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Nuclear Power Plant Decommissioning Sourcebook

2017 TECHNICAL REPORT

Nuclear Power Plant Decommissioning Sourcebook

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Abstract

Decommissioning a commercial nuclear power plant (NPP) is a complex and long-term process that includes specialties as diverse as communications, human resources, licensing, engineering, health physics, environment, security, and waste management. Experience in NPP decommissioning has demonstrated beneficial ways to manage and execute decommissioning that are not readily identifiable in available literature and may require extensive searching and review to gain the information needed.

This report provides an overview of aspects of NPP decommissioning along with a compilation of more than 160 references that address the primary functions associated with the decommissioning of a nuclear power facility. It is not intended to be a comprehensive, step-by-step guide; rather, it presents a broad overview of the functional aspects of NPP decommissioning, from planning through license termination, identifying key challenges to the planning and execution process, and providing experienced-based examples of the ways, methods, and solutions reached on specific projects with references to the primary information sources.

Keywords

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PRIMARY AUDIENCE: Decommissioning project managers, utility nuclear decommissioning management and staff responsible for planning and executing plant decommissioning

SECONDARY AUDIENCE: Utility contractors and staff involved in planning and execution of nuclear plant decommissioning

KEY RESEARCH QUESTION

Decommissioning a commercial nuclear power plant (NPP) is a complex and long-term process. Experience in NPP decommissioning has demonstrated beneficial ways to manage and execute decommissioning that are not readily identifiable in available literature and may require extensive searching and review to gain the information needed. This report provides an overview of aspects of NPP decommissioning and provides the reader primary references for more detailed information on individual topics.

RESEARCH OVERVIEW

This sourcebook provides a compilation of more than 160 content-specific, decommissioning-related references that address the primary functions associated with the decommissioning of a nuclear power facility. It is not intended to be a comprehensive, step-by-step guide; rather, it presents a broad overview of the functional aspects of NPP decommissioning from planning through license termination, identifying key challenges to the planning and execution process. The sourcebook provides experienced-based examples of the means, methods, and solutions reached on specific projects with references to the primary information sources.

KEY FINDINGS

- Create an organization that can efficiently handle all aspects of the decommissioning project related to legal requirements, finances, staffing, and technical options or constraints. Senior management must be integrally involved on a continual basis to evaluate the options and make decisions to direct the organization on the plan or plan revision.
- Staffing costs may constitute 40 percent or more of the NPP industry’s decommissioning costs. The degree of staffing reductions and timing on cost burden will be affected by the decommissioning strategy chosen. For example, prompt dismantlement will require that a larger staff remain, loading staffing costs on the front end of decommissioning, while safe storage would enable staffing reductions on the front end, but drive staffing costs over a longer term with increased costs on the back end.
- Early initial site characterization as part of the historical site assessment (HSA) is critical to successful decommissioning planning and has direct benefits to reducing cost overruns and delays during site decommissioning. Early site characterization allows a licensee to leverage the historical knowledge of key staff before reductions in force, enables the integration of nonradiological elements into decommissioning management, and enables outreach to a broad group of nonradiological stakeholders who can significantly influence the schedule and cost of the decommissioning program.

- Activities required to prepare a site for dismantling (repowering, re-establishment of site security boundaries, spent fuel management, full system chemical decontamination, asbestos abatement, and management of operational wastes) may drive access to decommissioning funds and/or approvals to commence decommissioning. In the US, only three percent of the total decommissioning trust fund is available to the licensee until the Post-Shutdown Decommissioning Activities Report (PSDAR) is submitted. Some European countries require that the spent fuel be removed from the spent fuel pool prior to the commencement of major dismantlement activities.
- Decontamination efforts, in conjunction with proper dismantling techniques and an effective reuse and recycling program, can reduce the waste inventory, thereby reducing costs. Considerations on the choice of dismantling methods depend on factors such as disposal options, dose, contamination levels, material being sectioned, and access to the component. The use of mechanical means of demolition requires area- and objective-specific financial, engineering, and safety analysis to arrive at the most cost-effective, practical, and safe approach for particular structures at each site.
- The availability of waste disposal options is a primary driver in determining disposal costs and, therefore, the decommissioning budget. Because disposal facility capacity has decreased with time, disposal costs have risen and availability of facilities has decreased with time. For these reasons, some licensees have opted for immediate dismantling to ensure that treatment, storage, and disposal facilities, which are a limited commodity in most countries, are available for receiving a given waste stream. Because of the cost of treating and disposing of radioactive waste, waste minimization is a fundamental aspect of treatment.

WHY THIS MATTERS

This report provides a broad overview of the NPP decommissioning process with experience-based examples of the means and methods of managing and executing decommissioning challenges along with a compendium of references for more detailed information on a variety of topics. This report is intended to serve as a valuable reference to the NPP industry, providing a rapid means of identifying up-to-date, practical decommissioning literature.

HOW TO APPLY RESULTS

This report is not intended to be a comprehensive, step-by-step decommissioning guide; rather, it is organized to provide an overview of the NPP decommissioning process with specific examples and references to key practical industry guidance and operating experience summary documents.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Each year, several workshops and conferences on decommissioning-related topics are held, including EPRI workshops, such as the two conferences described here. Additional workshops and conferences include the Waste Management Symposium and the International Symposium on Preparation for Decommissioning.
    - Since 2002, EPRI has organized the EPRI International Decommissioning Workshop as an international forum that covers a wide range of decommissioning, environmental remediation, and radioactive waste issues. These workshops, held in European countries actively involved in decommissioning, present information from a worldwide perspective, highlighting technologies and noteworthy experiences from various organizations. In addition, EPRI provides an update of research programs and experience gained in U.S. projects and EPRI Research and Development.
    - Since 2015, EPRI has organized a Decommissioning Workshop in conjunction with the EPRI/ASME Radwaste Workshop and EPRI International Low-Level Waste Conference, typically held in the summer in the United States.
- Plants within five years of permanent shutdown may consider participation in EPRI's supplemental decommissioning technology program.

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Abbreviations and Acronyms

ALARA	as low as reasonably achievable
BWR	boiling water reactor
CANDU	Canadian deuterium/uranium reactor
DCGL	derived concentration guideline level
DOC	decommissioning operations contractor
DQO	data quality objective
EDF	Électricité de France
ENRESA	Empresa Nacional de Residuos Radiactivos, S.A.
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FES	final environmental statement
FSS	final status survey
GEIS	generic environmental impact statement
GTCC	greater than class C
HEPA	high-efficiency particulate air
HLW	high-level (radioactive) waste
HSA	historical site assessment
IAEA	International Atomic Energy Agency
ILW	intermediate-level (radioactive) waste
ISFSI	independent spent fuel storage installation
KHNP	Korea Hydro & Nuclear Power Co. Ltd.

LLW	low-level (radioactive) waste
LWR	light water reactor
MARSAME	Multi-Agency Radiation Survey and Assessment of Materials and Equipment
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
MNA	monitored natural attenuation
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NSA	Nuclear Safety Act
NSSC	Nuclear Safety and Security Commission
OSHA	Occupational Safety and Health Administration
PCB	polychlorinated biphenyl
PEL	permissible exposure level
PPE	personnel protection equipment
PSDAR	post-shutdown decommissioning activities report
PWR	pressurized water reactor
QA	quality assurance
RCA	radiological controls area
RESRAD	RESidual RADioactivity (software)
RSGNS	Rancho Seco Nuclear Generating Station
SFP	spent-fuel pool
SFPI	spent-fuel pool island
SSC	systems, structures, and components
TEDE	total effective dose equivalent
VLLW	very-low-level (radioactive) waste

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Section 1: Introduction

1.2 Introduction

This sourcebook provides a summary of steps required for decommissioning of a nuclear power plant. It is not intended to be a comprehensive, step-by-step guide; rather, it presents key aspects of the major activities included in a typical decommissioning project. Specific functions and activities are described and references are provided for more detailed information.

From a functional standpoint, decommissioning consists of the following steps:

- Project planning;
- Fuel assembly management and defueling;
- Radioactive material characterization and quantification;
- Systems, structures, and components (SSC) decontamination;
- SSC dismantling;
- Waste characterization and management;
- Free release and clearance;
- Structures demolition; and
- Final site release and license termination.

Decommissioning a commercial nuclear power plant is a complex, long-term, process that includes specialties as diverse as communications, human resources, licensing, engineering, health physics, environmental, security, and waste management. Licensees must be able to successfully work with regulators from different branches of government as well as stakeholders at the local, regional (e.g., state or provincial), and national level. Furthermore, and in contrast to the plant's operation period, the site workforce at a plant that is being decommissioned is fairly dynamic with different mixes of expertise required as the project progresses. This report provides an overview of the different aspects of decommissioning and provides the reader primary references for more detailed information on each topic.

Section 2: Decommissioning Planning

2.1 Introduction

2.1.1 Approach

The purpose of a decommissioning plan is to outline the activities required to successfully complete the safe decommissioning of a nuclear facility in compliance with applicable regulations and negotiated stakeholder requirements within budgetary constraints. The plan informs utility management and staff, site and contractor personnel directly involved in on-site activities, regulators and other stakeholders, and members of the public. In many cases, a detailed decommissioning plan is required to gain regulatory approval for decontamination and dismantlement activities.

