: equipment and structures that have been exposed to neutron irradiation. This group comprises the reactor pressure vessel, reactor vessel internals, and equipment located in the reactor's concrete vault within the neutron radiation field.
- Group 2: components with the presence of radioactive deposits (contamination) on the surfaces. This group comprises all other components of a nuclear facility, such as steam generators, main circulation pumps, and the main circuit equipment.

Radiological inventory during decommissioning of the EI-2 reactor at the Production and Demonstration Centre for Uranium-Graphite Reactors JSC (PDC UGR) in Seversk, Tomsk region, Russian Federation (image courtesy PDC UGR)

Portable measuring equipment for gamma analysis of contaminated structures (images courtesy PDC UGR)

A decrease in the radioactivity of Group 1 equipment can be achieved through the natural decay of radionuclides. A decrease in the radioactivity of Group 2 equipment can be achieved through either natural decay or decontamination.

The activity concentration can be determined by calculation, modelling or measurement. By monitoring the activity of particular isotopes prior to final shutdown, the activity in the structures before dismantling can be forecast.

The radiological inventory should be prepared as early as possible, starting with the main units (reactor, pipelines, dry shielding, *etc.*) and developed in further detail over time.

During the development of techniques for dismantling, plant structures should be divided into categories according to their degree of radiological hazard. Information related to a reactor facility's radioactivity status can be collected, processed, and provided either via automated systems or through monitoring activities. This could involve the collection of samples, followed by processing and quantification using stationary and mobile/portable measuring equipment (see images above).

Information on the activation product radioactivity of a reactor's structural components can be gained experimentally through taking samples and measuring their activity. One typical feature of reactor designs is spatial non-uniformity of the activity distribution, resulting in the need for further refinement of parameters obtained through predictive modelling. Predictive calculation is also required where direct measurements near neutron-activated equipment, materials, and structural components cannot be carried out due to very high dose rates. The specific activity levels in a reactor's structural components are determined by gamma- and beta-emitting radionuclides (*e.g.* ^{59}Ni, ^{63}Ni, ^{54}Mn, ^{55}Fe, ^{60}Co) resulting from the presence of nickel and other impurities in the construction materials. Different national regulations can require additional controls of these radionuclides.

Group 1 – neutron irradiated equipment and structures

Among the main equipment, the biggest radiation hazard following final shutdown is posed by the reactor vessel internals, reactor vessel and biological shield. In non-metal waste, the principal radiation hazard is posed by concrete arising from the dismantling of the radiation shielding immediately adjacent to the reactor's structural components, and should be classified as solid intermediate- or low-level waste.

Experience shows that the main radionuclides that account for the radioactivity of concrete structures are the chemical impurities in fillers used in the concrete production. The main radionuclides (especially with long decay times) associated with the activity of metal structures of a reactor facility are the long-lived isotopes of nickel.

As an example, in the Russian Federation, all equipment related to reactor vessels is divided into groups of solid radioactive waste according to the specific beta activity*:

- High-level waste: $A > 10^7$ Bq/g.
- Intermediate-level waste: 10^7 Bq/g $> A > 10^4$ Bq/g.
- Low-level waste: 10^4 Bq/g $> A > 10^3$ Bq/g.
- Very low-level waste: $A < 10^3$ Bq/g.

The mass of main equipment activated by neutron irradiation after 30 years of operation of a VVER-1200 reactor was calculated according to various storage times (see Table 3.1).

Table 3.1. Neutron activated radioactive waste from decommissioning a VVER-1200 reactor [7]

Storage time (years)	3	5	10	50	100
High-level waste					
Metal construction (tonnes)	236	236	236	236	106
Intermediate-level waste					
Metal construction (tonnes)	27	27	27	27	139
Serpentinite concrete (tonnes)	63	63	63	63	-
Construction concrete (tonnes)	58	38	-	-	-
Low-level waste					
Metal construction (tonnes)	-	-	-	-	18
Serpentinite concrete (tonnes)	-	-	-	-	63
Construction concrete (tonnes)	107	104	99	-	-
Total (tonnes)	491	468	425	326	326

From the analysis of the calculation results, it follows that for a VVER-1200 reactor the specific activity of the reactor vessel complies with the ILW category after 100 years of storage, and

* This division is necessary for sorting and developing working procedures onsite but it is not official waste classification in the Russian Federation.

the specific activity of biological shielding after 80 years of storage corresponds to the LLW category as a result of the natural decay of radionuclides. The noticeable decrease of the mass of the radioactive waste occurs during the first 50 years of the unit storage – by 165 tonnes. Furthermore, the waste mass decrease is not significant between 50 and 150 years.

Group 2 – all other contaminated equipment and structures

Equipment and areas of the plant can become sources of ionising radiation as a result of several factors (*e.g.* radioactive contamination by fission products from damaged fuel elements and accidents during operation). The processes used to determine the composition and activity levels of contamination require experimental studies of residual radioactivity. Such studies include full-scale monitoring of residual radioactivity of equipment, rooms and areas (*e.g.* measurement of dose rates; identification and evaluation of sources of radioactive contamination, their nuclide composition, activity and geometry; determining the depth of radioactive contamination in concrete structures).

As mentioned earlier, knowing the nuclear facility's history and evolution is crucial, particularly for preparing the radiological inventory. If any new buildings need to be built during operation or decommissioning (for example onsite radioactive waste storage), it is necessary to carry out geological surveys of those areas to assess their suitability for the construction of such buildings.

In NUREG-1437 (*Generic Environmental Impact Statement for License Renewal of Nuclear Plants*) [8], the US Nuclear Regulatory Commission (NRC) provides figures for typical radioactive waste volumes of light water reactor units after 40 years of operation (see Table 3.2). It corresponds with the 'rule of thumb' that a boiling water reactor (BWR) generates about twice as much waste as a pressurised water reactor (PWR).

Table 3.2. Typical radioactive waste volumes* for PWR and BWR after 40 years of operation [8]

	Class A (m^3)	Class B/C (m^3)	GTCC (m^3)
PWR	6797	184	11
BWR	13,903	372	7

For the Russian VVER-1200 reactor design, approximately 17,000 m^3 of very low-level, low-level and intermediate-level dismantling waste is estimated to be generated during decommissioning.

In Germany some commercial nuclear plants have been decommissioned either fully or are in the process of decommissioning. Two projects, one BWR and one PWR, are to a large extent completed and by many considered as international reference projects. Both have been successful in reducing the volume of radioactive waste for disposal (see Table 3.3).

* Low-level radioactive waste categorisations in Table 3.2 are according classifications defined by the Nuclear Regulatory Commission. Classes A and B waste contain relatively short half-life radionuclides and may be disposed of in near surface facilities. Class C waste can be disposed of at a moderate depth or near surface with engineered barriers. Near surface disposal is not allowed for greater than Class C (GTCC) waste (see Box on page 87).

Table 3.3. Material from controlled areas for Würgassen and Stade

	Released (t)	Controlled Recycling (t)	Radioactive Waste (t)
Würgassen (BWR)	255,000	3000	4600
Stade (PWR)	124,000	500	3000

The composition of the 3000 tonnes of waste for disposal for Stade was 820 t of contaminated systems, 630 t construction material, 500 t of activated components, 430 t of biological shield and approximately 600 t of other waste [9].

European Union radioactive waste inventory

At the end of 2013 the estimated total inventory of radioactive waste in the European Union was 3,313,000 m^3, with 70% disposed of (2,316,000 m^3 including enrichment tails), and 30% stored (997,000 m^3). Figure 3.1 summarises the overall share of radioactive waste in the European Union [10]. It shows that low-level waste (LLW) is the dominating waste class comprising around 74% of the total, while very low-level waste (VLLW) and intermediate-level waste (ILW) is estimated to be 15% and 10% respectively. High-level waste (HLW) accounts for only 0.2% of the overall waste volume. These figures are typical for a country generating radioactive waste from nuclear energy.

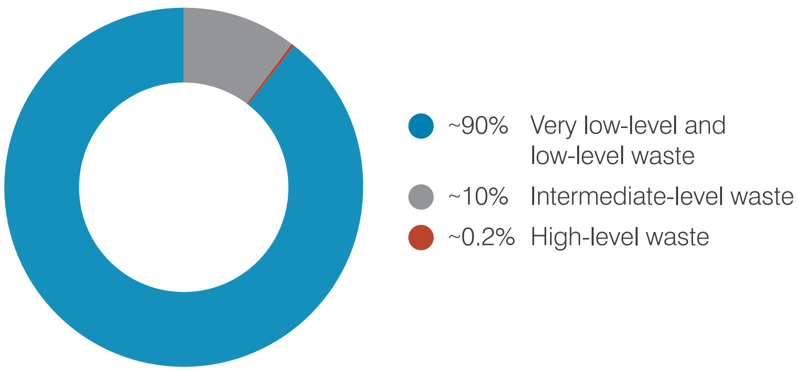


Figure 3.1. Share of radioactive waste inventory (by volume) in the European Union (2013) [10]

Table 3.4. Radioactive waste inventory in the European Union [10]

Waste category	Total amount (m^3)			
	2004	2007	2010	2013
VLLW+LLW	2,438,000	2,715,000	2,770,000	2,969,000
ILW	206,000	288,000	321,000	338,000
HLW	5000	4000	5000	6000
	Total amount (tHM)			
Spent fuel	38,100	44,900	53,300	54,300

In summary, a nuclear plant infrastructure radiological inventory can be characterised as follows:

- Despite the variety of nuclear plant types, there are common patterns in the formation of radiation fields due to residual radioactivity, although the quantities of specific radioactive contaminants can vary greatly.
- The main radionuclides causing surface radioactive contamination of equipment and protective structures are ^{137}Cs, ^{60}Co, ^{134}Cs, ^{90}Sr+^{90}Y, ^{110m}Ag, ^{54}Mn. The presence of the last two radionuclides is typical only for relatively short (not more than two years) exposure times.
- Radiation fields, particularly the distribution of dose rates, are uneven, both within individual rooms and for the whole unit. Absolute values of gamma radiation dose rate can range from thousandths to tens of millisieverts per second, and can exceed the allowable dose to workers by hundreds or even thousands of times. The information could assist the planning for decommissioning work undertaken on the site.
- Activity of contaminated concrete is mainly determined by the ^{137}Cs nuclide associated with leaks of radioactive coolant. More than 80% of activity is concentrated on the first 5-10 mm of the structure. Deeper contamination of the concrete, where the material is considered radioactive waste, does not generally exceed 15-25 mm.
- The main source of radioactive contamination for equipment is determined by ^{60}Co and for structures by ^{137}Cs and ^{90}Sr+^{90}Y, so without carrying out decontamination there will be no substantial improvement in radiation levels as a result of radioactive decay.

One way to develop the radiological inventory is through zoning the waste areas. This identifies areas of facilities which are deemed nuclear waste and those which are not. Waste zoning uses an analytical approach in which the facility's design, operation and history are considered to determine the presence or lack of radioactivity. The analysis is backed up by radiological maps that will help to confirm the appropriateness of the classification and to ensure that the materials are segregated.

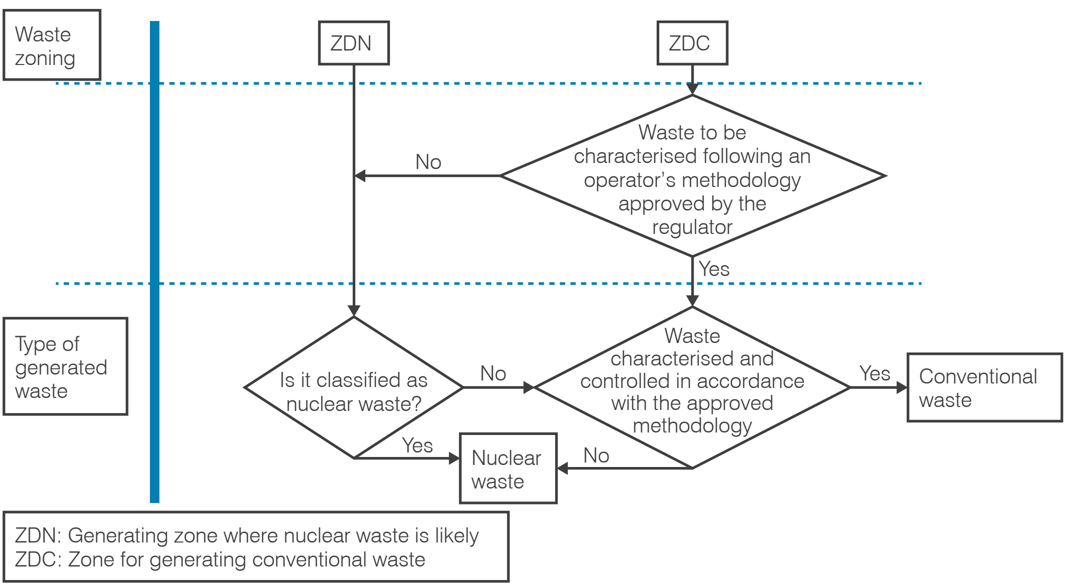


Figure 3.2. Waste classification resulting from waste zoning

Waste area zoning is different from (but consistent with) radiation protection zoning. It evolves as modifications or work performed on the facility are carried out, or following an incident. Any changes over time must be traceable. Waste classification principles based on waste area zoning are presented in Figure 3.2.

In the Russian Federation, assessment of the volume and state of radioactive waste is carried out using a comprehensive engineering and radiation survey of the facility and site at the end of its operation. The radiation and technical condition of equipment, systems, buildings, structures and site area are estimated and the resulting data is represented on a radiation map of the buildings showing personnel access limits. The scope of the survey depends on the decommissioning strategy. For example, when the strategy is immediate dismantling, the radiation component should be the main focus. When the strategy is deferred dismantling, the engineering aspect should be the focus.

A significant amount of the radioactive waste generated from decommissioning can be released from regulatory controls relating to radioactive waste and classed as conventional waste, reducing the cost of decommissioning. The main goal is to keep clean, potentially radioactive and radioactive waste and materials apart. Clean materials can be handled in a conventional way, potentially radioactive waste can be subject to clearance, and radioactive waste should be divided into categories to allow recycling/re-use followed by clearance or disposal.

3.3.3. Chemical and biological inventory

In common with physical and radiological characterisation, chemical and biological characterisation is required to be taken into consideration as part of waste acceptance criteria (WAC).

Chemical components arise from the composition of the original construction materials, chemicals used in operational processes, and chemical spills and incidents associated with the facility. Understanding these is particularly important for worker safety and meeting the specific WAC of potential waste treatment and disposal routes. Important chemical components can be metals, volatile organic compounds and other chemical compounds. For example, understanding the presence and location of asbestos is particularly important to ensure worker safety and to develop the decommissioning plan. Understanding the presence and chemical form of reactive metals such as sodium, magnesium and aluminium can be very important with respect to waste treatment, storage and disposal.

Biological properties may also be important, particularly where decommissioning has been deferred. For example, algal growth in ponds or tanks can create organic rich sludge; bird or bat guano can lead to the generation of the organic rich and biologically hazardous waste streams; and the presence of gas generating microbes within packaged waste has the potential to lead to package deformation and/or early loss of package integrity within interim storage and disposal facilities. This has the potential to affect clearance (including re-use and recycling) and meeting acceptance criteria for disposal.

4 | Waste Routing

Summary

- The material properties, logistical challenges, as well as regulatory and stakeholder requirements require a variety of waste routes. Given that particular waste routes may be temporarily or permanently unavailable, it is recommended that at least two waste routes should be kept open for each category of material wherever it is practically possible.
- Waste management optimisation should focus on reducing the waste volume for disposal. The waste hierarchy, strategy, schedule, risk analysis and available resources help to identify appropriate waste routes.
- A wide range of waste routes is available and used worldwide. For certain countries and regions, the options may be limited to just a few routes, or for certain waste categories, even a single route.
- The preference should be to select the most efficient routes to achieving the material end state at the lowest possible total cost, taking short-term and long-term risks and consequences (including environmental impact) into account.

Ringhals 4 steam generator being transported to external treatment facility (image courtesy EDF/Cyclife)

4.1 Introduction

The waste routing, *i.e.* the activities and logistics for managing the material generated, is a key point in a decommissioning project. It determines the routes from the material inventory to the envisaged material end states. The selection of the waste routes in a decommissioning project depends on several factors, in particular:

- The total waste management cost including disposal. Indirect costs such as the impact on the decommissioning schedule and investment in infrastructure and organisation should be included.
- The potential to carry out release of material from the practical, regulatory and public perspectives.
- The national programme for management and disposal of radioactive waste, including the availability of final repositories.
- The availability of dedicated external waste treatment facilities.

In terms of sustainability, the 'waste hierarchy' (see Figure 4.1) should be applied to routing materials from nuclear facilities. According to the waste hierarchy, the preferred end state is re-use or recycling of the waste as material or, more preferably, the avoidance of waste generation.

In addition, treatments (such as decontamination and thermal treatment) that can reduce the volumes requiring disposal as radioactive waste should be considered.

Avoidance	Avoid the introduction of additional material into the controlled area during decommissioning activities, *e.g.* packaging material, additional tools, temporary equipment.
Re-use	Re-use dismantled equipment (after appropriate cleaning/decontamination and maintenance) within the nuclear industry.
Recycling	Recycle material from decommissioning within or outside the nuclear industry.
Reclassification	Reclassify radioactive waste using more accurate activity measurement techniques, as well as by increasing the degree of segregation and decontamination.
Volume reduction	The remaining radioactive waste should be treated to reduce the volume as much as is reasonably achievable.
Disposal	Proper conditioning, qualification and safe disposal of remaining waste.

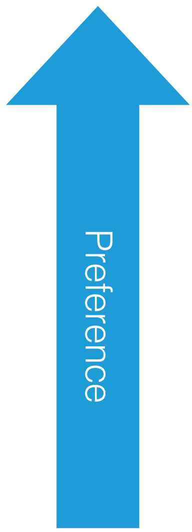


Figure 4.1. Radioactive waste hierarchy

The generation of waste streams/waste packages without a disposal route, or with significant uncertainties in composition or properties that are hard to manage, should be avoided. If waste needs to be reconditioned or retrieved, this could be very costly. It is therefore important to carry out full planning and waste route analyses to ensure that the waste is effectively and efficiently managed.

Another important parameter is the need to secure availability and capacity of waste routes. Short-term bottlenecks or any delay in the removal of the waste from the site often has an impact on other site activities. If possible, at least two alternative waste routes should be identified for the main categories of waste and kept available throughout the decommissioning project. All routes should be direct to the material end state if possible, but it is more important that waste is removed from the site so that other site operations are not impeded. Waste forms without a disposal route should never be generated.

4.2 Influence of decommissioning strategy on waste route

The decommissioning strategy can have a major influence on the waste routes.

If the strategy is immediate decommissioning in order to delicense and release the site in a short time, the waste should be transported offsite as soon as possible – either for direct disposal, or to an external treatment or interim storage facility.

For deferred decommissioning, it can be useful to have an onsite waste treatment facility. This might include intermediate storage to allow for decay and provide flexibility in the rate of waste flow through the facility.

The decision on whether to contract out decommissioning activities or for the operational staff to carry them out within the organisation can also have a major impact on the waste routes. If the intention is to utilise the operational staff as much as possible for decommissioning, then local waste treatment capacity should be built, with a waste treatment organisation made up of existing staff.

If the waste management is to be contracted out, there are advantages in shipping material to an external site operated under another licence. For most decommissioning projects, there will normally be a combination of onsite and offsite waste management.

Direct disposal of conditionally cleared materials in licensed landfills or conventional landfills may be an alternative solution, where the regulatory system allows.

A licensed landfill facility on the decommissioning site may be an attractive solution for very low-level radioactive waste (VLLW) and potentially contaminated waste. Since the cost for such a landfill is typically low, it may provide an efficient way of disposing of building rubble.

Based on the rapid development of recycling as a management option (especially for conventional material), and the value of the recycled material, the difference in the total cost between disposal and material recycling may be very small.

4.3 Influence of inventory on waste route

The inventories, especially the total volume of waste, may have a large impact on the waste routes. The larger the amount of contaminated or potentially contaminated waste, the higher the proportion of the decommissioning budget will have to be allocated to waste management.

The nuclide composition may influence the selection of waste routes. For example, surface repositories (landfills) may have strict restrictions on long-lived nuclides. Another example is that caesium- and alpha-contaminated steel can be fully decontaminated by thermal treatment, making clearance of the metal attractive.

Physical parameters may also influence the waste routes. Objects that are surface-contaminated could be suitable for decontamination and clearance either locally or at an external dedicated facility, provided that the surfaces are accessible for decontamination and clearance measurements. Given that large objects may require a lot of segmentation to fit into approved disposal containers, decontamination and clearance – or disposal as a large object – is often preferred.

Chemical and organic substances may, in combination with radiological contamination, restrict the number of available waste routes significantly. In some cases, waste treatment is mandatory to qualify the waste for disposal as radioactive waste.

Waste with biological content may face the same difficulties as waste containing regulated chemical substances.

4.4 Material/waste route options

The potential material/waste route options have to be mapped and analysed for all categories of material. There could be local, fleet-wide, national or international waste route options.

Typical waste route options can be categorised as:

- Disposal without treatment.
- Local waste treatment centre within the facility being decommissioned.
- Local waste treatment centre outside the facility being decommissioned but still onsite.
- Transport to external waste treatment facility.

The external waste treatment facility can either be a centralised facility owned and operated by a utility (or a number of utilities), or by a national decommissioning organisation, or by a third party operating on commercial basis.

Another option is to have mobile or temporary facilities that are transported from site to site for specific waste treatment operations. Such facilities can be developed and provided by and within a nuclear fleet or national programme. They can also be provided by an external service provider.

The 619 MWe Connecticut Yankee PWR at Haddam Neck operated from 1968 until 1996, and was decommissioned in 1998-2007. The image shows the Connecticut Yankee reactor pressure vessel shipment by barge during decommissioning (image courtesy Connecticut Yankee)

The schedule for the chosen decommissioning programme is a key parameter when selecting the routes, and vice versa.

These routing options are discussed further below.

4.4.1 Disposal without treatment

Disposal of waste after dismantling only requires segmentation to fit into waste containers, and conditioning of the waste packages. In most cases this is one of the simplest ways to manage the waste, as decontamination or treatment for volume reduction are not carried out.

The only objective is to qualify the waste for disposal, *i.e.* to meet the specific waste acceptance criteria. Such criteria differ significantly from country to country, but also between waste classes and repositories within individual countries.

This waste route option is attractive in countries with low disposal costs and no regulatory requirements on clearance and recycling.

Main advantage	Simple, with no waste treatment required.
Main disadvantage	Significantly higher volume of waste for disposal.

4.4.2 Local waste treatment centre within the facility

A low investment alternative is to establish a local waste treatment centre inside the facility to be decommissioned (for example in the turbine hall of a BWR). The main challenge is to make the waste treatment centre available in accordance with the decommissioning schedule.

Segmentation of waste local to generation (image courtesy EDF/Cyclife)

The design requirements for this type of waste treatment centre depend on the waste management strategy, access to external treatment facilities, available disposal space, the possibility to dispose of large components and associated costs. Typical installations are cold cutting equipment, mechanical decontamination units, equipment for clearance measurements and radiological analyses, as well as arrangements for conditioning of disposal packages (see Chapter 5).

This waste route option is attractive for organisations aiming to carry out the decommissioning activities themselves.

Main advantage	Makes use of existing buildings.
Main disadvantage	Not operational from the start of the dismantling project and not available to the end of it.

4.4.3 Local waste treatment centre outside facility but onsite

A fairly costly but attractive alternative is to build a new local waste treatment centre outside the facility being decommissioned but onsite. One important advantage is that it has a low impact on the dismantling process. It is important to remember that such a facility should be licensed, built, commissioned, and upon completion of service, decommissioned.

The equipment in a specially built waste treatment centre is in most cases similar to that for a centre within a facility to be decommissioned, although a specially built facility may include provisions for hot cutting.

These waste treatment facilities can be permanent or modular structures. The advantage with a modular facility is that it may be possible to be moved to another site for re-use when the project is over.

This waste route option is attractive for licensees with several units to be decommissioned. It allows for site staff to carry out decommissioning and optimises the decommissioning schedule (as the waste treatment centre can be built and commissioned while the reactors still are in operational mode). For utilities with several sites not located too far from each other it may also fit into a fleet approach.

Main advantage	Construction of the facility does not affect the decommissioning schedule.
Main disadvantage	Requires investment in, and licensing of, a new facility.

4.4.4 External treatment and conditioning

In most countries, it is possible to transport radioactive waste to a dedicated external waste treatment facility. Such facilities can either be part of a fleet approach, part of a national programme, or owned by external commercial service providers. By transporting the waste for treatment at a dedicated facility at another location, some of the decommissioning work is transferred away from the site, allowing the onsite staff to focus on the main tasks. In many cases, this option will lead to a significant reduction of volume for disposal. The overall direct cost can be higher than for local treatment as it will include transport costs as well as the fees of the service provider. However, this should be balanced against the reduced risk, removal of the need for local treatment and storage (including training of staff), and reduced waste volume for disposal associated with this this option.

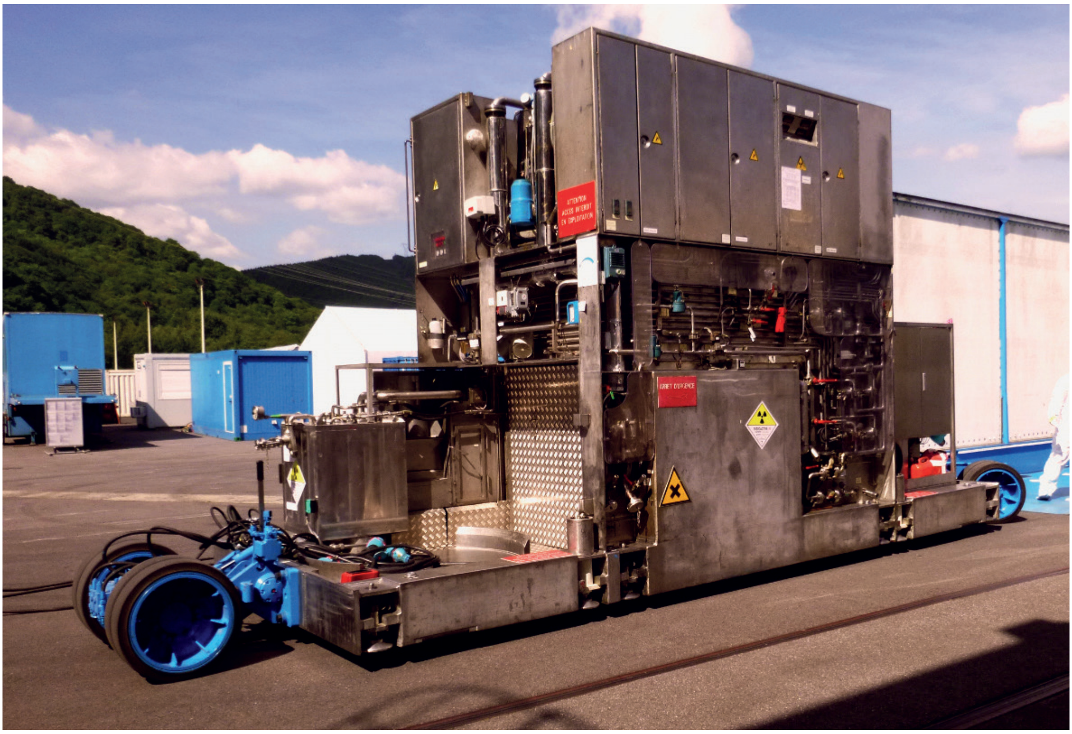
Main advantage	Reduction of waste for disposal.
Main disadvantage	External transport of waste required.

4.4.5 Mobile waste treatment facilities

For certain waste streams, where the tasks will be undertaken in a time-limited manner (*e.g.* removal of reactor internals), it may be necessary to bring mobile waste treatment facilities to the decommissioning site instead of moving the waste to an external waste treatment facility.

This applies in particular to waste which is especially problematic from a technical or regulatory perspective, or very costly to transport (*e.g.* ILW resins and waste streams which are large in volume). The focus should be on waste streams for which the required equipment is easy to transport and install – for example, contaminated and potentially contaminated concrete, which has to be crushed and measured for clearance.

Main advantage	Shared equipment costs and no transport of untreated waste.
Main disadvantage	Booking the facility (which may need to be done a long time in advance) in line with the decommissioning schedule.



The Mercure mobile ion exchange resin treatment machine can be moved to different sites. It embeds ion exchange resins originating from chemical volume control system (CVCS) circuits into shielded containers prior to near-surface disposal (image courtesy EDF)

4.5 Strategic options for waste treatment

An important decision with regard to radioactive waste management relates to the choice between onsite and external facilities. A utility with several nuclear units spread over a number of sites may decide to develop a centralised waste treatment facility as part of a fleet approach. This approach may also include fleet-specific interim storage facilities and final repositories. The advantages of a waste management fleet approach are potential cost savings (resulting from economies of scale) and reduced risk (due to repeating the same activities). It is also possible for a number of utilities to cooperate with each other to adopt a fleet-wide approach for their combined plants.

During the decision-making process, existing buildings and facilities should be taken into account. An important consideration is the level of investment in equipment and organisation required for proper and efficient handling and treatment of the material. On the other hand, the necessity to transport the waste material from the decommissioning site to an external site and, if required, returning the conditioned waste package back to the site, can result in significant costs.

There are currently a very limited number of treatment facilities for decommissioning waste. Table 4.1 is based on the assumption that both the local and the centralised treatment facilities would need to be built, whereas the commercial facility would be available or provided by a third-party.

Table 4.1. Comparison of onsite and offsite treatment facilities

Local Treatment	Centralised Facilities	Commercial Facilities
Investment required. Existing buildings, facilities and equipment can be used to a certain extent.	Shared investments and liabilities.	No investment required – service provided by external company and included in treatment fee.
Investment in equipment on decommissioning site.	A wider range of treatment processes can be arranged.	Specific waste treatment processes as offered by service provider.
Possibility of low efficiency.	Better capacity utilisation (potential to become more cost efficient). Important to have good coordination between shareholders.	Capacity utilisation could be an issue for the service provider.
No offsite transport prior to treatment.	External transport prior to treatment.	External transport prior to treatment.
Independent from external influences.	Dependent on the needs of the other owners/shareholders.	Contracted conditions.
Use of existing infrastructure.	Investment in new infrastructure.	Use of existing infrastructure.
Already licensed area.	Licensing of new facility/new site.	Already licensed area.
Onsite interim storage required.	Waste that does not meet acceptance criteria sent to originator or interim storage, requiring additional transport.	Waste that does not meet acceptance criteria sent to originator or interim storage, requiring additional transport.
Part of the decommissioning project and included as a decommissioning liability.	Stand-alone facility that is both a long-term asset and liability.	Facility owned and operated by the service provider. Neither a liability nor asset for the customers.
Cost based.	As agreed between shareholders.	Commercial price.

4.6 Material end states

There are several possible material end states for decommissioning materials. They can be broadly categorised into two groups: clearance; and disposal as radioactive waste.

4.6.1 Clearance and release

There are three types of clearance and release: general clearance (free release); conditional clearance; and release for re-use or recycling within the nuclear sector. Clearance can be for re-use, recycling or disposal as conventional or hazardous waste.

General clearance applies to material that has been released from regulatory control and has no restrictions on its future use. There are international recommendations on the framework of general clearance and the associated clearance levels such as in International Atomic Energy Authority (IAEA) RS-G-1.7, *Application of the Concepts of Exclusion, Exemption and Clearance* [11]. Most countries also have national regulations on clearance, and these are typically based on and aligned with the IAEA recommendations.

General clearance is typically used for potentially or slightly contaminated objects. A graded approach is recommended for verification measurements when dealing with large volumes of material for general clearance.

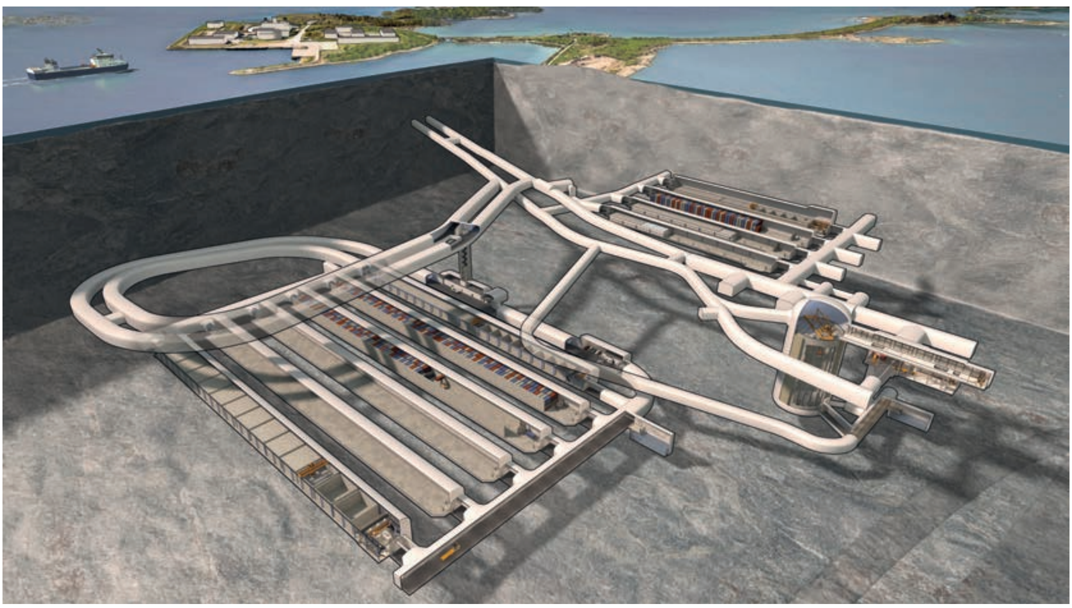
Waste subject to conditional clearance in accordance with special conditions may be metal to be recycled to the metal industry, concrete and sand to be recycled for road construction, or waste to be disposed of in a hazardous waste disposal site or the decommissioning site. This type of clearance typically requires that certain conditions stipulated in the regulations are fulfilled or that a special permit is obtained from the regulator.

One specific example of conditional clearance is metal ingots from a nuclear licensed metal treatment facility. The ingots are conditionally cleared and melted together with other metals forming products that can be used in the public domain.

4.6.2 Disposal as radioactive waste

The overall objective of a radioactive waste repository is to isolate it for a long enough period of time to allow the radioactivity to decay down to levels that are considered safe. For some waste, a few generations will be enough; while other types require isolation for thousands of years. Several different types of repository have been developed worldwide, *e.g.* surface repositories, near surface repositories, deep geological repositories. These types take into account the properties of the radioactive waste to be disposed of, the nature of the potential disposal sites, and the legislation that applies to the site. The repositories might be local (onsite), or provided by a commercial service operator, or part of a national programme.

Disposal should be seen a rare resource and only considered as a last resort.



SKB's Final Repository for Short-Lived Radioactive Waste (SFR) in Sweden's Östhammar municipality accepts nuclear plant operational waste (as well as medical and research waste) and will be extended to accept waste from decommissioning nuclear plants. The image shows the existing facility towards the right and the planned extension in the left foreground (image courtesy SKB)

4.7 Influence of material end state on the management of decommissioning materials

The aims of the management of materials and waste from decommissioning are to make the total decommissioning project as cost-efficient as possible, as well as to comply with legislation and meet stakeholder expectations.

Material and waste end states range from the different clearance levels to the various repositories for radioactive waste. Defining the material end state and its criteria will avoid, or at least reduce, the risk of waste not meeting the waste acceptance criteria. Waste that does not meet acceptance criteria may require time-consuming and costly reconditioning.

The selected material end states will put certain requirements on waste management. For example, some countries do not have final repositories for low- and intermediate-level waste, and long-term intermediate storage onsite or offsite may be required. For all end state options, any treatment must not generate waste forms that do not have an available route for clearance or disposal.

4.7.1 Waste routing towards clearance for recycling

The objective of waste routing towards clearance for recycling is that the waste material should comply with the appropriate criteria. In terms of treatment, it may require segregation, segmentation and decontamination prior to radiological assessment. In addition, the decommissioning organisation may be required to demonstrate that certain limits on hazardous substances are not exceeded.

It is crucial that there is overall stakeholder buy-in and that the recycling industry has confidence in the clearance process. Although the risk of radioactive material entering the public domain is extremely low, the clearance process must be reliable and thorough.

4.7.2 Waste routing towards clearance for disposal

The objective is to meet both the clearance criteria and the specific acceptance criteria for disposal at conventional, industrial or hazardous landfill sites.

The treatment required may be similar to that for recycling.

Demonstration may be required to provide assurance that certain limits on hazardous substances are not exceeded.

The disposal company must have confidence in the robustness of the clearance processes and there must be overall stakeholder buy-in.

4.7.3 Waste routing towards disposal in a nuclear licensed surface repository

The objective is to demonstrate that the waste should comply with the acceptance criteria for disposal. Treatment and the conditioning might be required to reduce the radioactivity of the waste, allowing for reclassification and hence reducing disposal costs.

However, a thorough analysis should be carried out, as reducing the waste classification could also incur significant treatment costs and generate decontamination waste with elevated activity levels.

In addition, demonstration may be required to show that certain limits on hazardous substances are not exceeded.

4.7.4 Waste routing towards disposal in a nuclear licensed geological repository

The objective is to demonstrate that the acceptance criteria for disposal are met.

In addition, the decommissioning organisation may be required to demonstrate that certain limits on hazardous substances, metals (*e.g.* aluminium, galvanised steel), and organics are not exceeded.

Disposal in a geological repository is typically the most costly option. It requires long-term planning and in most cases a strategic investment by the nuclear operators in a multinational or national initiative. The disposal cost (not including the cost of the repository itself) is usually equal to or lower than the costs of advanced treatment for clearance (unless spare treatment capacity is considered to be a strategic asset).

Very low-level waste disposal cell at Enresa's El Cabril facility in Córdoba, Spain (image courtesy Enresa)

4.8 Route selection and costs of waste treatment and disposal

The different waste treatment and disposal costs per unit volume – including the management, conditioning and transport costs – are important parameters in the evaluation of the different waste routes. These costs may also have an impact on the overall decommissioning plan.

A low VLLW disposal cost may favour disposal without treatment as it could be significantly cheaper to consider all VLLW and all potentially contaminated waste as VLLW.

On the other hand, if the regulatory system prescribes waste minimisation or if the disposal costs are high, this would favour investments in advanced waste treatment centres and/or agreements with external treatment facilities. If there are large differences in cost between VLLW and LLW disposal, then treatment to reclassify LLW to VLLW prior to disposal is favoured.

Long distance shipments of waste for treatment, especially in complicated regulatory environments, drives investment towards local waste treatment solutions.