A successfully planned decommissioning project has the following characteristics:

- The project has well-defined end-state criteria to support license termination.
- The management style decision is made early in the project (self-performance or contracted to a third party).
- The objectives are clear and understood by the team.
- The project team has good relationships with stakeholders.
- The project has effective sequencing.
- The project has an effective waste management program.
- The project has a tangible decommissioning budget and schedule planning.

By its nature, decommissioning planning is an iterative process. Some aspects—such as the nature of the facility (type, size, contamination levels, complexity, and history) and legal constraints—are fixed. Other aspects—such as field conditions different than anticipated, finances, and waste disposal options—are dynamic, and these aspects should be accounted for as they arise. The licensee's approach must create an organization that can efficiently handle all aspects of the decommissioning project. It should thoroughly incorporate the known aspects and yet be flexible enough to respond to changes in plans driven by conditions in the field and other aspects beyond the organization's control.

Because of this iterative nature, the decommissioning planning organization must have representatives from all departments to address issues related to legal requirements, finances, staffing, and technical options or constraints. Senior management must be intimately involved to evaluate the options and make decisions to direct the organization on the plan or plan revision.

2.1.2 Decommissioning Planning Phase

A decommissioning plan is required in most countries; in many cases, the plan must be submitted to the nuclear safety authority for approval. Generally, an overall plan is developed while the facility is still operational. This plan, called an *initial decommissioning plan*, serves as the basis for cost estimates used to assess the adequacy of decommissioning funding contributions [1, 2]. The initial decommissioning plan is based on the proposed decommissioning strategy. It should include information on the decommissioning stages, the end state of the facility, and an estimate of decommissioning costs. The licensee should establish the desired end state of the decommissioning project as early as practicable—ideally, before facility shutdown—because this decision will affect every aspect of planning and project execution. The initial decommissioning plan is general in nature and should be updated while the facility is operational [3, 4].

Activities conducted during this phase may include the following [3, 5]:

- Identify major safety issues and measures to address them.
- Perform a generic study showing the feasibility of decommissioning.
- Estimate the types and quantities of waste and radioactive effluents.
- Develop the basis for the estimated costs.
- Estimate total project costs, and identify funding source and adequacy.
- For sites on which operating reactors will remain, identify interdependencies and measures to separate the units undergoing decommissioning from the operating units [2].
- Identify the decommissioning strategy to be used (prompt or delayed decommissioning).
- Evaluate the need for full or partial system chemical decontamination.
- Develop the approach for spent fuel management.
- Establish the timeline for regulatory submittals [5].
- Prepare for the historical site assessment (HSA).

The final decommissioning plan is based on the initial decommissioning plan. Final decommissioning plan development should be initiated together with the decommissioning safety evaluation, before the permanent facility shutdown [3]. Before decontamination and dismantlement activities are initiated, the final decommissioning plan should be finalized and submitted to the regulator for approval, if required. The final decommissioning plan should be updated during decommissioning to address facility and timeline changes [3].

The final decommissioning plan should include a description of the decommissioning project that will be managed, including the following [6]:

- Site management plan
- Organizations and their roles
- Safety and radiation management
- Quality assurance (QA) and nuclear oversight
- Environmental impact statement
- A waste management plan
- Facility security (physical and otherwise)

Furthermore, the final decommissioning plan should have the following characteristics [3]:

- It is consistent with the chosen decommissioning strategy.
- It is aligned with the safety case.
- It describes the decommissioning activities, such as the schedule and the proposed end state for the facility at license termination.
- It includes facility descriptions, including SSCs.
- It describes the organizational structure, including required skill sets and qualifications.
- It describes management of wastes and proposed disposition options for radioactive and mixed wastes.
- It describes how the final status survey (FSS) will be implemented, including applicable limits to be achieved.

The decommissioning safety evaluation contains the findings of a safety assessment as evidence of the safety of the facility and the activities to be conducted during decommissioning, as well as the confidence in those assertions [3]. In some countries, the safety evaluation and any updates may need to be submitted to the regulator.

2.1.2.1 Prompt Decommissioning Strategy

Prompt decommissioning or immediate dismantling [2] is understood to allow the licensee to terminate the license in the shortest period possible [5]. Other advantages of prompt decommissioning are that the facility has access to a workforce that is familiar with the plant, plant systems are still functional, and maintenance is current. Prompt decommissioning is known as DECON in the U.S.

2.1.2.2 Delayed Decommissioning Strategy

Delayed decommissioning [2] is a strategy to place the facility in a condition that allows for long-term storage for some period before completing decommissioning. The length of time allowed varies by country, but the allowed term for decommissioning may be 60 years or longer after permanent shutdown, including both delayed decommissioning and prompt decommissioning phases. Delayed decommissioning is usually chosen if the facility's decommissioning funds are inadequate to complete the project. Personnel exposures are also considered to be less as a function of the decay of short-lived radioisotopes during the storage period. Disadvantages associated with delayed decommissioning include a lack of access to a workforce with operational knowledge and experience with the facility, nonfunctioning systems, and uncertainty regarding future costs associated with the disposal of low-level waste (LLW) and mixed (hazardous and radioactive) waste [5]. Delayed decommissioning is known as SAFSTOR in the U.S.

2.1.3 Organizational Transition Phase

After the licensee has decided to permanently shut down a nuclear power plant, it can be assumed that surplus staff will be laid off or terminated because their services are not required at a decommissioning site. This is a significant task at any decommissioning site due to the costs associated with personnel (see Figure 2-1) [7], which must be balanced with the impact of layoffs on the community and the inefficiencies associated with not retaining the appropriate mix of skills needed for the project.

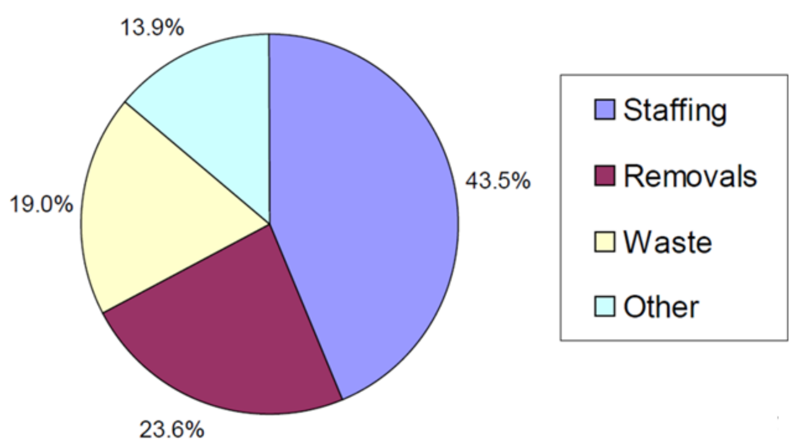

Figure 2-1
Staffing is the largest cost associated with decommissioning a nuclear facility [7]

Two general approaches are taken with regard to staffing a facility during decommissioning. In the first case, the facility performs some staffing reductions but use their own staff for the bulk of decommissioning work. The opposite approach, that is, retaining minimal staff and having most of the work performed by contractors has also been used [5]. Some facilities have used a decommissioning operations contractor (DOC) with a fixed price contract [8]. One utility observed that there are two approaches to staffing reduction. The first is to let those staff who wish to leave depart, and build a program with the remaining staff. The alternative is to implement the program and control the departure of staff [5].

At Oyster Creek Nuclear Generating Station, a study was performed to determine which staff were required during decommissioning. Approximately 800 full-time personnel work at the plant (the plant performed decommissioning studies in the 1990s, but continued to operate after it was purchased by another company). The results of the study showed that after the facility is shut down, staffing can be reduced to 400, with another 100 people laid off within a few months [9]. The degree of staffing reductions will be affected by the decommissioning strategy chosen. During the second half of the transition period, staffing reductions will typically be greater at facilities that are being placed in safe storage versus those that will use prompt dismantlement [10]. Although the personnel costs will initially be less for the facilities in safe storage, the long-term personnel changes may be greater because more temporary staff will need to be hired to perform the final dismantlement, demolition, decontamination, and clearance surveys.

Staffing size and flux is a challenge for human resources and management. The skill sets for decommissioning work are different than those for power generation, and the skills needed change over time. There are also the issues associated with keeping highly skilled staff on site until their services are no longer required [11]. To keep valued staff from leaving, the licensee may need to implement a program for incentives that the employee will receive only after satisfactory completion of the required services.

2.1.4 Facility Transition Phase (United States)

After a facility has been permanently shut down, a series of activities must take place according to regulatory requirements. Facility licensing and management must work together to ensure that required submittals are developed and sent to the appropriate regulator or stakeholders within the allotted timeframes. These requirements for plants that are regulated by the United States Nuclear Regulatory Commission (NRC) are well established.

2.1.4.1 Early Stage Decommissioning Planning

Some of the following activities may have been performed earlier, in the organizational transition phase [10]:

- Prepare and submit required documents to appropriate regulators.
- Reconfigure the facility for decommissioning. These changes may require revisions to the appropriate sections of the final safety analysis report or the defueled safety analysis report.