5 | Treatment and Processes

Summary

- The different amounts and types of materials, waste routes and waste management strategies require a variety of treatment processes.
- The application of the ‘waste hierarchy’ principle encourages recycling and thus minimises the amount of waste for final disposal.
- Selection of suitable treatment technologies for radioactive waste must be carried out in accordance with the respective waste acceptance criteria (WAC). Where WAC are not yet available, the waste treatment technologies should generate inert, water-free matrices.
- In future, regulations for transport and final disposal are likely to be more restrictive and will require the development of more advanced technical solutions.
- Solutions for the management of irradiated graphite need to be found.
- The risks related to transport of decommissioning waste are generally very low compared to the risks related to the transport of other dangerous goods.
- For all radioactive material handling and management, the ‘do it right the first time’ principle should be followed. This should avoid:
  - Reconditioning waste packages not suitable for final disposal.
  - Extensive sorting of mixed material, which if managed separately, could be declassified or free released.
  - Sending material to disposal which could be re-used or recycled.

The Wet ILW Retrieval and Encapsulation Plant (WILWREP) at the Hunterston A plant in Scotland. Wet ILW is placed in stainless steel drums and encapsulated with cement prior to storage for several decades (image courtesy Magnox Limited)

5.1 Introduction

The political and strategic decisions on the management of waste from decommissioning a nuclear plant significantly impact the eventual inventory and handling of the material/waste. The material/waste identified in the overall inventory can be moved to the most suitable and cost-efficient outlet, based on the technologies possible for management, waste acceptance criteria and available waste routes.

All waste generated from a decommissioning project should have a dedicated and agreed waste route and material end state – principally 'clearance and release' and 'disposal as radioactive waste' (see Chapter 4). A principle target scenario with the following characteristics should be developed:

- Contaminated material is decontaminated and free-released.
- Aqueous-based waste is concentrated, evaporated and free-released.
- Active residues from decontamination and all organic materials are thermally treated.
- Lower temperature thermal processes are considered for waste containing volatile radionuclides.
- Concentrates and ash are encapsulated in a hydrogen-free matrix, such as Synroc or a glass/graphite matrix.
- Activated metal is melted into ingots, left to decay, and then free released or sent to final disposal.

5.2 Influence of decommissioning strategy on material end state

The chosen strategy and associated schedule for decommissioning can have a major influence on the generated radioactive waste volume for disposal. As described in Chapter 2, there are different scenarios for the site end state. Figure 5.1 illustrates the effect of decisions made during the decommissioning process (to achieve either an unrestricted or restricted release of the site) with regard to the amount of generated radioactive waste, and the material end state.

The first decision concerns the site end state that should result from decommissioning. Depending on the site end state, the volume of radioactive waste can range from the total volume of all the materials to only a small amount of the materials. For example, in the case of entombment, the non-contaminated building structures are treated in the same way as the radioactive material.

Where the aim is for an unrestricted or restricted site release, the next step is to analyse the options for re-use or recycling of some of the material. Optimising the routing of the material towards re-use and recycling will minimise the radioactive waste inventory and preserve natural resources as well as reduce the environmental impact.

For the material that cannot be re-used or recycled, further analysis has to be carried out to decide whether volume reduction of the material is possible. Where volume reduction is not possible, the material will be classed as radioactive waste.

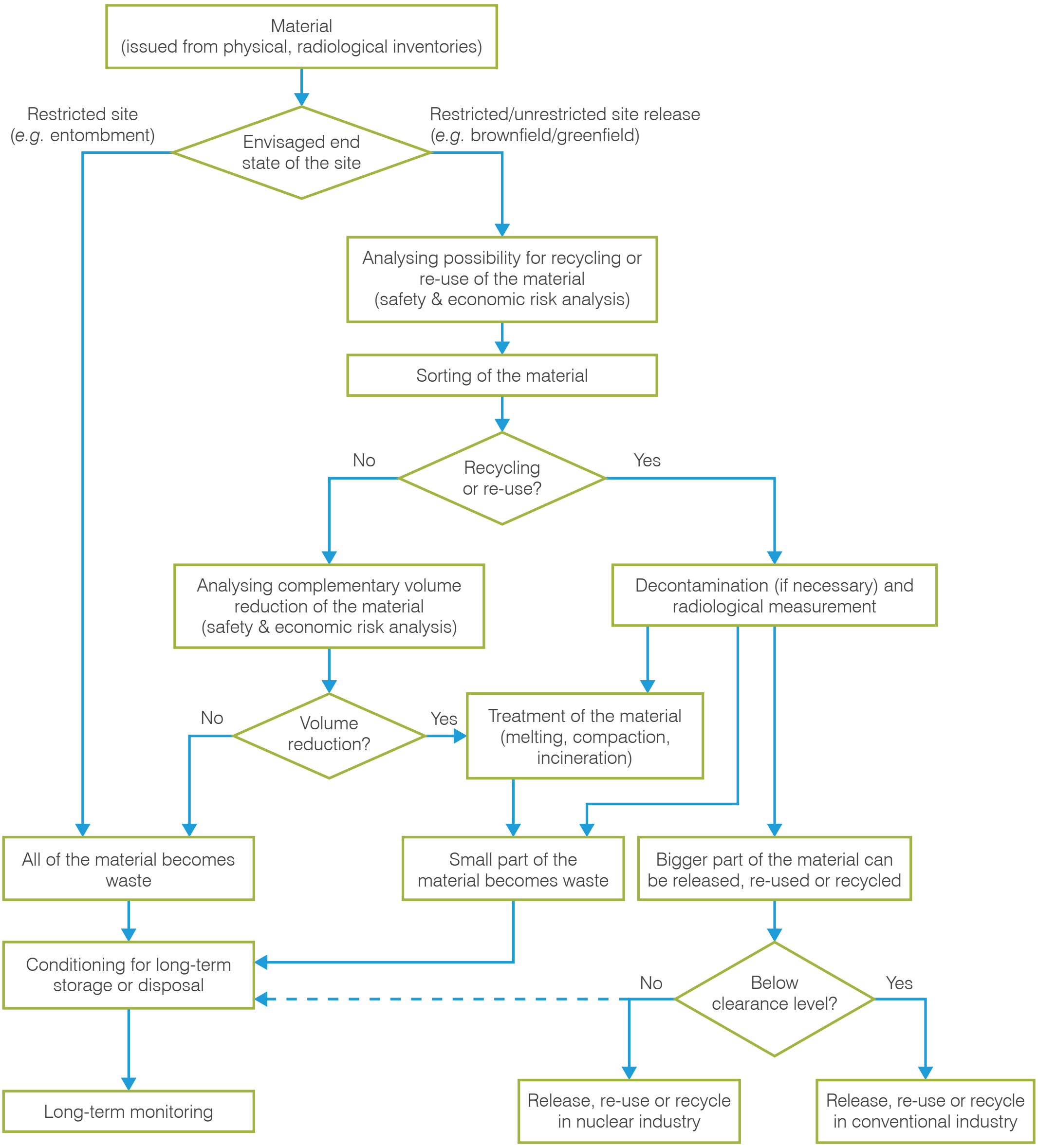


Figure 5.1. Influence of chosen decommissioning strategy on material end state

The material to be re-used or recycled has to be measured for contamination. Contaminated material might be treated in volume reduction systems depending on the specific requirements.

Volume reduction can be carried out by surface decontamination in order to separate the radioactivity from the material; or by other treatment methods such as incineration, compaction, or melting. The resulting concentrated radioactive material will be classed as radioactive waste.

The decontaminated material together with the material to be re-used or recycled will then be measured for free release, or where this is not an option, to become very low-level waste. The aim of the various decision-making processes during decommissioning is to minimise the amount of material that is classed as radioactive waste, in order to reduce the costs associated with long-term storage and disposal.

As described earlier, it is essential to have a detailed inventory of the existing and expected material types. Not only should the inventory existing at the end of the operational lifetime of the nuclear plant be taken into account, but also how this inventory will be affected by the chosen strategy. The decision whether to have immediate or deferred decommissioning will have a direct impact on the amount and type of radioactive waste that results.

- Deferred decommissioning will reduce the activity level of the generated radioactive waste due to decay and may allow more manual (as opposed to remote) handling. This will lead to lower disposal costs, but potentially higher overall decommissioning costs due to the longer post-operational duration.
- Immediate decommissioning will lead to higher activity levels of the generated radioactive waste due to the lack of time in which decay can occur. Nevertheless, it will shorten the overall duration of the decommissioning project by reducing the amount of work required (for example, less maintenance, fewer surveys, fewer inventory updates required) and therefore lower overall costs are expected.

Both the post-operational and disposal costs are key parameters; the decision between immediate and deferred decommissioning needs to be made on a case-by-case basis.

5.3 Influence of inventory on waste management

The appropriate radioactive waste management methodologies and waste routes can be identified after analysing the volumes, types and nature (physical, radiological and chemical/biological) of the material inventory.

The inventory physical data can affect the waste management strategy in the following ways:

- The location can influence the sizing of waste forms (due to routing offsite).
- The maximum weight of the waste form is affected by the transport options available.
- Automation or remote operation may be necessary in restricted areas.
- Constraints on space may limit the use of some technologies.
- The materials have an influence on the dismantling technologies employed and, later, on waste management.
- Effluent/emissions from dismantling activities have to be properly handled.
- Large amounts are easier to recycle than small quantities of material.

For the inventory radiological data:

- Suitable material treatment, separation and decontamination methods to lower the classification of material will be selected according to the inventory characteristics.
- Higher activity material requires the use of remote handling during decommissioning.
- The resulting inventory of the respective waste form may require remote handling or automation for offsite transfer.
- Depending on the radiological inventory, suitable radiological protection measures have to be established for individual areas within the site.

For the inventory chemical/biological data:

- Based on the composition of the material to be dismantled, management of hazardous substances may be required.
- The method of managing emissions (aerosols, dust, water pollutants) depends on the selected dismantling technology.
- Organic material should be kept separate to facilitate compliance with the waste acceptance criteria of the respective disposal site.
- In addition to the radioactivity, any hazardous substances contained in the waste for clearance need to be taken into account. Additional measures to separate hazardous substances will have to be carried out.
- Recycling or re-use of materials from decommissioning requires knowledge of the chemical composition and the content of hazardous substances in order to select suitable routes.

5.4 Application of the waste hierarchy

The most suitable waste routes rely on the waste management strategy, which depends on the site end state and selected decommissioning strategy (immediate or deferred). In a non-nuclear environment, waste management follows the waste hierarchy principle (reduce, re-use, recycle, recover and landfill disposal), which is legally binding in several countries. In the nuclear environment, decontamination, volume reduction and conditioning of the radioactive waste are additional measures used to minimise the waste prior to final disposal (see Section 4.1 on page 30).

It is essential to keep the material arising from decommissioning separated in order to fully manage the waste according to the waste hierarchy. This means:

- Non-contaminated material should be kept clear from contaminated material.
- Lower activity material should be separated from higher activity material.
- Contaminated material, which can be decontaminated, should be segregated from activated material.

The segregation of material will maximise the amount of non-contaminated or non-activated material to be re-used or recycled and minimise the amount of contaminated material.

The radioactive waste should be collected separately based on its phase (liquid, solid), activity level (VLLW, LLW, ILW, HLW), as well as other characteristics such as combustibility, compactibilty, bulkiness, *etc.* Specific treatment methods can be applied to further decontaminate, reduce volume, reclassify (reduce the specific activity to a lower activity category or to below clearance levels). These measures will result in:

- The minimum number of waste packages required for final disposal.
- Preservation of storage capacity – repositories should be considered to be a rare resource.
- Reduced waste liabilities and risk, especially where a repository does not exist.
- Optimisation of the overall waste management cost.

5.5 Selection of treatment and disposal technologies

In addition to schedule and cost, the selection of treatment technology for the material and waste resulting from decommissioning a nuclear plant is based on the following factors:

- The resulting waste form needs to fulfil the waste acceptance criteria of the selected disposal site.
- The selected processes should be flexible enough to manage the different kinds of incoming waste and their specific treatment aim (recycling and re-use, segregation, decontamination, inertisation, packaging, reclassification).
- The selected processes should be able to be adapted according to the characteristics of the incoming radioactive waste.
- The selected processes should reduce the volume of radioactive waste to a minimum and preserve natural resources.

5.5.1 Waste acceptance criteria of final repository

Due to the lack of final repositories, there is also a lack of finalised waste acceptance criteria. In those countries with operating final repositories, past experience shows that requirements for safe disposal become increasingly stringent, *e.g.* the period of consideration moving from 100,000 years to one million years. This trend could continue in the future, making it difficult to define the parameters for the final waste package to be used in the waste conditioning process.

Some products that seemed acceptable for final disposal in the past might now be considered unacceptable due to a change in views on organic material entering the disposal facilities, especially with respect to long-term stability and fire hazard.

Organic material

Organic material under irradiation may form hydrogen and organic gases, *e.g.* in some instances, gas formation from bituminised waste occurred after a certain storage time. More evidence on the long-term stability of waste forms containing organic compounds, or using organic binders, could be required and therefore these waste forms may be excluded from final disposal. Thermal treatment of organic radioactive waste (*e.g.* incineration, pyrohydrolysis, plasma heating) eliminates this risk. The resulting waste can be embedded in an inorganic matrix if required.

Water containing matrix

Most final waste forms use a matrix material or bulky material (such as metal parts from decommissioning). The most common matrix material, *i.e.* cement, contains water, which can give rise to hydrogen formation.

Alternative matrices are available:

- Glass and Synroc are quite well-established matrix materials, but seem to be sensitive towards the waste composition. This can be problematic for badly-defined and changing waste.
- Graphite/glass composites seem to be more robust.
- Metals, *e.g.* steel.

One important aspect of long-term safety of a disposal facility is the possibility of water ingress into the repository. Even with the additional barrier of a non-water-containing matrix, metal waste from decommissioning may corrode and form hydrogen.

A small surface/volume ratio will help to minimise this risk. Molten ingots produced from the metal resulting from decommissioning will not only reduce the waste volume but also provide a minimised surface/volume ratio.

Irradiated graphite

Generation I and II nuclear reactors (and plutonium production reactors) have made use of graphite as moderator to a great extent.

More than 250,000 t of irradiated graphite will have to be disposed of worldwide, with significant shares in the UK, France, Russia and the USA.

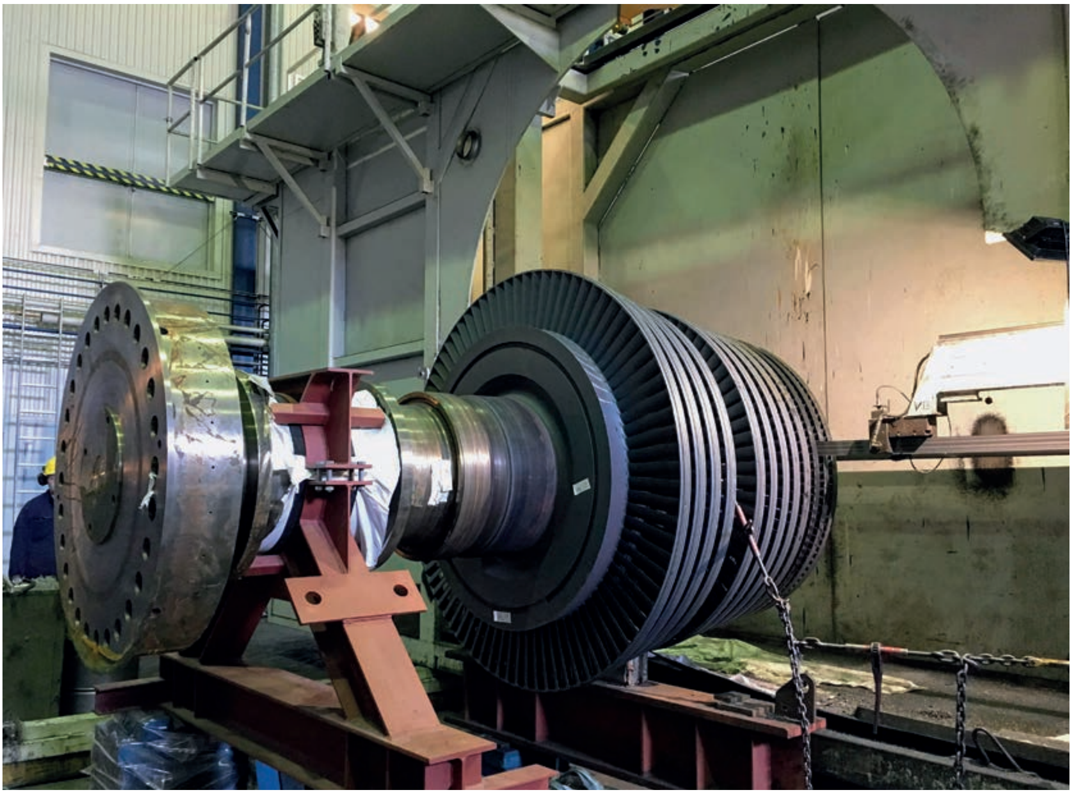
The most relevant radionuclides are carbon-14, chlorine-37 and tritium – although these are beta emitters, their long half-lives, as well as their mobility, make them difficult to handle:

- Shallow land disposal requires high corrosion resistance, which is not associated with graphite *per se* due to its high porosity.
- For deep geological disposal the volumes are too large.

Recent activities (besides simple incineration and release of activity into the atmosphere) follow two directions: decontamination, and improvement of leaching resistance (see Section A3.1 in Appendix 3).

5.5.2 Waste treatment

The management of radioactive waste from decommissioning is an important step in the overall decommissioning process. The main aim of this stage is to generate conditioned waste in packages that are qualified for interim storage pending final disposal. An important secondary aim is to reduce the volume either by decontamination or by other specific treatment processes.



Size reduction of BWR turbine rotor (image courtesy EDF/Cyclife)

The details of the waste management strategy depend on the particular inventory and waste routes, but in general the following methods will be applied:

Sorting

Waste sorting and characterisation helps to ensure that segregation can be carried out effectively onsite and that misrouting of waste types is avoided.

Segregation

Materials should be kept separate according to their properties such as radioactive waste category, non-contaminated versus contaminated or activated, or according to their physical-chemical properties.

Decontamination

- Building structures form the majority of the waste to be handled from decommissioning. Only a small part of this might be activated (*e.g.* biological shield) and some surfaces contaminated. Removal of these activated or contaminated surfaces from the buildings will drastically reduce the radioactive waste volume.
- Activated metals should be segregated at the place of origin. Surface contaminated metals can be decontaminated using dry processes (*e.g.* blasting) or wet processes (*e.g.* electrochemical).

Casting of steel at the Centraco plant in France (image courtesy EDF)

Volume reduction

Different options are available to reduce the volume of radioactive waste, depending on the waste type:

- Thermal treatment (incineration, pyrohydrolysis) for organic material; plasma heating for waste mixtures.
- Melting of metals to form ingots. These can be measured more easily than bulk material and may also have more predictable long-term behaviour in the repository.
- Compaction of materials such as insulation, metals, inorganic material, organics (if thermal treatment is not possible).

Conditioning

Some liquid wastes (*e.g.* evaporator concentrates) and solid wastes (*e.g.* ash from incineration) are solidified in the primary waste package using a matrix material. There is a variety of primary waste forms (*e.g.* 200-litre drums) and material (*e.g.* pellets from high force compaction) to be packed into the final waste package, which should be conditioned using grout or other embedding materials.

Waste form (waste containers)

The waste form used for the final waste package has to comply with the waste acceptance criteria of the respective disposal site. These criteria specify: basic requirements (*e.g.* material, shape and dimensions, stackability, and mechanical handling features); specific requirements (*e.g.* mechanical stability, thermal resistance, leak-tightness, and shielding function); and container requirements (*e.g.* surface coating, seals, vents, and void space restrictions).

Interim storage

Interim storage can provide different functions during a decommissioning project, for example:

- Storage of raw material from decommissioning at site prior to further treatment or handling steps.
- Storage of material for declassification or free release.
- Storage of containers with radioactive waste prior to final packaging of the waste form for disposal.
- Storage of the final waste form for disposal until the final disposal site is ready to accept waste.

It should be noted that storage often lasts longer than initially expected. Therefore additional measures against leakage, corrosion and biodegradation should be taken, and only well-characterised material should be stored.

Measurement

Measurement of radionuclides (including sampling) accompanies all decommissioning activities at nuclear sites (see Section A4.8 in Appendix 4).

By applying these measures to the radioactive waste generated during a facility's decommissioning, the space demand for storage and disposal will be minimised and therefore also the storage and disposal cost will be minimised.

5.6 Transport of waste

The transport of radioactive waste is frequently perceived to be problematic. Although this may be true for some waste types (*e.g.* spent nuclear fuel or high activity liquid waste), it is generally not the case for solid waste, as this is governed by specific internationally-agreed regulations. Public acceptance related to the transport of spent nuclear fuel and radioactive waste differs significantly from country to country.

For the full-scale decommissioning projects in Germany and elsewhere, as well as for several modernisation and power upgrade projects, thousands of tonnes of contaminated material have been transported without incident.

It should also be noted that the vast majority of decommissioning waste is in the VLLW category followed by LLW. These types of waste can be shipped using conventional containers and vehicles.

For most solid waste arising in decommissioning projects, standard IP-2 sea containers will comply with transport regulations. Intermediate-level radioactive waste may require shielding inside the container or a special container to meet the dose rate limits.

For large components, a range of transport concepts will have to be applied. Closed compartments without surface contamination can usually be transported without further

Boilers removed from the Berkeley site in the UK's Gloucestershire as part of the Magnox decommissioning programme. Fifteen 300 tonne boilers were taken to be recycled at Studsvik's metal treatment and recycling facility (now Cyclife) in Sweden (image courtesy Magnox Limited)

packaging, while other components such as turbine rotors should be enclosed by wrapping or an overpack.

For decommissioning projects implementing a concept for external treatment or disposal of large components, an efficient transport plan must be in place so that potential bottlenecks can be avoided.

6 | The Economics of Waste Management from Decommissioning

Summary

- Decommissioning would be simpler, faster, and less expensive if it were taken into consideration during the siting, design, construction, and operation phases of the nuclear plant life-cycle. This is also true for radioactive waste management.
- The proposed methodology for managing waste from decommissioning will have an impact on costs and financing, and will help inform cost estimates for new build programmes. However, decommissioning decisions must be based on funding availability.
- Because site operation and infrastructure, including project management, is the largest cost element, the allocation of roles and responsibilities is critical. Therefore, the plant owner must decide which activities to carry out within the organisation (*e.g.* material inventories conducted before the start of decommissioning) and which activities to contract out to third parties.
- While low-level radioactive waste from decommissioning is a cost driver, the total amount spent on waste conditioning, packaging, transport, and disposal is not as great as the amount spent on site operation including project management; hence pre-decommissioning planning and the absence of changes in scope during commissioning are important cost and cost uncertainty drivers.
- In Spain, the state-owned decommissioning and waste management company Enresa has assumed temporary ownership of the plant during decommissioning. In the USA, an organisational structure is emerging where the decommissioning contractor similarly assumes temporary ownership of the plant (*e.g.* at Zion 1&2) and returns the site to the original owner after decommissioning. As a consequence of national policies, Enresa is in charge of decommissioning and waste management, while in the USA, contractors and waste management providers compete with each other.
- All radioactive waste managers must follow national regulations and waste acceptance criteria, but the transfer of ownership of waste from decommissioning to a disposal site requires detailed information regarding the contents inside sealed waste packages. If the decommissioning contractor is also the waste manager, the single entity is incentivised to characterise in more detail the contents of each package that is sent from the decommissioning site to the waste management facility.

6.1 Introduction

Because site operation and infrastructure, including project management, is the largest cost element, the allocation of roles and responsibilities is critical. The emerging industrial set-up for decommissioning combines the decommissioning contractor with the waste facility owner to facilitate the shipment of waste from the nuclear plant site to the waste management/disposal site.

This is the concept being implemented in Spain where Enresa temporarily takes ownership of a shutdown plant; builds an interim spent fuel storage installation (ISFSI) at the site for removed used fuel; decontaminates and dismantles the plant; ships VLLW, LLW, and ILW to its own facilities; restores the site, excluding the ISFSI; and returns the land to the original owner of the plant (the ISFSI will be decommissioned when geological disposal becomes available) – see Appendix 6. In the USA, a similar structure for the decommissioning of Zion 1&2 has been created – see Section A7.1.2 in Appendix 7.

Even where radioactive waste management facilities are owned by the decommissioning contractor, storage space at these facilities is both limited and has to be regarded as a valuable resource. If there is no central planner responsible for planning, building, and operating waste management facilities (as in many European Union countries such as France and Germany), owners/operators must rely on market forces to anticipate decommissioning waste requirements.

Due to the changing regulatory requirements regarding radioactive waste, it is difficult to anticipate what the waste acceptance criteria might be for decommissioning waste after long periods of storage. This has resulted in some plant owners expecting the cost of waste management to rise as more units are decommissioned and compete for existing and planned waste storage space. This uncertainty has led to ranges of the present value of decommissioning and waste management costs increasing as storage periods stretch into the future. For this reason, some plant owners should select immediate decommissioning, which also allows them to rely on some of their current personnel helping in the planning and management of the project.

6.2 Cost estimates and financing strategies

There are variations in the end states (as described in Chapter 2) defining the release of the site for future use; for example, whether all underground structures must be removed or whether structures below one metre can be left in place (see Appendix 2 on *National End State Requirements*). In addition, national jurisdictions apply different standards regarding the management of radioactive waste and nuclear fuel onsite after the removal of all other material.

Because of these differences, each site can have different estimates of the costs of:

- Treatment and conditioning of the waste generated during decommissioning.
- Radioactive waste storage and disposal.
- Impacts related to the schedule of waste management activities during decommissioning.
- The removal of spent nuclear fuel (SNF) or the creation of an onsite interim spent fuel storage installation (ISFSI).

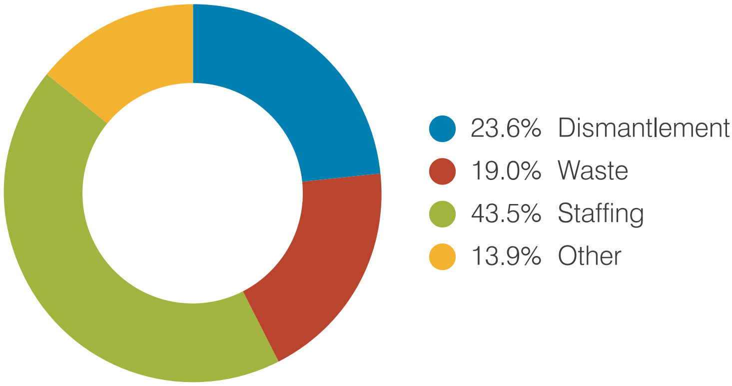


Figure 6.1. US cost categories as a percentage of the total decommissioning cost [12]*

The resulting estimates will affect the required annual contributions to funds dedicated to decommissioning.

The approximate shares of the different cost categories are shown in Figure 6.1 [12]. It should be noted that the data mainly reflects figures for first-of-a-kind single unit plants.

In general, decommissioning funds for a nuclear plant could be of the order of $1 million per megawatt (MWe). This should cover planning, project management including site operation, demolition, waste management up to and including disposal, and also onsite and offsite spent fuel storage.

However, it should be emphasised that project management costs (including site operation costs) – the highest decommissioning cost item – will increase to some extent in proportion to the length of the project. For the Zorita decommissioning project in Spain (see Appendix 6), project management and site operation contributed to 61% of the total decommissioning cost while radioactive waste processing, storage and disposal only contributed to 5%. The cost for project management and site operation was significantly higher (double) compared to the estimate prior to start of the project. This increase was to a large extent due to the extended schedule for the project.

The removal of the used fuel and the management of the decommissioning waste are in many projects on the critical path and therefore require special attention. Decontamination and removal of waste (including large components, where possible) should therefore begin as soon as possible and interim storage facilities should be constructed to accept the spent fuel. This frees up the fuel pool for cutting up the reactor internals and vessel (and other primary circuit components, not selected to be removed as one piece), which have the highest levels of radioactivity after the removal of the spent fuel.

** Spent fuel management and operational waste costs are not included.*


The low- and intermediate-level waste disposal area of Enresa's El Cabril facility in Córdoba (see Appendix 6) (image courtesy Enresa)

6.2.1 Cost drivers

The cost of waste management from decommissioning is influenced by several drivers that must be carefully handled to avoid cost escalation and schedule overruns:

Decommissioning policy and strategy
A global decommissioning policy and strategy must be defined as soon as possible, ideally at the time of plant construction licensing (see Chapter 2). This enables the required waste management and disposal infrastructure to be planned and developed.

Roles and duties of the respective stakeholders involved in the regulatory process
The regulatory framework surrounding decommissioning must be established with clarity and public acceptance (see Chapter 2). Operators of nuclear power plants generally are responsible for financing decommissioning costs, typically based on the revenues earned from the sales of the electricity. These operators are also responsible for paying for the management and disposal of the waste generated. The alignment of the chosen strategy with the provided funds is the responsibility of the owners/operators. Fulfilling this duty is key to maintaining credibility and solvency, as well as increasing public acceptance and stakeholder confidence.

Planning and site characterisation before decommissioning
Cost escalation and schedule delays are likely to occur if there is not a comprehensive site characterisation (systems, structures and land) based on an agreed site end state and waste disposal criteria in place before the start of decommissioning (see Chapter 3).

Management of spent fuel
The cost of spent fuel – including damaged fuel – or high-level radioactive waste management may not be a decommissioning cost per se (given that its disposal or reprocessing could be

the responsibility of the government) and is therefore not included in some decommissioning cost estimates. However, it must be considered when determining the adequacy of overall funding and has to be included in the overall decommissioning schedule.

Dismantling operations and related waste management
The effective planning and management of dismantling operations and the corresponding management of very low-level, low-level, and intermediate-level radioactive waste, including handling, conditioning, packaging, transport, and disposal, has a significant influence on costs and schedule. A major objective of radioactive waste management is clearance and reclassification in order to minimise radioactive waste volumes for disposal and simplify handling (see Chapter 5).

Manpower and contractor management
Staff costs comprise the largest expense associated with decommissioning. Employment expenses will grow significantly with schedule delays. Care must be taken in structuring decommissioning and waste management organisations to encourage the exchange of lessons learned. In all cases, the performance is enhanced by involving operations staff in characterising the plant site before the start of dismantling. In fact, the characterisation of sites (both operating nuclear plant and waste management facilities) should be carried out throughout the nuclear plant operating lifetime (see Chapter 3).

Risk management, uncertainties and contingencies
Risk and uncertainty management should be built into the decommissioning process by considering possible changes in underlying assumptions regarding cost and schedule as the project progresses. Active risk management increases the confidence in the decommissioning cost estimate (DCE), and hence the public acceptance of the project. Updating the DCE and performing sensitivity analyses regarding changes in assumptions before and during decommissioning are important prerequisites for establishing adequate funds.

In addition to reliable decommissioning cost estimates, flexible systems must be in place to ensure that funds are available when needed (see Chapter 2).

Decommissioning funding arrangements might be vulnerable to earlier than expected plant closure or the failure of a fund to reach a sufficient level of financing to cover the full costs of decommissioning. The responsibility for residual funding liability must be clearly defined should funds be unavailable to fully decommission the nuclear plant or for waste management. Countries must establish mechanisms defining responsibilities for ensuring that future generations (*i.e.* those that did not benefit from the nuclear plant's operation) are not burdened by waste created in the past or present, or from future decommissioning activities.

Funding policy and strategy
The requirements for financing nuclear plant and waste facility decommissioning must be formally established according to the national legal system. There are considerable variations among countries in the details of these requirements. In many cases, the systems currently in place have incorporated features intended to address deficiencies identified in earlier years, with countries introducing requirements for systematic reviews of both the DCE

and the corresponding decommissioning trust funds (DTFs), as well as the adequacy of the DTF to cover the DCE. The responsibility for DTF management and oversight must be legally defined. Careful consideration must be given to defining appropriate decommissioning expenses, such as research and development activities that could lower future costs or increase the speed of decommissioning (see discussion in Section A7.1.1 in Appendix 7 on San Onofre 1 DTF management, where anticipated LLW management cost escalation is projected to be greater than the return on the DTF).

6.3 Economic implications

Following the 'waste hierarchy' principles, as discussed on page 30, will increase the effectiveness of existing and planned waste facilities and infrastructure. This means that during decommissioning and waste management, all efforts should be made to: reduce cross-contamination of structures, equipment, and materials; reduce the volume, packaging, and transport of resulting waste; re-use or recycle structures, equipment, and materials whenever possible; and dispose of conditioned waste in a manner that minimises future exposure, and eliminates future handling and repackaging. These efforts will contribute to optimising overall decommissioning programmes with an associated reduction in cost.

While decommissioning waste is a lesser but still important part of the cost of decommissioning a nuclear plant, the failure to provide waste management routes and facilities aligned to the decommissioning programme could lengthen the schedule, hence increasing the project management costs, the largest cost of decommissioning. Furthermore, for the foreseeable future, the lack of radioactive waste disposal facilities will continue to increase the cost of radioactive waste management due to the need to provide additional interim storage solutions.

Pre-decommissioning planning and the absence of changes in scope during decommissioning are important cost and cost uncertainty drivers. Decommissioning planning should commence during the design phase with the plan being subject to routine updates throughout the nuclear plant's life-cycle. Understanding the inventory, decommissioning strategy and end state requirements permits the decommissioning waste management requirements to be identified early enough to plan for waste management resources and facilities.

Because site operation including project management is the largest cost element, the correct design of decommissioning and waste management organisation and allocation of roles and responsibilities is critical. The nuclear plant owner must decide which activities to carry out within the company (*e.g.* material inventories conducted before the start of decommissioning) and which activities to contract out to third parties.

Some emerging industrial decommissioning organisations combine the decommissioning contractor with the waste facility owner to facilitate the shipment of waste from the plant site to the waste management/disposal site. All radioactive waste producers must follow the national regulatory framework and waste acceptance criteria, but the transfer of ownership of decommissioning waste to a waste manager requires very detailed information regarding the contents inside sealed waste packages. If the decommissioning contractor is also the same organisation as the waste manager, the single entity will be more incentivised to accurately characterise the contents of each package leaving the plant site to the waste management site. As a consequence, delays due to data omissions and/or the re-work of packages is reduced.

Given the anticipated returns on decommissioning trust funds, the adequacy of funding arrangements for decommissioning nuclear facilities should be ensured.

To calculate the funding required:

- First, estimate the costs of decommissioning, radioactive waste management, and SNF/HLW management activities including appropriate contingencies.
- Second, subtract the amounts that have been contributed.
- Third, to calculate the annual contribution, divide by the number of years remaining for contributions (this is equivalent to assuming a 0% discount rate as is done in Finland).
- Fourth, repeat as often as necessary, *e.g.* every three years. If too much is collected, return the funds or save to pay for future costs.

Removal of steam generators during decommissioning of Exelon's Zion nuclear plant. Decommissioning commenced in 2010 and is being carried out by EnergySolutions subsidiary ZionSolutions – see Section A7.1.2 in Appendix 7 (image courtesy ZionSolutions)

7 | Recommendations and Conclusions

With more nuclear facilities reaching the end of their operating lifetimes – or being prematurely closed due to market forces or national policies – decommissioning and related material and waste management have become global challenges.

In the past, most nuclear facilities were not designed to be fully decommissioned; however nowadays new build projects should include dismantling and waste management operations from their earliest stages. Due to unexpected challenges that have arisen over the course of decommissioning projects, a substantial amount of experience has been accumulated and solutions based on actual cases have been developed. During this time, there has been a continuous focus on improving safety and economics, as well as on reducing the environmental impact.

This optimisation of dismantling and waste management is driving the development of a sound, mature decommissioning procedure. Despite some specific differences in national policies, a number of common principles have been identified:

- The end state and future use of the site should be defined at the beginning of the life-cycle of the plant, i.e. during the planning phase.
- Radiological, physical and chemical inventories should be established as early as possible and updated throughout the operational phase right up to plant shutdown. This information is needed to select the most suitable decommissioning strategy and waste management processes.
- Decommissioning and waste management techniques, operator training, as well as public engagement, should be continuously improved.
- Material from decommissioning should be sorted and segregated in order to maximise the quantity of material to be recycled in a economic and sustainable way. At the same time, the quantity of radioactive waste to be sent for disposal should be minimised in order to preserve waste storage capacity, which should be viewed as a valuable resource.

Over the last few decades, the nuclear industry has been expected to continuously improve its performance regarding its societal and environmental impact. In contrast to the early years of the industry – when military or energy security concerns were prioritised – increasingly stringent standards have come to be expected and the fate of the industry is dependent on conforming to them.

As a consequence, in order to maintain stakeholder confidence and public acceptance, nuclear operators have to provide assurance not only of their ability to carry out decommissioning in a safe and effective manner, but also of their competence in technical, financial, environmental and societal areas. The nuclear community should therefore always be carrying out research and development to identify ways of enhancing existing decommissioning and waste management processes.

Decommissioning and waste management should not be seen as separate from the operation of a nuclear facility, but simply as the last of the three normal phases of its life-cycle, after design and operation. Overcoming the financial and technical challenges of decommissioning and the associated waste management is a key part of demonstrating to the public and policy makers that nuclear power is an essential and practical form of low-carbon generation.

7.1 Main conclusions

Planning for decommissioning is a multidisciplinary task, involving designers, operators, researchers, developers, and economists. While the planning and execution of different decommissioning projects around the world are affected by different cultures, nuclear technologies, national policies and regulatory frameworks, a number of key principles have been identified in this report.

End state

The decisions on strategy and end state will have a direct impact on decommissioning planning. The earlier in the nuclear plant life-cycle that the decommissioning requirements and objectives can be identified, the earlier they can be defined, allowing the associated finances to be structured in line with the proposed project schedule and activities.

However, the decommissioning strategy and end state might not be selected on technical attributes or operational priorities alone, as a number of other criteria have to be taken into account. These include: national policy, space requirements, funding, waste management infrastructure availability, fleet closure programmes, and future use including re-use for nuclear. Currently, the main drivers are finance and waste management infrastructure availability.

Strategies based on immediate decommissioning may expose workers to higher doses and will generate more radioactive waste of a higher category than deferred or entombment strategies as the benefits of radioactivity decay over time are not realised. However, these strategies need to be carefully evaluated, taking into account long-term safety, environmental aspects and economics.

National approaches to end states normally have stated goals but are not prescriptive on how these are demonstrated or achieved. It is important for nuclear plant operators to define the processes to be deployed and the validation approaches prior to commencing decommissioning. This helps to ensure that the implementation of the processes and minimisation of waste are optimised.

The selection of the end state will mainly influence the quantity of the lower categories of radioactive waste (*i.e.* low- and very low-level radioactive waste) created during decommissioning since the more emphasis there is on removing the facility from regulatory control, the greater will be the resulting quantity of these wastes.