- Evaluate required changes to the classifications of plant systems.
- Develop detailed decommissioning project schedules.

The following activities should be completed at the conclusion of the facility transition phase [10]:

- Develop and submit the defueled safety analysis report.
- Develop and submit the defueled technical specifications.
- Submit a revised security plan.
- Submit a revised emergency plan.
- Complete a summary status of plant systems, including the following:
    - Open work item summary
    - Equipment status
    - Updates to design documents
- Develop, submit, and implement a certified fuel handler training program and associated exemptions from the requirements for licensed operators.
- Implement a revised configuration management system that supports reclassification of systems for decommissioning.
- Develop a revised training and qualification system aligned to a decommissioning project.
- Establish a community advisory panel and associated administrative structures.
- Establish a plan for long-term storage of spent fuel.
- Develop a decontamination plan to support placing the facility in delayed decommissioning (optional).

2.1.4.2 Ongoing Decommissioning Planning

This stage begins after the decommissioning strategy (prompt or delayed decommissioning) has been decided by the licensees. Planning activities in this stage are marked by large-scale projects such as offloading spent fuel from the spent fuel pool (SFP) to the independent spent fuel storage installation (ISFSI) or dismantling major components such as reactor internals or the reactor vessel [5].

Examples of planning activities for this stage of the decommissioning project include the following:

- Develop site characterization and FSS to support license termination.
- Develop project plans for dismantling SSCs, including activities such as developing work packages, schedules, budgets, and contracts.
- Develop plans for facility dismantling and waste disposal.
- Develop plans for facility decontamination to support license termination.

2.1.5 Decommissioning Planning (Spain)

In Spain, Royal Decree 102/2014 of 21 February and Royal Decree 1839/1999 of 3 December establish the legal requirements for organizations and responsibilities at decommissioning nuclear facilities. Royal Decree 102/2014 of 21 February places responsibility for decommissioning activities with Empresa Nacional de Residuos Radiactivos, S.A. (ENRESA), which is the national radioactive waste company [12].

Operations and preparatory work is the responsibility of the facility operator. To receive authorization for decommissioning, the licensee must have defueled the reactor, and spent fuel must either be transferred to an interim or end storage facility or have a ministry-approved spent fuel management plan. The sequence of licenses at a nuclear facility in Spain is as follows [12]:

- Operational license
- Amended operational license for shutdown
- Decommissioning license
- License termination

ENRESA holds the responsibility to develop and submit a dismantling and decommissioning plan to the regulator for each facility that is shut down. The licensee's primary responsibilities are implementing the decommissioning plan, with ENRESA performing most of the planning activities. In some cases, the work responsibilities are shared by the licensee and ENRESA. Spain currently requires facilities to implement a prompt dismantling strategy, with work commencing three years after permanent shutdown and completed within 10 years [12].

Planning for decommissioning occurs after the decision has been made to permanently shut down the facility. Initial decommissioning planning is performed in the following sequence [12]:

- Complete planning and engineering and secure the license for decommissioning, including the following:
  - Complete a decommissioning strategy study, with inputs such as physical characteristics, radiological characteristics, and dismantling costs.
  - Complete basic engineering and licensing documentation after the decommissioning strategy is chosen. This work is a legal requirement that includes 1) developing the basic decommissioning plan and 2) generating the licensing documentation that is required by European Atomic Energy Community, regional and local authorities, and environmental laws.
- Complete the detailed engineering, which includes engineering and design work for projects such as site preparation and dismantling.
- Complete the licensing activities needed to provide documentation required for authorization from authorities to commence decommissioning.
- Complete a site radiological characterization. This characterization may begin before shutdown, and it continues until license termination. It supports inputs required for dismantling and includes both the facility and the surrounding environment.
- Prepare for dismantling. This preparation is started after permanent shutdown of the facility. It includes design modifications for systems that will be obsolete after shutdown and reclassification of safety systems to align them with their functions during decommissioning. It addresses preparation of the site for decommissioning, and it includes revising procedures to align them with new or altered processes during decommissioning.

2.1.6 Decommissioning Approach (Korea)

2.1.6.1 Regulatory Scheme

The primary nuclear safety regulatory organizations in Korea are the Nuclear Safety and Security Commission (NSSC) and the Korea Institute of Nuclear Safety. In accordance with the Nuclear Safety Act (NSA), NSSC is in charge of regulatory responsibilities for establishing licensing criteria with regard to decommissioning nuclear facilities. In addition, the established criteria must be verified through a public hearing. NSSC entrusts the Korea Institute of Nuclear Safety with the specialized decommissioning technology fields. Accordingly, the Korea Institute of Nuclear Safety has identified the current status and relevant issues of regulatory framework for decommissioning nuclear facilities with reference to the International Atomic Energy Agency (IAEA) safety standards. Figure 2-2 illustrates the regulatory scheme.

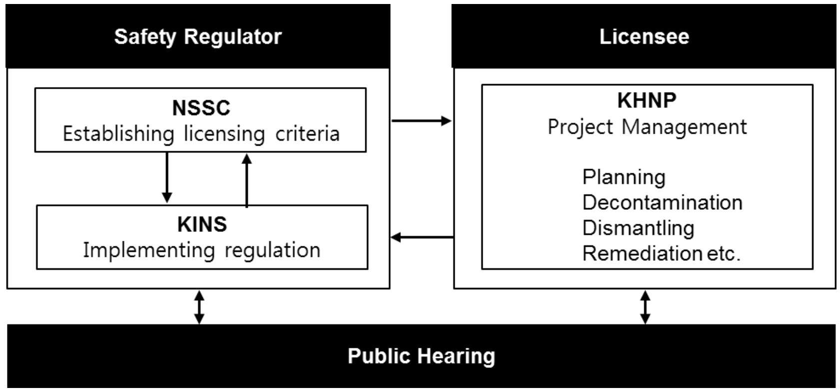

Figure 2-2
Regulatory scheme in Korea

With the government recommendation, Korea Hydro & Nuclear Power Co. Ltd. (KHNP), the licensee of nuclear power plants in Korea, announced in June 2015 that Kori Unit 1, the first commercial nuclear power plant, will be permanently shut down in June 2017 and then decommissioned. KHNP implemented the basic plan for the preparation of permanent shutdown and decommissioning. The mission of KHNP is to decommission nuclear power plants that approach the end of their operating license period in a safe and economic manner without causing any hazards to human health or the environment. In terms of commercial nuclear power plants, Korea does not have full experience in permanent shutdown and decommissioning, with only two research reactors being decommissioned.

2.1.6.2 Decommissioning Planning for Kori Unit 1

Kori Unit 1 is Korea's oldest commercial operating reactor. It was closed in 2017 without additional continued operation. It is a 576-MWe PWR that has been in operation since 1978. It was refurbished in 2007 and approved to run until 2017. Although a subsequent relicensing process with complete safety verification could have been undertaken for Kori Unit 1 to be operated until 2027, KHNP, the licensee managing and operating all the nuclear power plants in Korea, decided not to propose the second period of continued operation. As a result, Kori Unit 1 is the first nuclear plant to be decommissioned in Korea.

According to the immediate decommissioning strategy for Kori Unit 1, the entire decommissioning period is expected to take approximately 15 years; pre-decommissioning for two years, spent fuel cooldown for five years, decontamination and dismantlement for six years, and site remediation for two years. During the decommissioning, the licensee must report the decommissioning status to the regulatory body semiannually. The regulatory body must review the report and conduct inspections according to the final decommissioning plan and semiannual report.

At the completion of decommissioning activities, the licensee must submit the decommissioning completion report with final site status report to the regulatory body, which will review the report and conduct an inspection according to the final decommissioning plan, the decommissioning completion report, and the final site status report. Finally, the regulatory body will notify the licensee of the nuclear power plant of its termination of the operating license based on the inspection results. Figure 2-3 illustrates the decommissioning process.

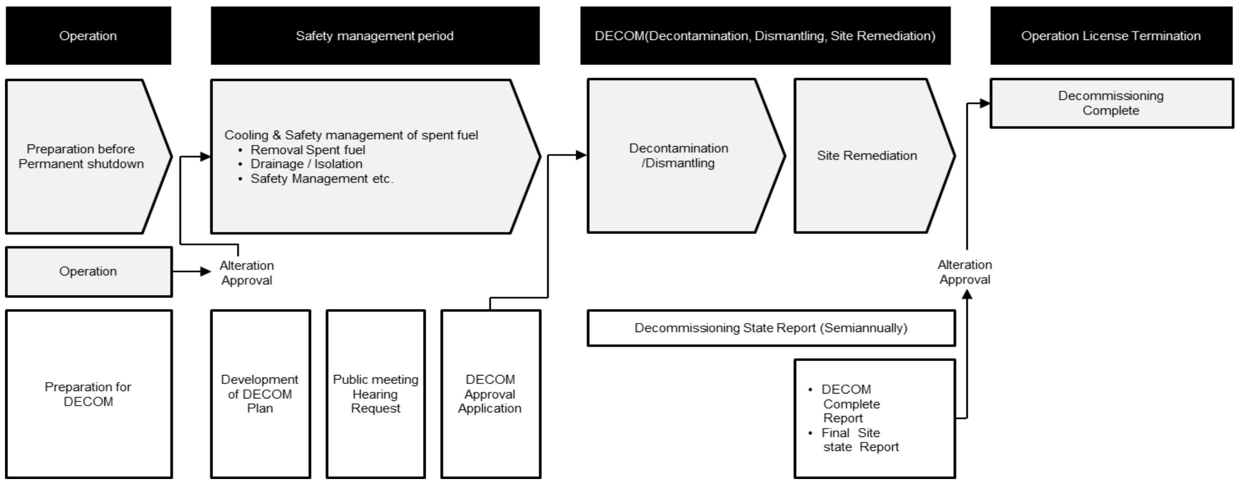

Figure 2-3
Decommissioning process for Kori Unit 1

2.1.6.3 Decommissioning Organization

Three organizations in KHNP are involved in decommissioning Kori Unit 1:

- The project management division with quality management function in the headquarters;
- The site engineering division; and
- The technology supporting institute.