If the selected end state is brownfield, the decommissioned site will require ongoing management and control to detect any residual risks. This is a common scenario for sites that will be re-used for future nuclear plant construction.

Inventories

A materials inventory should be recorded and maintained continuously, starting from the early design phase, continuing throughout operation, and regularly updated. A good understanding of the inventories eases nuclear plant maintenance during the several decades of operation and will reduce uncertainties when decommissioning occurs.

All information concerning modifications made to the equipment and systems, as well as about incidents and their consequences that have occurred during operation, should be promptly documented. Prior to the final shutdown of a nuclear facility, a decommissioning database should be developed and put in place.

A complete inventory needed to perform efficient decommissioning is based on three characterisation activities – physical, radiological, and chemical/biological. Since every reactor facility has its own specific properties, operation history, layout, chemical composition of materials, etc., each facility would normally require an independent calculation of the induced activity levels in its construction and shielding materials by the time of its decommissioning.

Waste routing

The national regulatory framework, existing and planned infrastructure for waste treatment and disposal facilities, international recommendations, along with decisions on strategy and schedule, are all important factors when identifying the appropriate waste routes.

A wide range of waste routes is used worldwide. However, for certain waste categories, not all the options may be available in a given country. The preference should be to select waste route alternatives where the site end state can be achieved most efficiently at an acceptable cost.

Material properties, logistical challenges, regulatory and stakeholder requirements, as well as the possibility of certain routes being temporarily or permanently stopped, require a variety of waste routes. The recommendation is that at least two waste routes should be kept open for each category of waste wherever reasonable.

Following the waste hierarchy will increase the effectiveness of existing and planned waste facilities. This means that during design, construction, operation, and decommissioning, all efforts should be made to: reduce contamination of structures, equipment, and materials; reduce the volume, packaging, and transport of resulting waste; re-use or recycle structures, equipment, and material whenever possible; and dispose of conditioned waste in a manner that minimises future exposure, repackaging, and transport, as well as preserves natural resources.

While decommissioning waste accounts for about one-fifth of the cost of decommissioning a nuclear plant, the lack of waste management routes and facilities can lengthen the schedule, which will increase the project management and site operation costs, the largest costs of decommissioning. Furthermore, for the foreseeable future, the lack of radioactive waste disposal facilities will continue to increase the cost of radioactive waste management.

Treatment and processes

The volume of radioactive waste arising during decommissioning activities and the related logistics are a main factor affecting the costs and schedule involved in managing radioactive waste from decommissioning. Processing and clearance leads to the reduction of radioactive waste volumes and conditioning makes it suitable for transport, storage and disposal.

The application of the ‘waste hierarchy’ principle encourages recycling and thus minimises the amount of waste for final disposal.

Selection of suitable treatment technologies for radioactive waste should to be carried out in accordance with the respective waste acceptance criteria (WAC). Where WAC are not yet available, the chosen treatment technologies should generate inert, water-free matrices.

Decommissioning economics

The cost of decommissioning is influenced by several drivers, in particular waste management, which must be carefully handled to avoid cost escalation and schedule overruns.

Taking into account long-term responsibilities and capabilities, the nuclear plant operator must decide which decommissioning activities to carry out within the company (*e.g.* materials inventories) and which ones to contract out to third parties.

Pre-decommissioning planning and the absence of changes in scope during decommissioning are important cost and cost uncertainty drivers. Because project management and site operation is the largest cost element, the allocation of roles and responsibilities is critical. In particular, waste management is an indirect driver of project costs; proper waste identification and routing will benefit the overall decommissioning cost and schedule.

Managing both the technical and financial aspects of decommissioning and waste management well is essential to gain stakeholder confidence and public acceptance.

7.2 Facing decommissioning challenges

This report presents decommissioning and the minimisation of waste in global terms on the basis of several interconnected key parameters: specific national policies; availability of resources and technological capabilities; economic considerations; and site and locality characteristics. The lessons learned in these areas from several countries have been drawn upon in preparing this report. However, several issues remain:

Harmonisation of regulations and multinational solutions

Harmonisation of regulations between countries is a challenge that should be overcome. Several reports concerning international cooperation in decommissioning and radioactive waste management claim that the lack of regulatory harmonisation between countries is hindering multinational approaches. Not only does this prevent innovation and improvements in efficiency, but also could confuse the public and put its acceptance at risk. Regulatory discrepancies prevent stakeholders from benchmarking the efficiency of decommissioning and waste management strategies between countries, making it difficult for them to identify the best available techniques.

Decommissioning and waste management solutions could be most efficiently optimised at an international level. Therefore, multinational decommissioning expert groups should be established to identify the requirements, skills, technological capabilities and resources that are needed. This might also include the communication of these requirements – taking into account the specific characteristics and challenges of individual projects – to the countries and operators hosting decommissioning operations.

A similar approach is currently being developed by the European Repository Development Organisation (ERDO) for a multinational radioactive waste repository on behalf of several international organisations. This project should address the need of countries that have a sufficient amount of radioactive waste for a deep geological disposal facility but lack suitable host rock formations, as well as those that might be better suited to hosting a repository but do not have enough waste for it to be economically practical.

Company structuring and organisation

It would appear that companies that are structured and organised on an integrated model find it easier to manage entire projects. Worldwide experience has shown that companies involved in all aspects of a decommissioning project (planning, operation, maintenance, waste characterisation, treatment, disposal, *etc*.) have faced less difficulty in planning and managing the project – including in optimising their human resources and skills – than ones dealing with a number of separate organisations. Several examples of integrated organisations have demonstrated that they have been able to avoid the conflicts of interest that can arise between plant owners and waste treatment and disposal facilities when responsibilities are separated.

This approach is also advantageous in terms of public acceptance, particularly in gaining the support of the local community, as the operator remains responsible for the site throughout its life-cycle.

New nuclear technologies

The ongoing development of advanced nuclear plant concepts and technologies is vital to the future use of nuclear energy worldwide. However, advanced nuclear plant concepts and technologies unavoidably bring new technical challenges, constraints and impacts, which cannot be foreseen during the early phase of development. Some of these issues will only be identified when they occur and have to be addressed accordingly. This can weaken the industry's credibility as well as have adverse financial consequences.

In contrast, after more than 50 years of LWR operation, most issues have been solved and any remaining ones are close to being solved. It is unlikely that new risks will be discovered as existing LWR technology has been mastered. Further optimisation of the duration of decommissioning and environmental impact of this proven technology should result in increased acceptance along with economic, societal and environmental benefits.

Long-term sustainability – replacement of major components

Some major components such as the reactor pressure vessel are currently defining the operational lifetime of a nuclear power plant. However, the facility core structures (*i.e.* the concrete buildings and the site infrastructure) are able to last significantly longer than the critical components. Therefore more consideration should be given during nuclear plant design to the replacement of critical components.

The benefits of replacement of such components include:

- Shorter project time to the re-use of the site compared with a new build project.
- A significant decrease in the overall project cost.
- A reduction of the waste amount since complete plant demolition is not required.

Should all plant components – including the reactor pressure vessel – be replaceable, then a full plant replacement could be carried out within a few years of shutdown, accelerating site re-use and reducing the overall cost of nuclear power generation. Solving this issue would be a major improvement, transforming decommissioning from a costly project lasting 20-30 years to a maintenance period of no more than five years.

Human resource planning would be easier to manage as the closure of one facility would be followed by the restart of the unit with new components, without the need for relocation and significant rehiring.

Societal impacts would be minimised as the social network, skills, industrial resources and capabilities around the plant could be maintained, leading to stronger public acceptance and stakeholder confidence.

The environmental impact would also be significantly reduced in line with the reduction of the amount of waste to be managed. Dismantling would be incorporated into the operational phase as an extended maintenance period, reinforcing the concept of decommissioning being a normal part of the nuclear plant life-cycle.

In order to achieve this goal, the experience gained from successful replacement of critical components such as steam generators may be drawn upon. Such tasks, which have been regularly carried out over decades of nuclear plant operation, are very similar to those required for decommissioning. As a consequence, the replacement of major components should be taken into account during the design phase.

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9. Goers, TÜV Nord, *Experience and lessons learned from decommissioning of German NPPs Stade, Greifswald, Würgassen and Lingen* (2015)
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11. International Atomic Energy Agency, *Application of the Concepts of Exclusion, Exemption and Clearance*, Safety Standards Series No. RS-G-1.7 (August 2004)
12. Electric Power Research Institute, *Decommissioning Experience and Lessons Learned: Decommissioning Costs*, #1023025 (November 2011)

Appendix 1 | National Decommissioning Strategies

Country	Preferred Decommissioning Strategy
Canada[a]	No preference is stated in either policy or regulations. Most operators of large nuclear facilities have adopted deferred decommissioning in order to: • Reduce occupational doses by allowing time for radiological decay. • Take advantage of efficiencies of scale by coordinating the decommissioning of different facilities located on the same site. Prompt decommissioning has been adopted for some smaller facilities (*e.g.* SLOWPOKE II research reactors).
China[b]	The *Safety Requirements for Decommissioning of Nuclear Facilities*, GB/T 19597-2004, states a preference for prompt decommissioning. Deferred decommissioning is also allowable depending on the financial or technical factors. To date there is no experience of decommissioning commercial nuclear plants in China. The expenses for decommissioning nuclear installations and for disposal of radioactive waste shall be withdrawn in advance and shall be included in the budgetary estimates of investment or in production costs.
Finland[a]	The Radiation and Nuclear Safety Authority (STUK) YVL Guide D.4, *Predisposal Management of Low and Intermediate Level Nuclear Waste and Decommissioning of a Nuclear Facility* (November 2013), states: “Dismantling the facility and other measures taken for the decommissioning of the facility may not be postponed without due cause.” Decommissioning plans for two of the four operating power reactors are based on prompt decommissioning while the plans for the other two are based on deferred decommissioning (due to the presence of another reactor on the site that will still be in operation).
France[a]	The regulators state a preference for prompt decommissioning but this is not a regulatory requirement. Some operators have adopted deferred dismantling (with a 50-year deferral period) due to the lack of required waste management facilities.
Germany[a]	The regulations allow either prompt decommissioning or deferred decommissioning. Operators have tended to favour prompt decommissioning but some have adopted deferred dismantling due to the lack of appropriate waste management facilities.
India[c]	The process of decommissioning begins after the final shutdown of the facility or after an abnormal event when the facility is no longer considered viable for operation. The Atomic Energy Regulatory Board Safety Manual AERB/SM/DECOM.-1, *Decommissioning of Nuclear Facilities* (March 1998), outlines the requirements for decommissioning.
Italy[a]	Government policies or strategy documents call for: • Adoption of an immediate decommissioning strategy for all national shutdown nuclear installations. • Completion of decommissioning of all major nuclear facilities by 2024. Most facilities have been forced to adopt deferred decommissioning due to a lack of waste management facilities.

Russian Federation[b]	Immediate decommissioning, deferred decommissioning or even entombment are allowed. All shutdown commercial nuclear plants have adopted deferred decommissioning in order to: • Reduce occupational doses by allowing time for radiological decay. • Take advantage of efficiencies of scale by coordinating the decommissioning of different facilities located on the same site. Prompt decommissioning has been adopted for research reactors, radiochemically polluted facilities (laboratories, fabrication facilities), and uranium conversion, enrichment and other nuclear facilities. Most of the completed decommissioning projects have been carried out to a brownfield end state. Plutonium-producing reactors have been decommissioned by entombment.
Sweden[b]	Sweden has a general preference for immediate decommissioning or as soon as the repository for decommissioning waste is available (around 2030). The three power reactor operators with permanently shutdown reactors, or reactors which will be permanently shutdown in the near term, intend to perform immediate decommissioning. Deferred decommissioning was adopted for the Ågesta district heating nuclear plant. This facility was shut down in 1974 and is planned to be decommissioned in the early 2020s.
United Kingdom[a]	No preference is stated in either policy or regulations. The Nuclear Decommissioning Authority identified both ‘continuous decommissioning’ and ‘deferred decommissioning’ as credible decommissioning strategies (continuous decommissioning begins immediately after shutdown but may continue over a long period while deferred decommissioning includes a deferral period to allow for radioactive decay). Most facilities (including most of the research reactors and some non-reactor facilities) have adopted deferred decommissioning but the Magnox plants have recently adopted the Magnox Optimized Decommissioning Programme (MODP) which uses a hybrid approach similar to that adopted at Vandellòs 1 in Spain. This approach consists of an accelerated transition to safe storage (care and maintenance), which includes the work required to dismantle both radioactive and non-radioactive plant and buildings where radiological benefit cannot be achieved from deferral. Other buildings are to be placed into a passively safe and secure state, which will not require the presence of staff onsite on a routine basis, for an extended period of storage.
United States[a]	Regulations require decommissioning of reactors to be completed within 60 years of shutdown. Both prompt and deferred decommissioning have been adopted by operators depending on their specific needs or circumstances. Several commercial nuclear power plants have largely completed decommissioning but the used fuel remains in storage onsite due to the lack of required high-level waste management facilities. In-situ confinement has been adopted at US Department of Energy sites for the decommissioning of: • Two large reactors (P and R reactors) and their ancillary facilities at the Savannah River Site near Augusta, Georgia. • Two fuel processing facilities, *i.e.* Buildings CPP-601 (Fuel Processing Building) and CPP-640 (Headend Processing Plant) at the Idaho National Laboratory and the U Plant at the Hanford in Washington. • The below grade portion of several small reactor facilities at Idaho National Laboratory.

Sources:
Candesco, International Benchmarking on Decommissioning Strategies (June 2014)
World Nuclear Association contact with Swedish, Russian and Chinese industry sources
S.A.H. Ashraf and S.K. Chande, Atomic Energy Regulatory Board (India), Decommissioning of Nuclear Facilities, Indian Perspective, CN-93[56]

Appendix 2 | National End State Requirements

Country	End State Goal	End State Controlling Regulations
Belgium[a]	Before a site can be released from regulatory control, the licensee shall perform a final survey to demonstrate that the end state, as approved by the regulatory body, has been met. For restricted use, the licensee shall provide a long-term impact assessment, an appropriate surveillance regime, and any proposed land use restrictions.	Final remediation objectives are expected to be achieved on a case-by-case basis. The basic framework for remediation of contaminated sites is established in the *Royal Decree of 20 July 2001 concerning the general regulations for the protection of the public, workers and the environment against the hazards of ionising radiation* (ARBIS), with release criteria and effective individual dose <10 μSv/yr.
Canada[a]	The goal of nuclear site remediation is determined on a case-by-case basis. For the Port Hope area, the clean-up goals were developed based on an acceptable risk to residential (unrestricted) users of the land. At Chalk River Laboratories (CRL), the clean-up goals were based on potential restricted industrial uses. The degree of stakeholder involvement in developing those goals has also varied from case to case. Stakeholder involvement was extensive for developing Port Hope clean-up goals while stakeholder involvement has been limited to date in the development of the CRL clean-up goals as it remains an operational site. The public will be involved as the CRL long-term strategy is developed and clean-up progresses.	Case-by-case (depends on site use). Specific regulations and policies for environmental remediation on nuclear sites do not exist in Canada. These activities are covered under various overarching documents concerning nuclear activities generally, such as the Nuclear Safety and Control Act which establishes the regulatory framework for nuclear activities in Canada. Regulations made under the Act include *Class I Nuclear Facilities Regulations* (SOR/2000-204), *General Nuclear Safety and Control Regulations* (SOR/2000-202), *Nuclear Substances and Radiation Devices Regulations* (SOR/2000-207) and *Radiation Protection Regulations* (SOR/2000-203). The Canadian Nuclear Safety Commission (CNSC) has established policies for nuclear activities that are applicable to environmental remediation at nuclear sites, such as P-290, *Managing Radioactive Waste,* and P-223, *Protection of the Environment*.
China[b]	The decommissioning works should minimise the radioactive waste in order to reduce the impact on humans and the environment. The end state goal is to make sure the site or facilities can be reopened and re-used with or without any restrictions.	*Regulation for Radiation Protection of Reactor Decommissioning* (GB 11850-1989), *Basic Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources* (GB 18871-2002), *Safety Requirements for Decommissioning of Nuclear Facilities* (GB/T 19597-2004) state the required regulations and precise limitations for end state control.

China (continued)		The *Regulation on the Safety Management of Radioactive Waste* was published in 2011 as a supplement and summary of different regulations on radioactive protection and radioactive waste management. The national legal document to manage and control radioactive pollution including decommissioning activities, *Law of People's Republic of China on Prevention and Control of Radioactive Pollution*, stipulates that the operator of nuclear installations shall draw up plans for decommissioning such installations.
France[a]	To date the goal is to remove all the contamination, although the regulatory authority does not refer to the option of greenfield.	Remove all the contamination; the regulatory authority prefers the operator to remain the owner. The National Safety Authority, the Environment Ministry and the Institute for Radiological Protection and Nuclear Safety published in 2011 a guideline for the remediation of area polluted by radioactive substances. In addition, the National Safety Authority is expected to publish specific rules for the remediation of nuclear installations.
Germany[a]	The goal is usually clearance for unrestricted use. A letter from the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety to the federal state ministries says that only unconditional clearance of sites should be accepted and that any radiological models used as a basis for this should take into account all relevant exposure pathways.	Clearance for unrestricted use. In Germany, clearance of (larger) sites of nuclear installations was first carried out in the early 1990s. Therefore, a considerable regulatory framework has been developed. Sites are 'cleared' in Germany, *i.e.* the *de minimis* principle is applied upon release. Site clearance is one of the clearance options laid down in the Radiation Protection Ordinance (*Strahlenschutzverordnung*) in Section 9 §29 (2) 1c.
Italy[a]	The national policy is for site end states to be greenfield. However, the use of the sites has not yet been defined, since the achievement of this state will take at least ten years from now. Sogin is the owner of the sites; for the nuclear research sites, these are still owned by ENEA and the final decision on re-use will be up to this organisation. The dose standard is 10 μSv/yr.	No specific regulations or standards currently exist. In compliance with the Euratom directive on ionising radiation, in Italy Article 55 of Legislative Decree No. 230/1995 defines the authorisation for decommissioning.

India[c]	The process of decommissioning ends with the release of the site for use by a responsible organisation as authorised by the Atomic Energy Regulatory Board or for unrestricted use by the public.	The Atomic Energy Regulatory Board Safety Manual AERB/SM/DECOM.-1, Decommissioning of Nuclear Facilities (March 1998), discusses various aspects of decommissioning including: criteria for occupational exposures; discharge of radionuclides to the environment; criteria for long-term waste disposal; and clearance levels. It also prescribes the requirements with regard to advance planning for decommissioning of nuclear facilities and quality assurance during decommissioning. The criteria for categorisation of wastes and their mode of disposal are also prescribed.
Netherlands[a]	The policy and legislation on decommissioning require that the licensee shall restore greenfield conditions, unless there is a special permit from the regulatory body to leave specified and approved restrictions on the site, or to leave for example a building that will be re-used. The release of the site is based on the 10 μSv per year criterion. Besides environmental and worker protection, the goal of remediation is to allow for re-use of land, which is scarce in the Netherlands.	Greenfield, re-use of land but special permits for restrictions on site use are possible. The 'polluter pays' principle is generally applied in the nuclear policy of the Netherlands; however the principle itself has not been formalised in the legislation. Based on this principle, on the basis of the Nuclear Energy Act, the licensee for a nuclear reactor is required to secure appropriate funding for (planned) decommissioning.
Russian Federation[b]	Full or partial nuclear unit removal from state regulation control.	Case-by-case (depends on decommissioning strategy or project for current unit). Most of the completed decommissioning projects have been carried out to a brownfield end state.
Spain[a]	Final remediation objectives are established on a case-by-case basis, in accordance with the anticipated uses of the site.	Case-by-case (depends on site use). The national policy (*General Radioactive Waste Plan*, GRWP) promotes immediate decommissioning, although this is not established as policy. The framework for remediation of contaminated sites is established in the *Regulation on Health Protection Against Ionizing Radiation*.