The project management division is responsible for planning the organization hierarchy as the project progresses. In addition, this division manages decommissioning costs, QA, and license-related work.

The site engineering division is in charge of all decommissioning activities at the site. Its main responsibilities are to draw out spent fuel from the reactor, transfer it into the SFP, and maintain essential systems and facilities needed to decommission. In addition, this organization will manage the schedule, decontamination and dismantlement work, safety, and waste disposal. During site remediation, measurement and assessment of residual radioactivity is carried out.

The duty of the technology-supporting institute is not only to develop the initial and final decommissioning plans but also to provide technologies and engineering to be used for decommissioning. Furthermore, it supports all licensing work in every stage whenever requested by the regulatory body.

2.1.6.4 Decommissioning Strategy

The strategy of the Kori Unit 1 decommissioning was determined to be immediate dismantling and restoration to brownfield condition, although multiple strategies might be needed due to the adjacent Kori Unit 2, which will continue in safe operation. Considering multi-site issues, nonradioactive areas would be first to be dismantled, while a strategy of hot to cold could be adopted to prevent further contamination. KHNP could begin to dismantle radioactively contaminated SSCs after removing the spent fuel from Kori Unit 1.

2.1.6.5 Decommissioning-Related Research and Development Status

In accordance with the Nuclear Safety Act, KHNP developed an initial decommissioning plan for Shin-Kori Units 5 and 6 that was submitted to the government in July 2015. In addition, based on the experience of developing the initial decommissioning plan for Shin-Kori Units 5 and 6, a decommissioning plan for Shin-Hanul 3 and 4 was developed and submitted to the government in January 2016 and is under the licensing process.

Several research and development projects are also in progress, such as reactor vessel and reactor vessel internals segmentation and dismantling, decontamination and remediation, waste management, site characterization, and environmental monitoring projects.

2.2 Decommissioning Organization

A major part of any transition from an operating facility to a decommissioning project is correctly sizing the organization for the new tasks and priorities. Some organizations will require a reduction in staffing, whereas other organizations will increase in importance and size, although the work may be done by contractors.

Staffing levels will fluctuate throughout the course of a decommissioning project. For example, for sites performing prompt decommissioning, the following staffing level trends may be expected for workers solely occupied with decommissioning. From the initiation of the project, staff levels increased and peaked during systems removal. This is followed by a decline in staffing levels during the reactor vessel removal project. After all the spent fuel is in dry casks and on the ISFSI, staffing level will be further reduced. Staffing levels will decrease to two-thirds of the peak level seen during systems removal during the demolition and site closure phase. Throughout the demolition and site closure stage, staffing levels continued to drop until that work is completed [13].

2.2.1 Organization Composition

The composition of the organization reflects the needs of decommissioning projects. As those needs change over time, they cause the makeup of the organization to be in flux. Organizational planning requires identifying, documenting, and assigning project roles and responsibilities. To perform effective project planning, the following inputs for project interfaces are required:

- Organizational interfaces between project teams
- Technical interfaces between project disciplines
- Interpersonal interfaces

Further inputs to the analyses include human resource policies and requests from stakeholders. The output from the analyses include a staffing management plan, which outlines when staff with specific qualifications and expertise are required and when they should be let go.

During the course of a decommissioning project, the composition of site staff will change, with the number of operations personnel decreasing and decommissioning staff increasing.

2.2.2 Programmatic Approach to Managing Staffing Levels

There are two approaches to staffing reductions during the transition from an operating power plant to a decommissioning project [11]. One approach lets employees who wish to leave depart and then develop a plan for the remaining staff. Alternatively, a plant can establish a program for the staff and control their departure by providing incentives for critical staff to remain until their services are no longer required. The first option does not require further description, as it is totally unregulated.

One facility that successfully regulated staffing reductions during the transition period and throughout the decommissioning project realized only 1% uncontrolled attrition [11]. This successful program, which was implemented at a U.S. commercial nuclear power plant to manage staffing levels, was developed with consultations between management and site staff. Meetings were held with employees to determine which issues were of most concern during a period of potential layoffs. Furthermore, human resources staff collected information on what employees felt was needed in any plan to managing staffing levels during the decommissioning project. Because employees were engaged in developing the plan, there was a high degree of acceptance when it was implemented.

2.3 Changes to Plant Technical Specifications and Work Procedures

As early as possible in the transition phase, and preferably while the facility is still operating, site personnel should perform a study to determine which technical specifications can be deleted at their facility after it has permanently ceased operations. This study should evaluate all plant SSCs and determine which ones are required for a permanently defueled plant. These SSCs will form the basis for the permanently defueled technical specifications, and the regulator can be petitioned to allow the licensee to delete the unnecessary technical specifications [8].

Technical specifications that are frequently improved or removed from the standard include those associated with the following [14, 15, 16]:

- Safety limits
- Reactivity control systems
- Power distribution requirements or limits
- Instrumentation
- Reactor coolant system
- Emergency core cooling systems
- Containment system
- Plant systems (such as main steam isolation valves, auxiliary feedwater, control room ventilation, and secondary-side-specific activity)
- Electrical power systems
- Refueling operations (such as boron concentrations, residual heat reduction cooling circulation, and refueling cavity water level)
- Design features (reactor core)
- Elimination of limiting condition of operations
  - Reactor protection systems
  - Control rod system
  - Core cooling systems
  - Containment systems
  - Radioactive effluents
  - Auxiliary electrical power systems
  - Reactor fuel assembly
  - Refueling and spent fuel handling
    - Refueling interlocks
    - Core monitoring
    - Control rod and control rod drive maintenance
    - Extended core maintenance
    - Fuel movement
  - Design features for reactor, reactor vessel and containment
- New fuel storage requirements

After the licensee has evaluated all the technical specifications and determined which specifications are required, staff should prepare and submit an application to the regulator for revising the standard (or improved) technical specifications to establish the permanently defueled technical specifications for the facility.

Upon approval of submitted permanently defueled technical specifications by the regulator, the licensee must then revise facility procedures to align with the new technical specifications. Typically, the regulator will allow 60 days for the licensee to implement the new technical specifications.

2.4 Contracting Strategies (Decommissioning Operations Contractor or Licensee)

Decommissioning requires specialized knowledge in many different areas. Because this expertise is not usually required while the facility is operating, contractors will be required to assist licensee staff. The degree of assistance required depends on the availability of such specialized knowledge in house, as well as corporate approaches to risk [8, 17].

Some licensees have decided to contract the overall project to a DOC. The intent was to reassign some of the risk of the project to a large firm with demolition experience that could perform the work safely and efficiently [8].

The risk ownership, comparing the DOC and the licensee acting as a general contractor for the decommissioning project, was summarized as shown in Table 2-1 [8].

In addition to the transfer of some project risks, a DOC offers the licensee the following advantages [8]:

- A fixed price (if so negotiated)
- Schedule-driven project
- Shared risks
- Union concessions
- Retraining and reuse of select site personnel
- Regulator acceptance due to fixed price for decommissioning
- Savings for owner through use of an experienced contractor project management team

However, using a DOC also creates some disadvantages, including the following:

- Front-loaded site characterization before accepting bids
- Bid cycle time
- Loss of owner control
- Owner pays for unused contingencies
- Exposure to costs outside contract

Before generating a request for quote, the following must be completed or established:

- Initial site characterization
- Repowering
- Fuel storage method
- Chemical decontamination method
- Site drawings package

After bids are received, the quotes must be evaluated, ideally by both the licensee and third-party experts, to assess the bids with regard to financials, LLW management, general contracting, and repowering. Specific bid evaluation criteria include the following [8]:

- Record for industrial and radiological safety
- Experience working at nuclear facilities
- Experience with other demolition projects
- Key personnel qualifications and credentials
- Financial health and credit ratings
- Proposed decommissioning approach
- The following contractual conditions have proven to be advantageous to the licensee [8]:
  - Contracts between the subcontractors and the DOC could be assumed by the licensee, if needed.
  - Tight financial controls were mandated, including the review of all DOC payments to subcontractors.
  - In the case of DOC insolvency, the contract could be terminated.

Earned value should be the basis of the financial agreement between the DOC and licensee for labor and service contracts. An estimate for the number of hours to complete each task should be generated. Payment to the DOC should be based on performance—that is, the hours completed versus the estimate.

Table 2-1
Risk distribution between licensee project management and a decommissioning operations contractor for Maine Yankee Atomic Power Plant [8]

Task	Decommissioning Operations Contractor (DOC) Project Management	Licensee Project Management
Transition management	Licensee or contractor	Licensee
Project management	DOC	Licensee
Site management	DOC	Licensee
Site labor management	DOC	Various
Cold and dark preparations	DOC	Licensee with contractor
Primary system decontamination	Licensee with contractor	Licensee with contractor
Site characterization	Licensee with contractor	Licensee with contractor
Large component removal	DOC	Contractor
Commodity removal	DOC	Contractor
Waste packaging, shipping, and disposal	DOC	Contractor*
Licensing	Licensee and DOC	Licensee with contractor
Radiation protection and health physics	DOC	Licensee with contractor
Facility administration	DOC	Licensee with contractor
Procurement	DOC	Licensee with contractor
Fuel handling	DOC	Licensee with contractor
Fuel storage facility	DOC	Licensee with contractor
Final status survey	DOC	Licensee with contractor
Asset recovery	Licensee and DOC	Licensee
Repowering	DOC	Licensee

* The licensee owns the waste and therefore must be involved in waste characterization and shipping.

2.5 Design Changes and Isolation of the Decommissioning Facility (Repowering, Temporary Control Room, Spent Fuel Pool Isolation)

When planning the decommissioning of a permanently shut down facility, consideration must be given to the inevitable design changes and systems isolations that will be required. There will be changes in technical specifications and security requirements associated with these physical system changes. Systems required for operating the plant and, as appropriate, technical specifications associated with those systems, will no longer be applicable during decommissioning. Examples of changes that can affect system designs are the following:

- Repowering (also known as *cold and dark*)
- Changes, both functional and physical, to the control room
- Spent fuel storage location (Spent Fuel Pool Island (SFPI) or ISFSI)
- Furthermore, new, temporary systems that are required during decommissioning have different criteria than the original plant systems, which were scaled for larger loads and designed for heavy use and longevity. Examples include the following [1]:
  - During the operational phase, the facility relied on permanent structures that may have included technical specifications. During decommissioning, temporary structures may be preferred.
  - While the plant was operating, personnel were focused on maintaining functioning systems according to technical specifications. During decommissioning, the systems may need to be sized for smaller volumes with fewer technical requirements after the removal of spent fuel to the ISFSI.

2.6 Reclassification of Structures, Systems, and Equipment

After the facility has entered permanent shutdown status, many systems that were previously classified as nuclear safety-related will no longer require that classification. Before shutdown, personnel should undertake an evaluation of the safety classification of plant SSCs [18]. Many systems are no longer required for nuclear safety after the reactor is permanently defueled and the SFP is isolated or all spent fuel is transferred to an ISFSI [16].

Nonnuclear safety systems will have reduced maintenance, inspection, and QA requirements, which will result in lower expenses during decommissioning. Categories of systems that generally retain their nuclear safety classification during decommissioning are those associated with spent fuel, fire protection, and radiation detection [18].

A systematic approach to assessing which SSCs can be reclassified to nonnuclear safety should be evaluated against established criteria such as the following [8]:

- Is the SSC required to mitigate a design-basis accident at the permanently defueled facility?
- Is the SSC required to safely store radioactive waste or spent fuel?
- Is the SSC required to satisfy design, licensing bases, or technical specifications at the permanently defueled facility?
- Is the SSC required for day-to-day activities at the permanently defueled facility?

After all nuclear safety systems have been evaluated against these or other valid site-specific criteria and are no longer required to perform their nuclear safety functions, they can be reclassified as non-nuclear safety. One licensee also identified an additional benefit from the nuclear safety SSC evaluation: the site determined that the appropriate level of reduced control and instrumentation required during decommissioning was established [8].

2.7 Environmental Impact Assessment (U.S. Requirements)

An assessment of the potential environmental effects of decommissioning the facility is part of the PSDAR submittal. In the environmental impact statement, facility staff should compare the proposed decommissioning activities to those evaluated in the site's Facility Environmental impact Statement (FES), other site-specific studies, or the Generic Environmental Impact Statement (GEIS) [5]. Environmental effects that have not been evaluated in previous environmental assessments must be researched by the licensee, and the results of that research must be submitted in a supplement to the current environmental report [19].

The U.S. NRC has provided environmental evaluation of many decommissioning activities that have the potential to affect the environment. NUREG-0586 [20] provides the results of the analyses of activities that may occur at decommissioning sites. These are summarized and form the basis of the GEIS [20]. Decommissioning activities that have not been evaluated by the GEIS, FES, or other site-specific evaluations will need to be assessed with regard to their environmental effects [21].

When planning a specific activity, the effects of which fall within the bounds described in Section 4 of NUREG-0586 [20], the licensee may proceed without further risk analyses. However, if the effects fall outside the bounds of the analyses, the activity cannot proceed until a further evaluation on the risks and impacts of the activity is completed.

2.8 Management of Radioactive Effluents

Radiological and environmental monitoring will continue during decommissioning. However, the scope of the effluent monitoring may be reduced to levels required for monitoring effluents from the SFP (assuming the reactor is in a permanently defueled state) and certain decommissioning activities (such as dismantling reactor internals).

Any proposed changes to station ventilation systems must be evaluated against the facility's off-site dose calculation manual to ensure that modeling and criteria for releases are evaluated and that the manual is revised accordingly, if necessary. Moreover, decommissioning projects must be evaluated to assess the potential changes to the plant ventilation system, and therefore, effluent monitoring system requirements and assumptions. Effluent dose models used to determine whether off-site dose calculation manual limits are met are based on site-specific criteria, including effluent exhaust rates and building wake effects. The risk is that physical changes from dismantling the facility may alter these variables. If this is not evaluated beforehand and models updated as required, the calculated dose rates may no longer be accurate, possibly in a non-conservative way [20].

2.9 Quality Assurance

Quality Assurance (QA), also known as *nuclear oversight*, plays as important a role in decommissioning as it did while the facility was operational. In addition to ensuring that work proceeds according to the decommissioning project plans, some sites have used QA to perform risk ranking of activities [22]. Specific functions performed by QA include the following:

- QA program changes
- Internal assessments
- Surveillance
- Inspections
- Corrective actions
- External (vendor) assessments

The QA program for the facility during decommissioning should be established before permanent shutdown of the facility. As with other site organizations, the QA program will change during the transition to decommissioning. Program management should institute a review of applicable legal requirements (in the United States, 10 CFR 50, Appendix B [24]) to determine which ones can be eliminated. In other cases, QA requirements may need to be expanded to support dismantling and shipment of large contaminated components [23].

As the site transitions to decommissioning, the staffing levels will decline. Therefore, the QA program during decommissioning should be devised so it is simple to implement by the remaining staff [25]. QA must also ensure that changes in staffing, maintenance, and equipment reliability requirements are made in a coordinated fashion.

QA is responsible for reviewing and verifying procedures and equipment used to manage these records to ensure that records are retrievable. QA must establish which records will be required when the facility has been decommissioned. Examples of such records are as follows [25]:

- Records related to waste and waste disposal
- Details of licensing documents
- Applicable decommissioning standards and criteria (these may change over time, so it is important to document which requirements were in force when specific decommissioning activities occurred)
- Details regarding procedures and equipment used

- Records of audits, corrective actions, agreements, endorsements, and recommendations made during the various phases of the decommissioning project
- Records related to safety standards and assessments
- References cited in documentation
- Decommissioning drawings
- Details pertaining to the FSS

Licensees should consider that these records are required for the following:

- Regulatory requirements
- Assisting with future decommissioning work
- Possible litigation

At a minimum, records require the following metadata:

- Basis for storing record (requirement)
- Record type
- Retention period
- Who generated the record
- Storage medium
- Encryption method
- Format
- Storage location

2.10 Fire Protection Program

As with other systems, the fire protection systems will change during decommissioning due to changes in the safety systems and a reduction in the amount of combustibles in the facility [8]. Associated with physical changes to the fire protection systems are changes to fire protection staffing and training [19].

The NRC has identified two conditions at a decommissioning site in which fire protection is required: 1) protecting SFP cooling and 2) minimizing the spread of contamination.

Using these bases, licensees can evaluate which systems require fire protection through an evaluation of the entire facility. As more SSCs are removed or dismantled, further evaluations must be made, so the determination of which systems require functioning fire protection system coverage is iterative [19].

Other regulators may have different requirements, so it is best to consult with them to determine the best course of action. The preferred approach is to perform the evaluation and withdrawal of fire protection systems in a systematic and logical manner and with considerable input from regulators and insurance carriers.

2.11 Maintenance Program

Maintenance needs at a decommissioning site will be considerably reduced from those at an operational facility. The new scope will be based on an assessment of required systems and will change through time as more systems are taken out of service. Maintenance personnel can be a critical source of information at the plant, a factor that must be taken into account when determining staffing reductions.