United Kingdom[a]	The overarching goal as defined within the decommissioning policy and Nuclear Decommissioning Authority strategy is to "remove the hazard the facility poses progressively, giving due regard to security considerations, the safety of workers and the general public and protecting the environment, while in the longer term reducing the number of sites and acreage of land which remain under regulatory control" (*The Decommissioning of the UK Nuclear Industry's Facilities*, paragraph 3, September 2004 statement of the UK Government and devolved administrations). Within the Energy Act 2004, the goal is to clean up nuclear legacy sites so that they are "suitable to be used for other purposes" (S.37).	Reducing safety risk (10 μSv/yr criteria), reducing the number of sites and re-use of land. There is no specific regulation but the Nuclear Installations Act 1965 covers site remediation. The Nuclear Installations Inspectorate (now Office for Nuclear Regulation, ONR) interpretation of "no danger" (as stated in the 1965 Act) requires that there must be no danger from ionising radiation "regardless of any foreseeable uses of the site." Annex 1 of the *Basic Safety Standards Directive* (Euratom 96/29) allows exemption of activities where "doses to members of the public are of the order of 10 μSv or less per year." The ONR considered this dose limit broadly equates to the one-in-a-million per year 'no danger' criterion. However, the ONR also expects consideration of the Health and Safety at Work Act which requires operators to ensure health and safety risks are reduced to "as low as reasonably practicable" (ALARP).
United States[a]	The goal of remediation is risk reduction, restoration of groundwater to the highest beneficial use where practical, containment and long-term monitoring and as low as reasonably achievable. In general federal and state clean-up goals for soil and groundwater are an objective and if not practical then institutional controls and other measures are required.	Cost-effective risk reduction and protection of soil and groundwater. The most recent summary of national policy and regulations on nuclear site remediation can be found in US Nuclear Regulatory Commission document *Nuclear Regulatory Legislation. 112th Congress; 2nd Session* NUREG-9080 Vol. 1, No. 10. Remediation of nuclear plants in the USA is regulated and managed by two agencies, the Nuclear Regulatory Commission (NRC) and the Environmental Protection Agency (EPA). The NRC regulates commercial reactors. The EPA oversees remediation of nuclear sites through the *Comprehensive Environmental Response, Compensation, and Liability Act* (CERCLA) and other national, state and local regulations.

Sources:
OECD Nuclear Energy Agency, Nuclear Site Remediation and Restoration during Decommissioning of Nuclear Installations, NEA No. 7192 (2014)
World Nuclear Association contact with Russian and Chinese industry sources
S.A.H. Ashraf and S.K. Chande, Atomic Energy Regulatory Board (India), Decommissioning of Nuclear Facilities, Indian Perspective, CN-93[56]

Appendix 3 | Specific Decommissioning Challenges

A3.1 Irradiated graphite

Graphite, which is used as a solid neutron moderator in reactors such as Magnox, AGR and RBMK, poses a unique challenge in the disposal of radioactive waste from decommissioning. This firstly stems from the fact that it has a higher accumulated neutron flux rate than most other reactor components. Secondly, in addition to its own induced activity, graphite is quite often contaminated with fission products and other isotopes introduced by coolant leakages. Removing this contamination while the reactor is in operation is much more difficult than in designs with a light- or heavy-water moderator, and is sometimes impractical. As a result, graphite moderators can be classified as ILW or long-lived LLW.

The weight of graphite in such reactors is considerable: some AGR reactors contain 1300 tonnes of graphite; UNGG – 2400 tonnes; and Magnox – 3000 tonnes, which is comparable to the amount of waste from dismantling the facility's metal structures. Its disposal is a technologically challenging, exceptionally capital- and energy-intensive task. It is no coincidence that most graphite reactors are subject to the deferred dismantling strategy and that so far no graphite moderators have been disposed of. An inventory for irradiated graphite (amount, condition, radioactivity level) seems to be a sensible starting point to embark on a decommissioning project for these types of reactor.

More than 250,000 tonnes of irradiated graphite will need to be disposed of worldwide, with significant shares in the UK, France, Russia and the USA. However, due to its high porosity, graphite is not suitable for shallow land disposal. And deep geological disposal is impractical due to the large volume of irradiated graphite.

The most relevant radionuclides are carbon-14, chlorine-37, and tritium – although these are beta emitters, their long half-lives, as well as their mobility, make them difficult to handle.

Recent activities (besides simple incineration and release of activity into the atmosphere) follow two directions: decontamination, and improvement of leaching resistance.

Decontamination

Elimination of Cl-37 and tritium is trivial: proper heat treatment will transfer these into the gas phase.

Neutron capture and energy dissipation of C-12 and C-13 results in the formation of 'excited' C-14 within the graphite lattice. C-14 is also formed on the surface of the graphite pores from gaseous components (*i.e*. CO_2 and N_2). In both cases, C-14 can be reacted with reagents such as O_2, CO, CO_2, H_2O at elevated temperatures.

A number of tests with different graphite samples have revealed confusing results. In some cases up to 90% of the C-14 could be removed, with only a 5% loss of the base graphite; however, other cases delivered much worse results. Other proposals include washing of graphite with acids.

Currently there are no processes available to decontaminate irradiated graphite to radioactivity levels which would allow recycling or conventional disposal.

Improvement of leaching resistance

Graphite, though very corrosion resistant, exhibits poor leaching resistance when in contact with water: its open porosity of approximately 15% allows easy access and exchange.

Examples of methods to close the pores include:

- Mixing graphite with TiO_2 and Al, which delivers, after ignition, a monolithic TiC/Al_2O_3 product. This increases the volume by a factor of 7. Volatile radionuclides are difficult to collect or keep in the product.
- Mixing irradiated graphite with boron silicate glass in a ratio allowing the filling of the pore volume, treated under 1000°C and 1000 bar, resulting in a monolithic form with excellent leaching resistance. Due to the process being in a closed system, the behavior of volatile nuclides can be easily controlled.

A3.2 Liquid radioactive waste

Another challenge in the management of radioactive waste from decommissioning is liquid waste. The main sources of radioactive fluids arising during decommissioning are:

- Contaminated water of sanitary inspection rooms and gateways.
- Vat residue.
- Decontamination solutions and wastewater.
- Leakages in heat transfer equipment, tanks, *etc.*
- Wastewater from air ventilation and drainage equipment.
- Lubricating fluids and coolants in dismantling equipment.

These fluids require their own treatment, which makes creating an inventory very important. The main task in managing liquid waste is essentially immobilising concentrates and preventing radionuclides leaching from the matrix.

Currently there is a whole range of methods used for treating liquid waste with varying activity levels, salinity content (including seawater), and chemical composition. The main methods used are:

- Filtration (membrane filtration, osmosis).
- Concentration (evaporation).

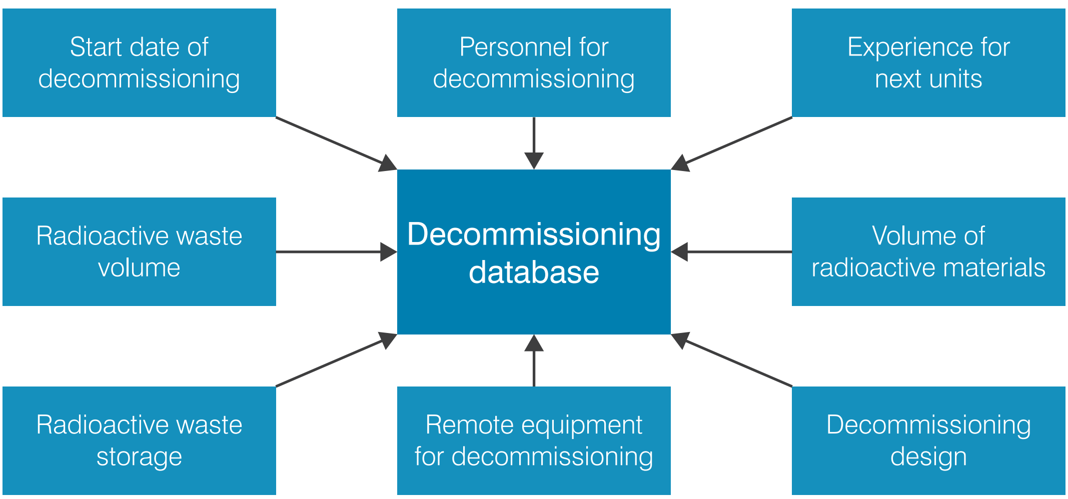
- Ion-selective adsorption.
- Uptake of radionuclides on special adsorbents.
- Cementation.
- Vitrification.

There is considerable experience in cementation. For example, Russia has developed and tested additives for different compositions of radioactive waste and conducted multiple research projects on degradation of cement matrices. Experience in vitrification of liquid radioactive waste in Russia dates back over 30 years. The main methods for achieving vitrification involve the use of direct electric heating melters and cold crucibles. The technologies applied are available both in stationary and portable/mobile device options.

A3.3 Decommissioning database

A database for design and operational documents that is consistently updated and maintained will provide long-term and reliable data on decommissioning operations. The decommissioning database will provide the future generations of nuclear workers with all the documentation and data required for the implementation of decommissioning plans.

Currently, efforts are under way in Russia to create facility decommissioning databases. In particular, the Leningrad plant has seen the creation of a constantly updated database featuring data on the station's four reactor units, engineering 2D and 3D models, lists of systems and equipment, entries on their weight and dimensions and other parameters, and electronic document archives. Relatively similar work has been completed for units 1&2 of the Beloyarsk nuclear plant. Varying degrees of progress have been made on projects to create databases at the Kursk, Bilibino, Smolensk, Kola, and Novovoronezh nuclear power stations. All of the systems created so far, however, only accomplish the basic tasks of systematising, preserving, and transferring knowledge over long periods of time.



A3.1. Application of decommissioning database

Appendix 4 | Treatment Technologies

Area	Technology	Remarks
Sorting	Mono-material sorting	Sorting criteria: • Steel types • Combustible, non-combustible • Activated, non-activated
	Post-segmentation	Targets of post-segmentation: • Removal of hazardous materials • Separation of plastic from metals • Disassembly of control cabinets, valves, motors, *etc.*
Segmentation / Decontamination	Mechanical processes	• Sawing • Milling • Grinding • Mechanical cutting • High-pressure water cutting • Abrasive blasting
	Thermal processes	• Autogenous cutting • Plasma cutting
	Chemical Processes	• Electrochemical decontamination • Ultrasonic polishing (normally in combination with electrochemical decontamination)
Volume Reduction	Compaction	• In-drum compaction (100-500 kN) • Low pressure compaction (500-5000 kN) • High force compaction (> 5000 kN) typically 20,000 kN
	Incineration	• Throughput range from 25-100 kg/hour • Feeding system • Combustion chamber • Post-combustion chamber • Quencher • Flue-gas cleaning • Fine filtration • Chemical and radiological emission control
	Evaporation	• Throughput range from 120 litres/hour to 6 m^3/hour • Natural convection
	Metal melting	• Stationary systems (material is sent to a service provider) • Mobile systems (service provider comes to site)
Conditioning	Solidification	• Embedding in cement matrix • Embedding in epoxy resin matrix • Grouting of bulk material
	Packaging	• For interim storage (drums, boxes) • Waste package for final disposal (steel container, concrete container, high integrity container, *etc.*)

Monitoring and Tracking	Monitoring	• Drum monitoring (dose rate, radionuclide content) • Container monitoring (dose rate, radionuclide content) • Devices for measurement of material in boxes • Continuous belt conveyor monitoring for bulk material • Documentation of the waste package characteristics • Documentation of treatment/handling steps
	Tracking	• Barcode reader • Radio-frequency identification chips • Software program to follow up all movement of radioactive waste and process steps • Waste package documentation

A4.1 Sorting

Once removed from the installation, raw materials have to be sorted according to:

- Radioactivity (high, intermediate, low, very low; contaminated, activated).
- Physical-chemical nature (metal, insulation, plastics, *etc.*).

Note that materials should also be separated according to their properties during dismantling.

A4.2 Decontamination

Building structures

Building structures account for the vast majority of waste to be handled (>100,000 tonnes).

A small part of the biological shield is expected to be activated with long-lived isotopes (Mn-54, Co-60, Zn-65, Ba-133 and Eu-152). The remaining structures may be contaminated, at the surface or, for anchor plates, ducts or defects, at a greater depth. After removal, the only management option is final disposal as radioactive waste.

In order to minimise the amount of radioactive waste, the material must be decontaminated wherever possible. The aim of the decontamination should be to downgrade the remaining material, *e.g.* from ILW to LLW; from LLW to VVLW/free release.

Surface removal should be for the minimum depth that is necessary, with extra attention given to those areas mentioned above. Measurement is the key to success – manual methods, including advanced ones such as *in-situ* measurement, are available.

The removed material can be partially decontaminated by making use of the tendency for contamination to intrude the space between coarse grains of concrete: milling and sieving separates coarse grains (less active) from the fine ones (more active).

The remaining structures should be demolished, separating the steel and concrete, which should be measured for free release. This can be recycled,for example, in road construction; steel can be smelted.

For the measurement of bulk material, several installations are available, from batch type models to continuous belt type models.

For the characterisation of radionuclides that are difficult to detect (*e.g.* beta emitters such as Sr-90), the application of nuclide-vectors is common practice.

Metals

Any metal that is not activated can be decontaminated. The extent to which this is done will depend mainly on economic conderations.

Dry, mechanical methods based on blasting are commonly applied, with various blasting media (sand, minerals, steel grit, dry ice); energy input (pneumatically with air, mechanically with blasting wheels); and arrangements (manual in blasting cabins, batch-wise in tumbling belts, continuous in through-type machines).

Re-usable blasting material (*e.g.* steel grit) requires integrated rework with separation of grit and removed material, and allows for the minimisation of secondary waste (below 1% of processed material).

For materials with high amounts of oil and grease, this application is limited.

Wet processes apply high pressure jets with water pressures above 2500 bar to remove paint, oil and grease from surfaces. A disadvantage is the necessity of cleaning the water, for recycling and for disposal.

Chemical/electrochemical wet processes are used for full system decontamination and can be carried out for removed parts in tanks. Again, water treatment is required.

The intensity of decontamination can be increased by the application of electric voltage, with treatment of the spent bath fluid.

After decontamination, measurement of activity will inform the decision on further management, *i.e.*:

- Free release and introduction to conventional residue material management.
- Or classification as waste according to the national regulations.

A4.3 Metal melting

The dismantling of equipment should be expected to generate very large quantities of intermediate- and low-activity radioactive metal waste, which would have to be both decontaminated and then melted in order to be reintroduced into the manufacturing cycle, or compacted and sent away for storage or disposal. Melting metal with a superficial radioactive contamination enables better decontamination and compaction of waste. However, in the case of induced radioactivity, melting fails to clean metal waste, hence it should be compacted and sent away for storage in order for Co-60 to decay.

A4.4 Conditioning

Conditioning is necessary for any kind of waste and any disposal route. The first step should always be volume reduction, with well-established methods depending on the waste.

Thermal treatment

Organic material, such as spent gloves, clothing, packing material, removed paint, resins from water treatment, can be sent to central incineration facilities, pyrolysis or plasma installations.

The volume should then be reduced as much as possible, and the ash no longer contains organic material, which is unwanted at disposal sites.

Plasma treatment delivers a slag, which exhibits excellent properties for final disposal.

Melting

Melting can achieve the highest density and lowest volume of steel, which cannot go for free release because of activation or insufficient decontamination. In addition, the molten ingot represents a product which is perfectly defined, and suitable for long-term intermediate storage, transport and final disposal.

Where allowed, it is an excellent product for decay storage, allowing for waste minimisation to be optimised.

Compaction

High force compaction reduces the waste volume by a factor of 2 to 50, depending on the material: high for insulation material, low for metals and construction material.

Solidification

Solidification of liquid and solid waste is often applied to improve the characteristics of the waste.

Typical matrices (inert material, which incorporates waste) are cement, bitumen, and special inorganic binders, for low-activity waste. Glass, Synroc or graphite compounds are used for higher requirements (leaching resistance, long-term stability). Depending on the load factors, the volume might increase significantly.

Plasma treatment may transform any material to a slag or glass, which is highly suitable for final disposal. Caesium volatility is higher than for other thermal treatments.

A4.5 Packaging

The last step in waste processing is placing into containers.

The variety is high: a drum of approximately 200 litres very often is the primary container. Others are steel sheet containers, concrete containers for low- and medium-activity waste, and cast iron or forged steel containers.

After packaging, waste should be ready for intermediate storage, transport and final disposal.

A4.6 Transport

The amount of transport required during decommissioning depends on the chosen strategy; for example, it is maximised with centralised treatment and intermediate storage.
Some factors need to be taken into account:

- The transport of liquid or incinerable waste is prohibited in some countries.
- In countries with a strong anti-nuclear movement, transport may be subject to political and public obstacles.

A4.7 Intermediate storage

Again, depending on the chosen strategy, intermediate storage may play a different role during decommissioning: there are particular requirements for storage of raw waste and for conditioned waste, be it centralised or onsite.

Technically, storage is not challenging, but in practice that has not always been the case.

Some points are worth noting:

- Only well-characterised material should be stored.
- Often storage lasts longer than expected; respective measures against leakage, corrosion, biodegradation should be taken accordingly.

A4.8 Measurement

Measurement of radionuclides (including sampling) accompanies all activities during decommissioning nuclear sites:

- Definition of the inventory and nuclide vectors prior to the start of dismantling.
- Measurement of materials removed, to decide on further handling.
- Measurement for free release of material.
- Measurement for declaration of packages for intermediate and final disposal.
- Measurement for final release of sites from nuclear regulation.

Several methods have been developed and successfully applied:

- *In-situ* sampling and measurement.
- Dose rate measurement and gamma spectroscopy.
- Surface contamination measurement with counters.
- *In-situ* measurement of building structures.
- Devices for measurement of material in boxes.
- Continuous conveyor belt monitoring equipment for bulk material.

Gamma emitting nuclides are most commonly measured. Definition of nuclide vectors allows, with some conservatism, declaration of alpha and beta emitters. Direct measurement techniques need to be improved.

Appendix 5 | Cutting Technologies for Decommissioning

Area	Technology	Remarks
Thermal	Autogenous oxygen cutting	Advantages: • Large thickness (starting from 30mm). • Low energy consumption. • Universal application. • Control and observation from distance. Disadvantages: • Unsuitable for stainless steel. • Generation of aerosols. • Separation of complex components not possible. Use underwater: • Shielding cap on torch. • Adjustment of gas pressure. • Lower cutting speed at increasing water depth.
	Plasma arc cutting	Advantages: • Very good automation. • High accuracy and cutting speed. • Comparatively low operating cost. • Control and observation from distance. • Underwater usage possible. Disadvantages: • Generation of aerosols (hydrolysis underwater). • Separation of complex components not possible. • Lower cutting speed with increasing water depth.
	Hot wire plasma cutting	Advantages: • Larger interstices can be bridged. • Majority of energy remains for cutting process. • Use on discontinued structures *e.g.* grids, hollow bodies. Disadvantages: • Generating aerosols (hydrolysis underwater) • Lower cutting speed and power at increasing water depth.
	Contact arc metal cutting (CAMC)	Advantages: • Compact process. • No particular geometric data necessary for starting a cut. • Separation of components with hollows, complicated profiles and material combinations. Disadvantages: • For underwater use only. • Generating aerosols (hydrolysis underwater). • Low cutting speed.