For this reason, critical steps in decommissioning a facility, such as chemical decontamination, should be implemented as early as practical to ensure that components such as pumps and valves have had all the required periodic maintenance performed and that experienced personnel are available to perform repairs if a component fails [26]. An additional factor with regard to maintenance and staffing is how spent fuel is being stored. If the site decides to store spent fuel in a spent fuel island, maintenance costs and requirements will be higher than for facilities that solely store their spent fuel in casks at an ISFSI [8].

The degree to which maintenance of critical components must be continued, with the concomitant levels of staffing of the department, depends on the decommissioning strategy implemented at the site. Maintenance costs will continue to a greater degree at sites that use delayed decommissioning compared to those that use prompt decommissioning [16].

2.12 Security Program

As with maintenance, nuclear security requirements will be reduced as the decommissioning project proceeds. This is a consequence of a general reduction in staff and a shrinking of the protected area. This may require use of augmented resources when major decommissioning projects require in-processing of larger numbers of contractors. In addition, a changing protected area can cause challenges to security staff.

The conclusion of projects in the decommissioning process related to the storage of spent fuel affect the security program at the site. The creation of a spent fuel pool island (SFPI) allows the security boundary to be reduced [8]. Moving the spent fuel to an ISFSI will further change the security boundary. According to 10 CFR 72 [27], the boundary around an ISFSI is at least 100 m (328 ft). At the Maine Yankee Atomic Power Plant, the design-basis threat evaluation for the ISFSI resulted in a 300-m (984-ft) exclusion zone [8].

2.13 Management of Knowledge and Information

Immediate dismantling is generally the preferred method for decommissioning a nuclear facility. An important aspect of this opinion is the realization that personnel with profound knowledge of the facility will leave at some point after the plant has been permanently shut down, and they will take their valuable expertise with them. However, for licensees that decide to use the delayed decommissioning strategy, maintenance of facility knowledge and information (documents) becomes even more important because the personnel who will need this information will require it decades after the facility has been shut down [28].

The type of knowledge accumulated by employees during their careers is referred to as *tacit knowledge*. There are methodologies for tacit-to-tacit knowledge transfer and tacit-to-explicit knowledge transfer, which is preferred [29, 30]. One example of an initiative to capture knowledge for future use in decommissioning a specific type of reactor (among other objectives such as design, construction, operations, and so on) is the IAEA project to establish a comprehensive, international inventory of data knowledge of fast reactors [31].

2.14 Planning Operational Experience

Because more than 100 power reactors have been permanently shut down worldwide, several licensees have experience in planning for decommissioning. Although planning for decommissioning should begin before the operational phase at a power reactor site [2], and records related to the operation, modifications, and spills and leaks of radioactive material should be maintained throughout the operational period, a program for transitioning to decommissioning should be initiated three to five years before the permanent shutdown of the facility [9, 32].

2.14.1 Advanced Gas-Cooled Reactors

At the Électricité de France (EDF) advanced gas-cooled reactors, early safe storage and deferred dismantlement after 85 years of storage is the currently preferred decommissioning strategy [32]. Programs for transition and preparatory work will start approximately five and one-half years before a planned shutdown. Activities include the following [32]:

- Prepare a defueled safety case
- Write a detailed decommissioning plan
- Generate a work plan
- Perform an environmental impact study
- Prepare an environmental impact statement
- Revise maintenance schedules
- Revise authorizations for discharges and disposal

2.1.4.2 Canadian Deuterium/Uranium Reactors

Several older Canadian deuterium/uranium reactor (CANDU) plants in Ontario, Canada, have been shut down since the early 1980s. Based on these experiences, it is recommended that maintenance and work practices receive more attention during planning to avoid problems such as the following [33]:

- Abandoned process system not completely drained, leading to the spread of contamination due to leaks or, in facilities sited in high elevations or latitudes, rupture due to freezing.
- Corrosion of components and structures
- Failures of foundations or drains leading to a pathway from buildings or excessive ground water intrusion
- Persistence of tritium in buildings, which requires vapor recovery in ventilation for drying
- Key activities to be addressed during the planning period include the following [33]:
  - Perform a radiological characterization of the facility immediately after cessation of operations
  - Generate a decommissioning waste management plan
  - Upgrade systems required during decommissioning
  - Develop a robust information management system, including records for operations and other essential information
  - Complete a decommissioning surveillance and maintenance plan
  - Develop a plan for partial dismantling during safe storage, if applicable

2.15 Primary References

The following documents serve as primary references on the topic of Decommissioning Planning:

[5] *Decommissioning Planning: Experiences from U.S. Utilities*. EPRI, Palo Alto, CA: 2006. 1013510.

[10] *Guidance for Transitioning from Operation to Decommissioning for Nuclear Power Plants*. EPRI, Palo Alto, CA: 2016. 3002007551.

[34] *Decommissioning Pre-Planning Manual*. EPRI, Palo Alto, CA: 2001. 1003025.

Section 3: Historical Site Assessment and Initial Site Characterization

The Historical Site Assessment and Site Characterization (surveys) are key components of the Multi-agency Radiation Survey and Site Investigation Manual (MARSSIM) process [35], and the substantially similar Environmental Radiation Survey and Site Execution Manual (EURSSEM) process [36]. These processes are designed to guide facilities through an approved site assessment and characterization process with the goal of ensuring that site characterization is adequate to demonstrate compliance with dose or risk-based regulations for sites contaminated with radioactive materials. The MARSSIM process provides a series of steps, some which are optional based on conditions at the site, concluding with the Final Status Survey [35].

While some steps of the MARSSIM process are optional, each step is designed to build on information acquired in the previous step and support later surveys up to, and including, the Final Status Survey. Information gathered in the MARSSIM process also supports the establishment of Site Release Criteria.

At a basic level, the HSA and subsequent characterization surveys delineate site impacted areas, i.e., actually, or possibly, containing plant-related radionuclides of concern above an established limit, from non-impacted areas.

Table 3-1
Steps of the MARSSIM Process for Sites with Known Radioactive Contamination [35]

MARSSIM Process	MARSSIM Guidance (From MARSSIM Table 2.1)
Historical Site Assessment	Provides information on collecting and assessing existing site data (MARSSIM sections 3.4 through 3.9) and potential sources of information (MARSSIM Appendix G)
Scoping Survey	Discusses the purpose and general approach for performing scoping surveys, especially as sources of information when planning final status surveys (MARSSIM Section 5.2)
Characterization Survey	Discusses the purpose and general approach for performing characterization surveys, especially as sources of information when planning final status surveys (MARSSIM Section 5.3)
Remedial Action Support Survey	Discusses the purpose and general approach for performing remedial action support surveys, especially as sources of information when planning final status surveys (MARSSIM Section 5.4)
Final Status Survey	Provides detailed guidance for planning final status surveys (MARSSIM Chapter 4 and Section 5.5), selecting measurement techniques (MARSSIM Chapter 6, 7, and Appendix H), and assessing the data collected during final status survey (MARSSIM Chapter 8 and 9)

3.1 Historical Site Assessment

Key to a successful site characterization campaign is the development of a thorough Historical Site Assessment (HSA). The HSA is the first step in determining the nature and extent of contamination at the site. The HSA is performed to document a facility's complete operational history to establish the nature and scope of contamination at the site. Upon completion, a HSA report should [35]:

- Identify potential, likely, or known sources of hazardous and radioactive material, or contamination resulting from the release of hazardous or radioactive materials to structures or the environment;
- Define impacted areas on site (i.e., those designated as Class 1, 2 or 3 Areas where known or potential radiological impacts exist, or may exist, exceeding applicable cleanup criteria) that may require decontamination or remediation, as well non-impacted areas (i.e., those with no known or potential impact from radiological materials) those that do not pose a threat to health and do not require decontamination or remediation;
- Document the assessment of the likelihood of off-site contaminant migration; and
- Be a source of information for planning scoping and characterization surveys.

For the successful development of an HSA, the following information should be compiled while the plant is operating, or during the initial stages of decommissioning [37]:

- Records regarding leaks and spills of radiological or hazardous materials [38];
- Records of the movement and disposal of solid and liquids wastes (including construction debris, soils, etc.) generated during plant operations and modifications;
- Documentation of systems that may have become cross-contaminated with plant-related radionuclides (NRC Bulletin 80-10 [39]);
- Documentation of changes to the site and its components from site aerial photographs and photographs of Systems, Structures, or Components (SSC);
- Information on spills, leaks, and related events should be compiled from questions on employee out-processing forms (see Reference [37] for an example questionnaire).
- Interviews with past and present site employees.
- Information from site environmental records and reports, especially those associated with the Radiological Environmental Monitoring Program and Radioactive Effluent Technical Specifications.
- Relevant corrective action program records.
- Relevant operations records.
- Characteristics of known radiologically contaminated systems.

Using this information, characterization plans can be developed to survey SSCs and environmental media (soil, groundwater, surface water and sediment) for plant-related contamination. Based on the HSA, initial site characterization surveys should be focused on SSCs and areas that are presumed to have been unaffected by plant operations to confirm this presumption.

3.2 Inventory of Radioactive Materials

The inventory of radioactive material for the site should comprise detailed inventories of individual SSCs. These inventories should detail the following for each SSC [40]:

- Radionuclide type and activity;
- Chemical and physical forms; and
- Weights and volumes.

The inventory of radioactive materials at a facility that has been permanently shut down is a critical pre-requisite to the assessment of potential site impacts, distinguishing non-impacted from impacted areas and planning the sequencing of site decommissioning. The degree and distribution of site contamination will affect aspects of the project such as decontamination efforts, shielding requirements, removal of components, and disposal options. An inventory of radioactive materials is also critical to assessing and mitigating potential radiation exposures to workers and possibly the public. Ultimately, the more accurate the inventory of radioactive materials is, the better management can estimate and constrain decommissioning costs. Sources of radioactive materials in facilities include spent fuel and contamination from fission products and activation products. Generally, radioactive waste produced at a facility while it was operating is not considered to be part of this inventory because these wastes are typically sent for disposal before, or during, the transition period after the facility has been permanently shut down [40].

The basic steps for generating a radioactive materials inventory are as follows [40]:

- Survey existing data on radioactive materials in SSCs and, if applicable, the environment.
- For contaminated SSCs, or those containing activation products, quantify physical parameters such as volume and density.
- For SSCs in which contamination levels are not adequately quantified, develop a plan for generation of radiological (and hazardous constituents, if applicable) characteristics through statistically valid sampling (data quality objectives [41]) and *in situ* measurements.
- Perform calculations to generate data needed to support waste characterization and dose estimates.

Characterization is exploratory in nature; therefore, these projects are typically iterative. It is also generally more cost-effective to conduct characterization in phases beginning with screening surveys to differentiate un-impacted from impacted areas and progressively more detailed, and generally higher cost, characterization surveys to define the nature and extent of the impact and to support remedial alternative evaluation. If surveys produce unexpected results, additional surveys may be required to adequately characterize the material. Characterization should be conducted to pre-established management, or cleanup, criteria to enable segregation of impacted from non-impacted areas and volumes and ensure accurate estimates of management areas and volumes.

Radionuclide inventory can vary widely between facilities and is due to factors such as [40]:

- Reactor type, design, and power level;
- Composition of materials used in construction; and
- Unplanned events.

AERI (Automatic Estimation of Radiological Inventory) is software published by EPRI to assist in generating a radiological inventory for the dismantling of nuclear facilities. This software provides estimated of specific radionuclide mass activity concentration in Bq/g as well as surface activity of SSCs in Bq/cm^2 [42].

Due to radioactive decay, the facility's radionuclide inventory will change during decommissioning. Because the overall trend is toward decreasing radioactivity, some sites take advantage of this by placing the facility into safe storage for several decades. However, in-growth of radionuclides such as americium-241 can take place in some systems in which transuranic contamination levels are high (such as facilities that had a history of failed nuclear fuel), and maximum activities will occur some 50 years after the facility is permanently shut down [43].

While this section has focused exclusively on the consideration of radiological impacts, similar approaches are necessary to address potential impacts from hazardous or other regulated materials (petroleum, asbestos, polychlorinated biphenyls (PCBs) [44].

3.3 Initial Radiological Characterization of Plant Systems, Structures, and Components

Proper characterization of potentially contaminated SSCs with regard to degree, type, and distribution of radioactivity at a facility is essential to manage radiological risk during decommissioning and to provide data needed for the proper disposal of radioactive wastes. Initial characterization of plant systems with high levels of contamination can provide information for management to evaluate the necessity for chemical decontamination, or hot-spot removal, in these systems to lower personnel dose during dismantling and other decommissioning activities. Accurate quantification of radioactive waste volume is critical to performing the dismantling within budget.

Initial radiological characterization of facility SSCs is performed to accomplish the following objectives:

- Estimate the total waste (by category) that may be generated;
- Develop cost estimates;
- Estimate dose budgets;
- Provide estimates on potential gaseous and liquid releases from the site during decommissioning; and
- Provide data to determine the effort needed for the free release of the facility.

Preparations for characterizing potentially contaminated SSCs include determining whether the surveys will be biased, or unbiased. Unbiased surveys, i.e., where samples have an equal chance of being selected, such as those selected at random, or perhaps from a uniform grid are more appropriate for homogenous areas where the goal is to determine the average activity, or identify anomalies relative to the average. Biased surveys, i.e., those where professional judgment is used based on characteristics such as system processes or perhaps physical characteristic such as component discoloration, are appropriate for determining worst-case conditions within a heterogeneous distribution of SSCs, such as sumps, or areas where contamination may have been concentrated [35]. Biased surveys are also useful to bound activity for waste characterization.

In planning characterization activities, setting Data Quality Objectives (DQO) [35, 41] is important to ensure that the type and level of data collected is appropriate for the intended purpose. The DQO process includes formally describing the nature of the problem to be assessed (the objective), the type and level of data needed to achieve the objective, and the development of a sampling plan that will ensure the appropriate type and distribution of data needed is collected. The DQO process is generally more effective when characterization planning is divided into several distinct components consistent with site-specific characterization objectives. Component planning helps ensure that the data collected will support the overall goals of the project. For example, collection of screening data over large areas may be used to support focused assessment involving the collection of selected samples at key locations for laboratory analysis in a subsequent phase.

In scoping site characterization, areas within the facility should be divided into discrete system identities. A system identity is defined by material type, contamination type, radionuclide mix, and process. The advantage of dividing SSCs into discrete system identities is that remedial decision-making can be streamlined. SSCs with similar characteristics and levels of impact can be generally be managed in a similar fashion.

SSCs that will remain in place through license termination will require characterization to prove that the systems have been decontaminated to meet site release criteria. SSCs that will be dismantled, and shipped for disposal, will require a different level of effort for adequate characterization to support proper shipping and to ensure the level of contamination in the SSC meets disposal site waste acceptance criteria.

3.4 Initial Radiological Characterization of Site Land and Water Areas, Including Surface and Subsurface Characterization

Comprehensive characterization of the environs adjacent to a facility that has been permanently shut down is required to determine the possible existence and extent of radiological (and hazardous materials) contamination. Media to be characterized include soils, sediment, groundwater and surface water. Key areas of potential concern include portions of the facility where radioactive and hazardous materials and wastes were used or stored. The HSA and initial site characterization should allow accomplishment of the following objectives [8, 16]:

- Clearly demarcate areas of contamination and determine non-impacted areas, as defined by MARSSIM [35], early in the decommissioning process.
- Identify areas of groundwater and soil contamination if the site did not perform groundwater monitoring, or track leaks and spills of radioactive or hazardous material while operational.
- Identify areas and media that need to be remediated to the degree necessary to achieve site cleanup objectives for un-restricted or restricted future use scenarios.

- Define the levels and limits of contamination that will affect costs associated with the removal, transportation, and disposal of waste.
- Provide information that will assist in establishing remedial options consistent with facility decommissioning objectives (e.g., long-term, or short-term options).
- Provide a basis for future compliance requirements, such as dose modeling for FSS designs, thereby potentially minimizing the number of review cycles by regulators and other stakeholders needed for license termination.

A proper site radiological characterization effort also has been shown to positively affect costs associated with contract work at the decommissioning site. Costs for projects are consistently lower and more accurate when contamination levels and doses are well understood by the contractor in advance of execution of work. Site characterization efforts can be quite extensive. At one project, approximately 130,000 site measurements were taken, and nearly 800 samples for laboratory analysis were obtained. Characterization work commonly results in unexpected findings, such as large variations in background radioactivity, or unexpected contamination outside radiologically restricted areas [10]. Early identification of unexpected findings enables proper advanced planning to positively affect costs.

One approach is to classify impacted, or potentially impacted, portions of the site consistent with MARSSIM by area based on the probability for the occurrence of contamination as indicated by site operational history [35]:

- Class 1 Areas: Areas that have, or had prior to remediation, the potential for radioactive contamination above license termination criteria.
- Class 2 Areas: Areas that have, or had prior to remediation, the potential for radioactive contamination, but not at a level expected to exceed license termination criteria.
- Class 3 Areas: Impacted areas not expected to contain any residual radioactivity, or only at levels that are a small fraction of license termination criteria.

Per MARSSIM guidance, Class 1 areas receive the most intense survey effort, with decreasing levels of effort for classes 2 and 3. Furthermore, areas are divided into survey units which should not exceed size guidelines based on class and whether the area is in a structure or open land.

In addition to the area classes, based on the potential for the occurrence of plant-related contamination, the facility should also identify "Background Reference Areas" to quantify background-levels of naturally-occurring radionuclide levels as well as those for anthropogenic radionuclides from nuclear weapons fallout [35]. Under these circumstances, a study must be undertaken in which a statistically valid number of soil samples are taken in areas beyond the potential zone of influence of the plant and analyzed for cesium-137 (as well as any other radionuclides potentially present in the local area background). The average background and standard deviation values are calculated and, if approved by the regulator, can be subtracted from cesium-137 in soil samples from potentially affected areas.