Thermal	Laser cutting	Advantages: • Contact-free, almost force-free handling. • High cutting speed. • Good cutting quality. • Hollow structures possible. Disadvantages: • Usage underwater not effective. • High investment costs. • Not proven for nuclear use yet.
Hydro-mechanical	Water abrasive suspension cutting (WASC)	Advantages: • Very compact. • Narrow kerf. • High cutting depth. • Separation of complicated geometries possible. • Control and observation locally or from distance. • Usage underwater possible. Disadvantages: • Abrasive additives as secondary waste. • Filtration plant and extraction unit for abrasive additives and kerf material are required.
Mechanical	Milling cutter	Advantages: • Segmenting big components with wall thicknesses. • Precise cutting edges. • Low aerosol formation. • Suitable for fire-threatened working areas. • Usage underwater possible. Disadvantages: • High generation of heat. • High introduction of restraining forces. • Tool change (miller).
	Nibbler	Advantages: • Very compact. • Low forces. Disadvantages: • Needs blade edge or drilling for starting the cut. • Only straight cuts or very big radii. • Low thickness.
	Bandsaw	Advantages: • Very compact. • Minor forces. Disadvantages: • Only straight cuts or very big radii. • Restricted wall thickness. • Saw blade exchange.
	Diamond wire saw	Advantages: • Big thicknesses. • Observation and control from distance. • Wet, dry and usable underwater. Disadvantages: • Complex wire management. • Wire change. • Secondary waste from worn wire.

Mechanical	Hyraulic shear	Advantages: • Minor wearing. • Barely any kerf material. • Application of large forces. Disadvantages: • Difficult handling.

Appendix 6 | Decommissioning Waste Management in Spain

Spain is a European Union country with ten nuclear power units comprising one gas-cooled reactor, two boiling water reactors, and seven pressurised water reactors. Vandellòs 1 was permanently shut down in 1990 and has been nearly decommissioned; all the structures except the graphite of the reactor have been decontaminated and dismantled. Jose Cabrera 1, also known as 'Zorita', is in the process of being decommissioned. Santa Maria de Garoña was defuelled in 2013 and six more units are due to be permanently shut down in 2020 or 2021. The last, Trillo 1, is expected to be shut down in 2024.

To decontaminate and dismantle these plants, the state-owned enterprise (SEO) Enresa (*Empresa Nacional de Residuos Radiactivos S.A.*) was created in 1984 to implement the Spanish Parliament's decisions regarding managing radioactive waste and decommissioning Spain's nuclear plants. It is owned (20%) through the SEPI Group (*Sociedad Estatal de Participaciones Industriales*, State Industrial Holdings Company) in the Ministry of Finance; and (80%) through CIEMAT (*Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas*, Research Centre for Energy, Environment and Technology) in the Ministry of Science, Innovation and Universities (see Figure A6.1). Therefore, Enresa is both the decommissioning contractor and the radioactive waste facilities manager, similar to EnergySolutions at Zion 1&2 (see Section A7.1.2 in Appendix 7). This includes management of very low-level radioactive waste (VLLW), low-level radioactive waste (LLW), and intermediate-level radioactive waste (ILW).

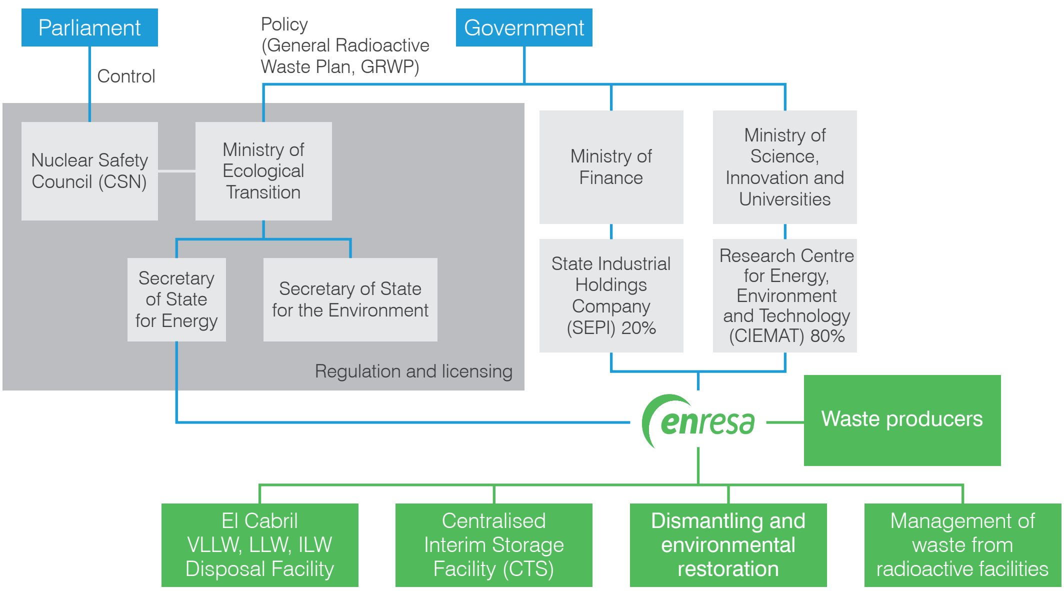
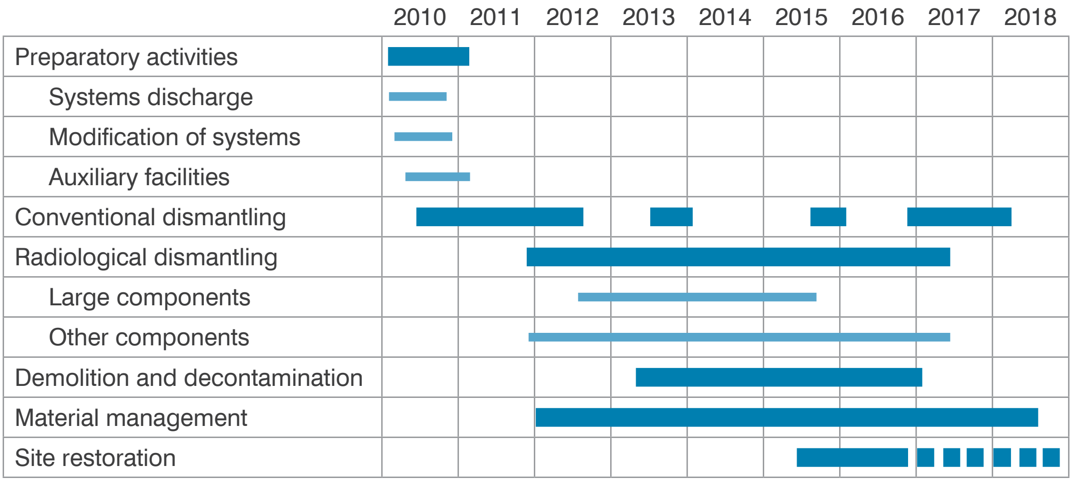


Figure A6.1. Organisation of Enresa

Enresa began to decommission Zorita in 2010 with the intention of finishing by 2016. However, this schedule has been extended (see Figure A6.2). The decontamination and decommissioning of Zorita will generate approximately 105,000 tonnes of waste (see Table A6.1). Most of this (about 95,000 tonnes) will be concrete that will be disposed of in conventional landfill facilities. Furthermore, scrap metal (about 4700 tonnes) will be recycled where possible. VLLW, LLW, and ILW will be shipped to Enresa's El Cabril facility. The SNF and reactor internals are stored at an onsite independent spent fuel storage installation (ISFSI) composed of concrete casks.



Source: Costs of Decommissioning Nuclear Power Plants, OECD Nuclear Energy Agency (2016); Emilio García, Jorge Borque, Adolfo Abreu, Enresa, Comparison of estimated and actual decommissioning cost of José Cabrera NPP, presented at the International Conference on the Financing of Decommissioning, Stockholm, Sweden (September 2016)

Figure A6.2. Decommissioning schedule of Jose Cabrera ('Zorita')

Table A6.1. Waste types at Zorita

Waste Type	Tonnes	Disposal
Conventional concrete debris	95,300	Landfill
Conventional scrap	4,700	Recycle
VLLW, LLW, ILW	4,000	El Cabril
Spent nuclear fuel	175	Onsite ISFSI
Reactor internals	43	Onsite ISFSI
Hazardous waste	Small amounts	Controlled storage
Total	~105,000	

Source: Costs of Decommissioning Nuclear Power Plants, p204, Nuclear Energy Agency (2016)

The estimated cost of decommissioning Zorita has changed from 2003 (€175 million) to 2014 (€217 million), and is likely to change again before completion of the project (see Table A6.2). Originally, the cost of the ISFSI (approximately €42 million) was not included in the cost estimate. Cost estimates change over time due to the uncertainties and risks associated with the cost drivers (project design, relationships with regulatory authorities, contracting, waste management, and project tracking).

Table A6.2. Anticipated costs of decommissioning Zorita, 2003 and 2014

Cost Item	2003 (in million 2013 €)	2014 (in million 2014 €)
Site infrastructure and operation	17.0	66.0
Project management, engineering, site support, and misc.	43.9	66.5
Dismantling activities within controlled area	54.2	42.0
Pre-decommissioning and facility shutdown	6.5	17.0
Conventional dismantling, demolition and site restoration	40.0	15.0
Waste processing, storage and disposal	14.0	10.0
Fuel and nuclear material	-	42.0
Total without fuel and nuclear material	175.6	216.5
Total	-	258.5

Sources: 2003 figures from Emilio García, Jorge Borque, Adolfo Abreu, Enresa, Comparison of estimated and actual decommissioning cost of José Cabrera NPP, presented at the International Conference on the Financing of Decommissioning, Stockholm, Sweden (September 2016); 2014 figures from Costs of Decommissioning Nuclear Power Plants, Table 9.3, p207, OECD Nuclear Energy Agency (2016)

Appendix 7 | Decommissioning Waste Management in the USA

It is difficult to plan the decommissioning of nuclear plant structures and equipment if waste management facilities, or capacity at existing waste management facilities, are limited (see Chapter 4). Although few geological repositories have been constructed, the safe and secure onsite or centralised management of spent fuel is now well understood. Therefore, in many cases, spent fuel can be managed under a different licence at the site where the plant has been operating. The construction of onsite spent fuel management facilities can begin well before the termination of operation of the plant, thus facilitating the planning of decommissioning activities (see Chapter 2).

There are a number of cases in the USA that illustrate the importance of having radioactive waste facilities available before decommissioning begins.

Low-level radioactive waste facilities

The US Nuclear Regulatory Commission (NRC) assigns low-level radioactive waste (LLW) to different classes: A (LLW-A), B (LLW-B), C (LLW-C), greater than Class C (GTCC), as well as low-level mixed hazardous waste (LLW-MIX). These classes are based on the wastes' concentrations, half-lives, and the types of radionuclides they contain. LLW-A consists of radionuclides with the shortest half-lives and lowest concentrations. It makes up 95% of LLW in the USA. Its radioactivity levels return to background levels within 100 years. LLW-B and LLW-C contain greater concentrations of radionuclides with longer half-lives, returning to background levels in less than 500 years. Any LLW that exceeds the requirements for LLW-C waste is known as GTCC, which makes up less than 1% of all LLW and is the responsibility of the US Department of Energy. Four facilities have been accepting LLW.

- Barnwell, South Carolina: This facility accepts LLW-A, LLW-B, and LLW-C waste from South Carolina, Connecticut, and New Jersey. The Barnwell Waste Management Facility is operated by Chem-Nuclear Systems (CNS), a subsidiary of EnergySolutions.
- Hanford, Washington: This facility accepts LLW-A, LLW- B, and LLW-C waste from Northwest Compact states (Washington, Alaska, Hawaii, Idaho, Montana, Oregon, and Wyoming) and Rocky Mountain Compact states (Colorado, Nevada, and New Mexico). The facility, operated by US Ecology (a subsidiary of American Ecology Corporation), is in Benton County, Washington, approximately 23 miles northwest of the city of Richland.
- Clive, Utah: This facility accepts only LLW-A and LLW-MIX waste from all regions of the USA. The Clive disposal facility, operated by EnergySolutions (previously Envirocare of Utah), is currently the largest LLW disposal facility in the USA.

- **Andrews County, Texas**: This recently licensed facility (Compact Waste Facility, CWF) is operated by Waste Control Specialists (WCS). A construction permit was issued in September 2009 by the Texas Commission on Environmental Quality and the site became operational in November 2011. The site is authorized to accept LLW and LLW-MIX from the US federal government, and LLW-A, LLW-B, and LLW-C from Texas and Vermont. Waste generators from other states must petition the Texas Compact Commission for disposition approval. Texas limits the total non-compact waste to 30% of the CWF's licensed capacity.

Although there are different prices for LLW waste shipped to each of these facilities depending on the state of origin, these four facilities offer multiple routes as called for in Chapter 4.

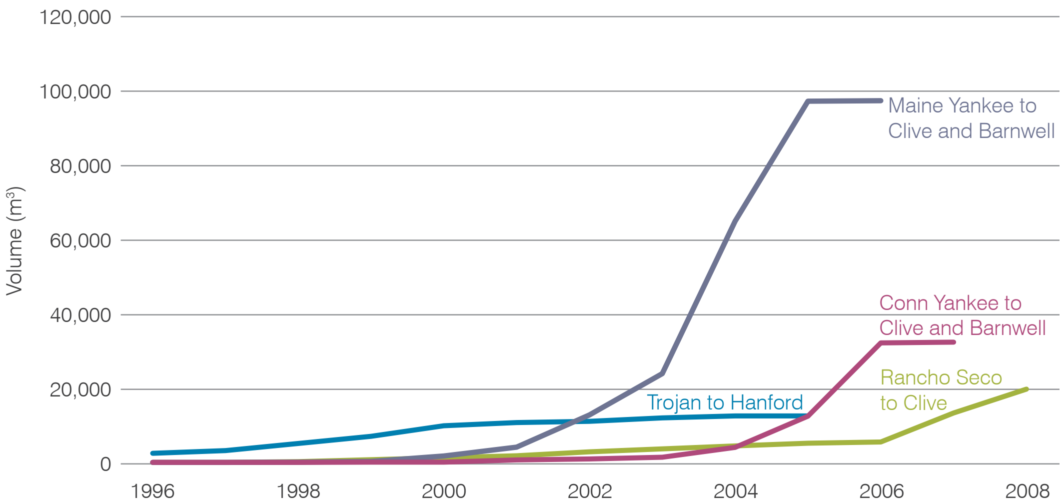
Table A7.1. Decommissioning completions and partial completions at US PWRs

Name (Owner or Operator)	State	Vendor	Capacity (MWe net)	First power	Shutdown	End of decom-missioning
Trojan (Portland General Electric)	OR	Westinghouse	1095	5/1976	11/1992	2005
Maine Yankee (Maine Yankee Atomic Power Company)	ME	Combustion Engineering	860	12/1972	8/1997	2005
Yankee Rowe (Yankee Atomic Electric Company)	MA	Westinghouse	167	11/1960	10/1991	2007
Connecticut Yankee (Haddam Neck) (Connecticut Yankee Atomic Power Company)	CT	Westinghouse	560	1/1968	12/1996	2007
Rancho Seco (Sacramento Municipal Utility District)	CA	Babcock & Wilcox	873	4/1975	6/1989	2009
Zion 1 (Exelon/EnergySolutions)	IL	Westinghouse	1040	12/1973	2/1998	(2020)
Zion 2 (Exelon/EnergySolutions)	IL	Westinghouse	1040	9/1974	2/1998	(2020)
Indian Point 1 (Entergy)	NY	Westinghouse	257	9/1962	10/1974	(2026)
San Onofre 1 (Southern California Edison)	CA	Westinghouse	436	1/1968	11/1992	(2030)
San Onofre 2 (Southern California Edison)	CA	Westinghouse	1070	6/1983	7/2013	(2030)
San Onofre 3 (Southern California Edison)	CA	Westinghouse	1080	4/1984	7/2013	(2030)
Nuclear Ship Savannah (US Maritime Administration)	MD	Babcock & Wilcox	74	04/1962	11/1970	(2031)
Three Mile Island 2 (FirstEnergy)	PA	Babcock & Wilcox	880	4/1978	3/1979	(2036)
Fort Calhoun (Omaha Public Power District)	NE	Combustion Engineering	482	8/1973	10/2016	(2065)
Kewaunee (Dominion Energy)	WI	Westinghouse	566	4/1974	5/2013	(2073)
Crystal River 3 (Duke Energy)	FL	Babcock & Wilcox	860	1/1977	2/2013	(2074)

Sources: Nuclear Reactor Shutdown List, U.S. Energy Information Administration; Locations of Power Reactor Sites Undergoing Decommissioning, U.S. Nuclear Regulatory Commission; Costs of Decommissioning Nuclear Power Plants, p27, Table 1.3, OECD Nuclear Energy Agency (2016)

Extensive information on either decommissioning waste generated or decommissioning costs is available for some of the nuclear plants listed in Table A7.1. Note that with 40-year operating licences, most of these units retired early, creating pressure on their decommissioning trust funds.

Waste from Connecticut Yankee, Maine Yankee, Trojan and Rancho Seco was shipped to the Barnwell, Hanford and Clive sites. Figure A7.1 shows how many cubic metres from each plant were shipped to each site. Unfortunately, there was little standardisation in reporting the conditioning of the waste shipped from the plant to the waste management facility or from the waste processor to the waste management facility. Furthermore, some of Trojan's highly contaminated equipment was shipped directly to Hanford with little decontamination. Therefore, it is difficult to compare levels of LLW generated during decommissioning at each plant.



Source: S.M. Short, M.C. Bierschbach, R.F. Layton, B.E. Greenfield, Assessment of the Adequacy of the 10 CFR 50.75(c) Minimum Decommissioning Fund Formula, Pacific Northwest National Laboratory on behalf of the Office of Nuclear Reactor Regulation, Nuclear Regulatory Commission (November 2011)

Figure A7.1. Cumulative volume of LLW-A, LLW-B, and LLW-C shipped to Clive, Utah, and Barnwell, South Carolina, and Hanford, Washington from the plants in Table A7.2.

A7.1 Major decommissioning scheduling milestones

When a US nuclear plant licensee (owner/operator) has permanently ceased operations ('long-term shutdown' as defined by the International Atomic Energy Agency), the licensee must submit a statement (certification) that the plant has been permanently shut down to the US Nuclear Regulatory Commission (NRC). In addition, once fuel has been permanently removed from the reactor (defuelled), the licensee must submit another certification to the NRC that the reactor has been defuelled. Decommissioning must be completed within 60 years of shutdown. Factors to be considered by the NRC in evaluating an alternative that provides for completion of decommissioning beyond 60 years of shutdown include, among other things, the unavailability of waste disposal capacity.

Within two years from shutdown, the licensee must submit a post-shutdown decommissioning activities report (PSDAR) to the NRC. The PSDAR must contain: a description of the planned decommissioning activities with a schedule for their completion; the reasons for concluding that the environmental impacts associated with site-specific decommissioning activities will be within the appropriate previously-issued (for operations) environmental impact statement; and a site-specific decommissioning cost estimate (DCE), including the projected cost of managing irradiated fuel. The DCE cannot be less than the generic DCE established by the US NRC, and could be much higher if required by the electric utility regulator.

All licensees must apply for termination of their licences. The application for licence termination must be accompanied or preceded by a licence termination plan (LTP) submitted for NRC approval. The LTP is a supplement to the final safety analysis report (FSAR) and must be submitted at least two years before the termination of the licence. The licence termination plan must include site characterisation, identification of remaining dismantling activities, plans for site remediation, detailed plans for the final radiation survey, a description of the end use of the site, an updated site-specific estimate of the remaining decommissioning costs, and a supplement to the environmental report describing any new information or significant environmental change associated with the licensee's proposed termination activities. The NRC will terminate the licence if it determines that the remaining dismantling will be performed in accordance with the approved LTP, the final radiation survey, and associated documentation, and demonstrates that the facility and site have met the decommissioning criteria.

Associated with the DCE are accounts of the decommissioning trust fund (DTF) to be used by licensees if: the withdrawals are for decommissioning activity expenses; the expenditure would not reduce the value of the DTF below an amount necessary to place and maintain the reactor in safe storage if unforeseen conditions or expenses arise; and the withdrawals would not inhibit the ability of the licensee to ultimately release the site. Initially, 3% of the generic DCE amount specified by the NRC in 10 CFR 50.75(c) can be used for decommissioning planning. For licensees that have submitted the required certifications, an additional 20% can be used. A site-specific DCE must be submitted to the NRC before the licensee may use any funding above these amounts. The Nuclear Energy Institute (NEI) suggests revising NRC guidance on what are considered to be allowable decommissioning expenses:

> *"The regulations in 10 CFR Part 50 do not specifically itemize which particular activities are 'legitimate decommissioning activities'. However, activities that go ... beyond the scope of decommissioning, as defined in 10 CFR § 50.2, such as restoration costs to prepare the site for its next use after license termination is complete, are not appropriate for inclusion in the decommissioning cost estimate as decommissioning activities. Decommissioning activities also do not include the removal, storage, management and disposal of spent fuel, or the disposal during operation of radiologically contaminated materials or the removal and disposal of nonradioactive structures and materials beyond that necessary to terminate the NRC license. Disposal of nonradioactive hazardous waste not necessary for NRC license termination is not covered by these regulations but would be treated by other appropriate agencies having responsibility over these wastes."*

Source: Nuclear Energy Institute, NEI 15-06 [Revision 0], Use of the Nuclear Decommissioning Trust Fund (May 2015)

After submitting its site-specific DCE and until the licensee has completed its final radiation survey, the licensee must annually submit to the NRC a financial assurance status report for the previous year and for totals for all previous years that includes the following information on the decommissioning of the plant and the management of irradiated fuel: the amount spent on decommissioning, both cumulative and over the previous calendar year, the remaining balance in the DTF, and the amount provided by other financial assurance methods; an estimate of the costs to complete decommissioning, reflecting any difference between estimated and actual costs for work performed during the year and the criteria on which the estimate is based; and any modifications to a licensee's current method of providing financial assurance. Furthermore, the report must discuss the amount of funds accumulated to cover the cost of managing the irradiated fuel and the projected cost of managing irradiated fuel until possession of the fuel is transferred to the Department of Energy. If the sum of the balance of any remaining decommissioning funds, plus earnings on such funds calculated at not greater than a 2% real rate of return, together with the amount provided by other financial assurance methods, does not cover the estimated cost to complete the decommissioning and the management of irradiated fuel, then the financial assurance status report must identify the additional financial resources to cover the estimated completion cost.

Table A7.2 shows the major milestones for the decommissioning of four pressurised water reactors (PWRs) discussed above: Connecticut Yankee (Haddam Neck), Maine Yankee,

Table A7.2. Dates of decommissioning activities at four US nuclear power plants (1996-2009)

Decommissioning Activity	Connecticut Yankee	Maine Yankee	Trojan	Rancho Seco
Plant shutdown	12/1996	8/1997	11/1992	6/1989
Post shutdown decommissioning activities report to NRC	8/1997	8/1997	8/1996	12/1996
Reactor cooling system decontamination	8/1998	12/1998	12/1995	1/2001
Steam generators	9/1999	6/2000	12/1995	4/2005
Reactor coolant pumps	12/2001	11/1999	12/1995	12/2002
Pressuriser	12/2001	6/2000	12/1995	4/2004
Reactor pressure vessel internals segmentation	8/2002	4/2002	8/1999	6/2006
Reactor pressure vessel offsite	1/2004	5/2003	8/1999	1/2007
ISFSI completion	4/2004	8/2002	3/1999	12/1995
Removal of fuel and greater than Class C (GTCC) waste	3/2005	2/2004	9/2003	8/2006
System/building decontamination and removal	7/2006	2/2005	9/2004	12/2008
Final status survey (not including ISFSI)	10/2007	9/2005	10/2004	9/2009
Site restoration completed (not including ISFSI)	11/2007	10/2005	4/2005	12/2008

Based on information from S.M. Short, M.C. Bierschbach, R.F. Layton, B.E. Greenfield, Assessment of the Adequacy of the 10 CFR 50.75(c) Minimum Decommissioning Fund Formula, Pacific Northwest National Laboratory on behalf of the Office of Nuclear Reactor Regulation, Nuclear Regulatory Commission (November 2011)

Trojan (in Oregon), and Rancho Seco (in California). Reactor cooling system (RCS) decontamination involves cleaning all piping systems delivering coolant to the reactor and from the reactor to the steam generator (in a PWR, or to the turbine in a BWR). In all cases RCS decontamination preceded all other decontamination activities. At Trojan, the dismantling of the RCS, the steam generator (SG), the reactor coolant pumps (RCPs), and the pressuriser were completed within three years of shutdown and before the submission of the post-shutdown decommissioning activities report (PSDAR). In the other cases there was no particular ordering of these dismantling tasks. In all cases the dismantling (segmentation) of the reactor pressure vessel (RPV) and the shipment of these highly contaminated pieces took place after the dismantling of the RCS, SG, RCP, and pressuriser.

One of the first steps in decommissioning is the removal of fuel from the reactor and placing it in the fuel pool or in an independent spent fuel storage installation (ISFSI) or at a consolidated interim storage facility (CISF). (In all four cases, an ISFSI was built at each site.) Removal of SNF and GTCC waste implies that this material has been moved offsite or into the ISFSI. Once the fuel and GTCC waste have been removed, other systems and buildings can be decontaminated, and the resulting waste removed from the site. After the plant has been decontaminated, dismantled, and the waste removed, a final status survey can be submitted to the NRC and the site can be restored to the intended end state, not necessarily in this order. (Restoration to unrestricted use does not include the decommissioning of the ISFSI.)

Delays in the decommissioning and increases in the costs of these four plants vary, given that each of them represents a 'first-of-a-kind' decommissioning for their owners. The large increases in cost at Connecticut Yankee (also known as Haddam Neck, its location) were primarily due to the termination of the original decommissioning contractor (operating from April 1999 to July 2003) and the assumption of project management by the plant owner-operator. A similar problem plagued Maine Yankee where the original decommissioning contractor declared Chapter 11 bankruptcy in July 2000 and the owner-operator was forced to assume management of the project. Trojan was in the Northwest Compact and thus had barge access to waste storage facilities at Hanford, Washington, allowing the shipping of large pieces of contaminated equipment up the Columbia River. The primary delay, leading to increased project management costs, was due to the late removal of SNF from the spent fuel pool to the interim storage facility. Regarding Rancho Seco, the Sacramento Municipal Utility District (SMUD) originally planned to defer decommissioning to 2008 to allow the DTF to grow. However, the cost of decommissioning continued to grow primarily due to the expectations of rising low-level waste disposal costs in the Southwest Compact. Therefore, the decision was made to immediately decommission the facility. Rapid progress was made from the decontamination of the reactor cooling system (January 2001) to the reactor segmentation and removal from the site (January 2007). Much of the waste was shipped to the EnergySolutions waste facility in Clive, Utah.

A7.1.1 San Onofre Nuclear Generating Station unit 1

For comparison, Table A7.3 shows the cumulative radioactive waste weights, volumes, packaging costs, transport costs, burial costs, and total disposal costs of waste arising from the decommissioning of San Onofre Nuclear Generating Station unit 1 (SONGS 1), some of which is being stored onsite until the entire site is released for unrestricted use. (These values do not include waste that has already been shipped from the site.) Table A7.4 gives costs per unit paid for waste disposal outside of California during the decommissioning of SONGS 1.

Table A7.3. Cumulative radioactive waste to be shipped from SONGS 1

Facility and Waste Class	Waste Weight (tonnes)	Waste Volume (m^3)	Packaging Cost (thousand 2014 $)	Transport Cost (thousand 2014 $)	Base Burial Cost (thousand 2014 $)	Total Disposal Cost (thousand 2014 $)
Class B, C & GTCC Facilities						
Class B & C	763	215	$525	$16,800	$36,311	$53,636
GTCC	14	1.56	$0	$210	$3441	$3651
Total	776	217	$525	$17,010	$39,752	$57,287
EnergySolutions: Class A – Debris	19	20.47	$1	$3	$46	$50
Other: Out of State						
Class III Landfill	77,773	67,762	$0	$11,760	$3633	$15,393
Scrap Metal Recycler	826	1,870	$0	$8	$0	$8
Total	78,598	69,633	$0	$11,768	$3633	$15,401
Grand Total	79,393	69,870	$526	$28,781	$43,431	$72,738

Source: Testimony on 2016 SONGS ! Decommissioning Cost Estimate, before the Public Utilities Commission of the State of California, Table 6-4, Southern California Edison (1 March 2016)

Table A7.4. Low-level radioactive waste disposal costs at SONGS 1 during decommissioning

Radioactive Waste Class	Base Rate (2008 $/$m^3$)	South West Compact Export Fee (2008 $/$m^3$)	Utah Tax	Disposal Rate (2008 $/$m^3$)
Class A Bulk (*e.g.*, Crushed Concrete Rubble, Scrap Metal)	$2013	$47.68	5%	$2164
Class A General (*e.g.*, Containerised Waste, High Density/Oversized Packages, Large Components)	$7875	$47.68	12%	$8873
Class B	$102,943	$47.68	N/A (Texas)	$102,991
Class C	$102,943	$47.68	N/A (Texas)	$102,991

Source: Testimony on SONGS ! Decommissioning Work Completed and Remaining Work Scope, before the Public Utilities Commission of the State of California, Table IV-2, Southern California Edison (3 April 2009)

SONGS 1 ceased operations in June 2013 with decontamination and decommissioning essentially completed. The turbine building was removed and the reactor pressure vessel (RPV) internal was segmented. However, Southern California Edison was unable to make arrangements for shipping the RPV to a disposal facility because of the size and weight of the vessel and shipping package. The reactor internals are stored onsite until the decommissioning activities for units 2&3 are completed. Costs of these future activities are shown in Table A7.5, which is taken from the 2016 *Nuclear Decommissioning Cost Triennial Proceedings* before the California Public Utility Commission.

Table A7.5. Cost estimate for remaining SONGS 1 decommissioning work

Period Description	Distributed Cost (million 2014 $)	Undistributed Cost (million 2014 $)	Total (million 2014 $)
Licence termination			
Decon Pd 7 decommissioning during fuel storage	$88.70	$20.20	$108.90
Decon Pd 8 licence termination during final site restoration	$7.20	$1.40	$8.60
Decon total	$95.90	$21.60	$117.50
Spent fuel (SONGS 1 share)			
SNF Pd 2	$0.00	$1.10	$1.10
SNF Pd 3 dry storage during decommissioning	$0.00	$19.10	$19.10
SNF Pd 4 dry storage only	$0.00	$5.40	$5.40
SNF D&D Pd 1 ISFSI licence termination	$0.00	$0.10	$0.10
SNF D&D Pd 2 ISFSI demolition	$3.70	$1.10	$4.80
SNF total	$3.70	$26.80	$30.50
Site restoration			
SR Pd 7 planning for completion of unit 1 site restoration	$2.70	$1.90	$4.60
SR Pd 8 final site restoration and lease termination	$76.50	$10.30	$86.80
Site restoration total	$0.20	$12.20	$91.40
Grand total	$178.80	$60.60	$239.40

Source: Testimony on 2016 SONGS ! Decommissioning Cost Estimate, before the Public Utilities Commission of the State of California, Table III-1, Southern California Edison (1 March 2016)

Notes:
'Decon Pd' cost categories refer to decontamination and decommissioning (D&D) costs (only Decon Pd 7 and 8 remain unfinished); 'SNF Pd' cost categories refer to spent nuclear fuel storage costs (only SNF Pd 1 has been completed); 'SNF D&D Pd' cost categories refer to the D&D costs of the ISFSI (SNF D&D Pd 1 and 2 will be completed after the D&D of SONGS 2&3); and 'SR Restoration Pd' cost categories refer to site restoration after the decommissioning of the ISFSI (only SR Pd 7 and 8 remain unfinished, and will remain so until the completion of site restoration of SONGS 2&3).

According to Table A7.5, $239.4 million was required in the SONGS 1 decommissioning trust fund (DTF) to cover these remaining cost items. These funds are being invested as shown in Table A7.6. Note that the SONGS 1 cost (share of the decomissioning of SONGS 1, 2&3) is $239 million in 2014 dollars, as in Table A7.5. Southern California Edison assumes that the nominal after-tax weighted average return on the DTF will be 3.35% from 2016 to 2025 and 3.31% from 2026 to 2051. At the same time, the nominal escalation rate (using the Nuclear Regulatory Commission decommissioning funding formula weightings) from 2016 to 2025 will be approximately 2.82%, *i.e.* the real rate of return on these funds is equal to the weighted rate of return minus the cost escalation rate, or (3.35% - 2.82%) = 0.53%.

On the other hand, the nominal escalation rate from 2026 to 2051 will be approximately 3.95%, *i.e.* the real rate of return on these funds is (3.31% - 3.95%) ≈ -0.64%. Southern California Edison is assuming that the return on these funds will be less than the cost escalation, implying that the longer it waits to dispose of its LLW, the higher the cost to complete the decommissioning of SONGS 1. This is because of the lack of LLW capacity in California. Therefore, it has an incentive to either encourage the construction of LLW facilities in California or ship its LLW offsite as soon as possible.

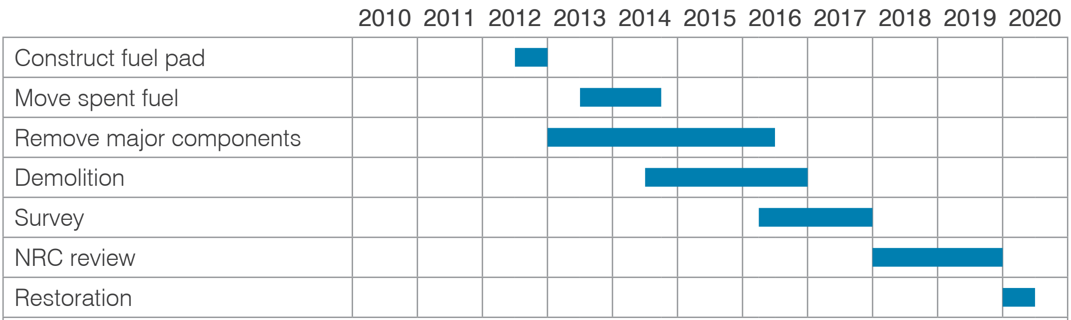
Table A7.6. SONGS 1 economic and financial assumptions: 2012 versus 2015 estimates

	2012 NDCTP December 2012	2015 NDCTP March 2016
SONGS 1 Cost (100% Share)	$182 million (2011$)	$239 million (2014$)
Escalation		
Labor	2.77%	3.07%
Material, Equipment, & Other	1.89%	2.36%
Low-Level Radioactive Waste Disposal	7.33%	2016 - 2026 2.36% 2027 - 2051 7.74%
Qualified Trust Rate of Return (SCE)		
Stock, Pre-Tax	7.79%	6.58%
Bonds, Pre-Tax	4.27%	3.36%
10-Year After-Tax Fund Return	2013 - 2022 = 4.07%	2016 - 2025 = 3.35%
Post-10-Year After Tax Fund Return	2023 - 2051 = 4.18%	2026 - 2051 = 3.31%
SONGS 1 Contribution Period	2014 - 2022 = (9 years)	2017 - 2022 (6 years)

Source: Southern California Edison, Table II-1, 2016 SCE Trust Fund Contributions and Financial Assumptions Before the Public Utilities Commission of the State of California (March 2016)
NDCTP = Nuclear Decommissioning Cost Triennial Proceeding

A7.1.2 Zion decommissioning

One of the next decommissioning projects to be completed in the USA is Zion 1&2. Originally constructed by Commonwealth Edison between December 1968 and September 1974, it came under the ownership of Exelon in 2000 with the merger of Commonwealth Edison (ComEd, later Unicom Corporation) and Philadelphia Electric Company (PECO Energy Company). When Zion 1&2 was closed in 1998, the selected decommissioning strategy was to place the plant in safe storage. This changed in 2010 when the Nuclear Regulatory Commission (NRC) approved the transfer of Zion's licence to a subsidiary of EnergySolutions, ZionSolutions, which used the 'rip and ship' method of shipping dismantled contaminated materials to EnergySolutions' waste storage facility in Utah for decontamination and conditioning. The spent nuclear fuel (SNF) was transferred to an onsite independent spent fuel storage installation (ISFSI) by the end of 2014 (see Figure A7.2). Once the site has been decontaminated and dismantled, ownership of the site licence will be transfer back to Exelon to manage the final status survey and transfer of the site licence to an ISFSI licence.



2012: Preparation to transfer spent nuclear fuel into dry storage canisters
2013: Complete segmentation of reactor vessel internals
2013: Begin transferring spent fuel
2014: Complete transfer of spent nuclear fuel
2014: Complete segmentation of reactor vessels
2015: Complete removal of contaminated equipment
2016: Complete demolition of the turbine and support buildings
2017: Complete all major demolition
2018-2019: Complete site restoration and final status surveys
2020: Complete project, transfer licence and remediated land back to Exelon; obtain NRC sign-off

Source: Figure IV-1 from Letter dated 18 March 2008 from ZionSolutions to NRC, Notification of "Amended Post-Shutdown Decommissioning Activities Report" (PSDAR) for Zion Nuclear Power Station, Units 1 and 2 in Accordance with 10 CFR 50.82(a)(7)

Figure A7.2. Zion 1&2 project timeline

About 85% of the decommissioning work had been completed at Zion 1&2 by the end of 2016. The total estimated cost at the end of 2016 was about $660 million plus the cost of SNF management (approximately $184 million, plus $30 million to 2020 when Exelon takes ownership of the ISFSI) plus the cost of site restoration (which could be as high as $50 million) for a total of about $920 million for the two units, or $460 million per unit, *i.e.* comparable to Rancho Seco.

The approach of the transfer of ownership of a retired nuclear plant was taken at Vermont Yankee with the transfer from Entergy to NorthStar Group Services (and partner Orano, both of which have started working on decommissioning projects on the site). NorthStar expects to pay for SNF fuel management and the ISFSI with funds from the US Department of Energy. The sale-decommissioning-resale approach is also being considered at the LaCrosse plant in Wisconsin.

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Methodology to Manage Material and Waste from Nuclear Decommissioning by the World Nuclear Association's Waste Management & Decommissioning Working Group serves as a guide for those facing new decommissioning challenges. Drawing on several decades of experience in decommissioning nuclear plants, the report highlights the key principles and stages of efficient waste management processes and good practices. Guidance is provided on:

- Stakeholder engagement to define end states and associated strategies.
- Characterisation and inventories.
- Material classification, acceptance criteria for waste disposal, and establishment of clearly defined waste routes.
- Treatment and optimisation techniques.
- Economics and financial planning, including managing uncertainties and unexpected challenges during dismantling.

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