3.5 Primary References

The following documents serve as primary references on the topic of Historical Site Assessment and Initial Site Characterization:

[35] *Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)*, NRC, NUREG-1575.

[36] *Environmental Radiation Survey and Site Execution Manual (EURSSEM Version 01.*

[37] *Capturing Historical Knowledge for Decommissioning of Nuclear Power Plants: Summary of Historical Site Assessments at Eight Decommissioning Plants*. EPRI, Palo Alto, CA: 2004. 1009410.

[66] *Characterization and Dose Modeling of Soil, Sediment and Bedrock during Nuclear Power Plant Decommissioning. Detailed Experiences 1993–2009.* EPRI, Palo Alto, CA: 2009. 1019228.

[68] *Final Status Survey and Site Release Experience Report, Detailed Experiences 1996–2007.* EPRI, Palo Alto, CA: 2008. 1015500.

Section 4: Site Preparations for Dismantlement

4.1 Introduction

As addressed in Section 2 of this sourcebook, a series of activities must take place, within prescribed timeframes, after a licensee has decided to permanently shut down a nuclear power plant. Some of these activities include the generation of documents sent to the regulator. In some cases, the submittal of these documents is tied to permission for the licensee to access parts of the decommissioning trust fund. For example, in the U.S., only three percent of the total decommissioning trust fund is available to the licensee until the Post Shutdown Decommissioning Activities Report (PSDAR) is submitted. Some European countries require that the spent fuel is removed from the spent fuel pool prior to the commencement of decommissioning activities.

Once the administrative and legal requirements have been completed, activities to transition the facility to safe storage, or prompt remediation, may commence. Some of the activities that may be required to prepare the site for dismantling include: repowering, re-establishment of site security boundaries, spent fuel management, full system chemical decontamination, asbestos abatement, and management of operational wastes.

4.2 Repowering

To facilitate the safe and efficient dismantling of a permanently shut down nuclear facility, a project referred to as *repowering,* or *cold and dark* status, may be implemented. The concept is to de-energize, or depressurize, legacy electrical, hydraulic, and pneumatic systems and to repower them, or to replace them with new, temporary, and easily identified systems that are required during decommissioning.

The following benefits to repowering have been identified [8]:

- It provides the greatest degree of nuclear security if the spent fuel is not stored at an ISFSI after the SFP has been isolated and is serviced by dedicated temporary systems;
- It provides the highest degree of industrial safety because all systems that remain energized are powered using clearly marked cabling and redundant systems are de-energized before dismantling activities begin;

- If the licensee uses a decommissioning operations contractor (DOC), the repowering simplifies evaluations, potentially resulting in lower bids; and
- Decommissioning work is more efficient because repowering eliminates the requirement to perform clearances before working on SSCs [22].

During a repowering campaign, related activities take place such as removal of operational wastes, control room relocation, changes to the physical security of the facility, and modification to ventilation systems.

The first step in implementing a repowering campaign is to identify which systems will be required during decommissioning [8, 18, 22]. This should include systems that will be needed to support habitability, radioactive waste systems, dismantling, security, fire protection, and the Spent Fuel Pool Island, if one is used.

Examples of criteria to be used when assessing which systems will be required during decommissioning include the following [8]:

- Whether the system is required to mitigate a design-basis accident;
- Whether the system is required for the safe storage of nuclear fuel;
- Whether the system is required to satisfy facility design, licensing bases, or technical specifications with the plant in a permanently defueled state; or
- Whether the system is required for other purposes (such as ventilation, radiation monitors, or security) during decommissioning

After the systems that can be abandoned have been identified, those systems required during decommissioning can be repowered, or replaced, by new temporary systems. Redundant legacy systems can be abandoned and dismantled as the schedule and availability of disposal facilities allow.

A repowering campaign is also an appropriate time to resize, modernize, and move systems needed during decommissioning. Temporary replacement power systems can be located in areas where they will not impede the dismantling of legacy systems. The new temporary systems are generally smaller, with fewer surveillance and maintenance requirements than the legacy systems that they replace.

Compared to the operational phase, the level of control and instrumentation monitoring is greatly reduced at a facility that has permanently ceased operations. Some decommissioning sites (San Onofre Nuclear Generating Station, Yankee Rowe Nuclear Power Station, and Maine Yankee Atomic Power Plant) decided to completely relocate the functions required for decommissioning from the original control room to a new facility. Although it is initially more-costly, this approach has the following advantages [8, 18]:

- It allows operators to focus on a smaller number of critical parameters and instruments.
- It removes the control room to a location where it will not interfere with dismantling activities.
- It allows for the dismantling of the original control room.

4.3 Reestablishing Site Security Boundaries

At a permanently shut down facility, the primary function of physical site security continues to be the protection of the nuclear fuel. During decommissioning, the actual security boundary can generally be reduced as spent fuel is moved to an SFPI, or ISFSI. This removal of spent fuel from the reactor to the SFPI, and later to the ISFSI, changes the facility's safety status by reducing the number of vital safety systems, and therefore, the plant's vital area [8, 16]. The smaller security zone will also facilitate dismantling activities.

The Maine Yankee Atomic Power Plant reduced the size the security boundaries after the reactor was defueled and the SFPI was created. The SFPI greatly reduced the number of systems that interfaced with the SFP, which naturally reduced the number of systems that required security [8]. The security boundary was changed again after all the spent fuel was transferred to dry storage canisters and moved to the ISFSI.

At the San Onofre Nuclear Generating Station, Unit 1, the site security boundary was reconfigured to include only the fuel storage building and the ISFSI. The remainder of the site was then designated as an industrial area. This allowed security to focus on two discrete areas and eliminated other barriers that would be an impediment to the decommissioning work [22]. Changes to the physical security of the site must be reflected in the security plan for the facility.

4.4 Spent Fuel Management

4.4.1 Overview

Options for long-term storage of spent fuel are constrained by government policies. Off-site storage at a federal repository is not an option in most countries. Consequently, licensees in these countries are left with two primary options to manage their spent fuel so that the decommissioning project may proceed. Spent fuel may be stored in an SFPI that is isolated from the rest of the facility. Alternatively, spent fuel may be transferred to dry storage casks and stored on site at an ISFSI [5]. Storing spent fuel at an ISFSI essentially eliminates the chance that decommissioning activities will affect spent fuel.

Although the SFPI may be a less expensive option initially, ultimately it is preferable to transfer the facility's spent fuel to an ISFSI for long-term storage. Planners must evaluate the cost of the two spent fuel storage options based on the potential effects on decommissioning work, risk, and the potential availability of a federal repository. Facilities in prompt dismantlement that initially established an SFPI ultimately built an ISFSI because spent fuel could not be shipped off-site in the foreseeable future and the presence of the SFPI was impeding decommissioning work [5].

One of the key considerations when managing spent fuel is the ability to handle the fuel for transfer to the next stage in the fuel cycle (e.g., dry storage, reprocessing or final disposal). Because an increasing number of facilities have opted for delayed dismantling, the method for retrieving and managing the spent fuel canisters must be well documented. The following issues have been reported with handling spent fuel [45]:

- The spent fuel assembly had a non-standard format.
- Incomplete records exist, which affects the plant's safety case and may reduce available management options.
- The original fuel handling tools were lost (scrapped). The facility could not move spent fuel until new tools were designed, fabricated, and certified.
- Operator knowledge was lost due to attrition.
- Fuel assemblies may have become mechanically unstable, bringing the risk that failures could occur when they were moved.
- Fuel handling equipment was not maintained.
- Radiolysis occurred in a cask during wet transport. A hazard was generated due to the evolution of hydrogen gas.

Each of these circumstances requires a response that will cause delays, including additional actions that can affect the project. In the case of damaged spent fuel, several solutions have been developed in recent years, although they are dependent on the type of spent fuel and the degree of damage [46].

4.4.2 Establishing a Spent Fuel Pool Island

If spent fuel cannot be shipped off-site for disposal or storage, and the capability for dry fuel storage in an ISFSI on site is not immediately available, an SFPI may be required to safely manage spent fuel to allow decommissioning to proceed. Indeed, some facilities have implemented an SFPI although an ISFSI would be operational within a few years of the permanent shutdown of the plant.

The intent of the SFPI is to isolate the systems associated with managing spent fuel in the pool so that decommissioning activities can be undertaken to dismantle and dispose of the remaining systems. Standards require that spent fuel storage facilities, regardless of type, are required to be durable and have the capacity for passive cooling with sufficient safety margin [47]. Furthermore, wet storage of spent fuel must also be appropriate from a technical standpoint. For Light-Water Reactor (LWR) spent fuel, it has been shown that zirconium alloys stored in water are stable for more than 50 years [46].

To implement an SFPI, a thorough study of all the interfaces between the SFP and other plant systems must be performed. Typical interfaces include electrical systems to support ventilation, cooling, water quality monitoring (such as temperature or radioactivity), and effluent monitoring. After these interfaces have been identified, planning can take place to engineer the temporary systems that will be required to take over the necessary functions for the SFPI and implement those changes. The licensee should evaluate worst-case operational periods (time that the temporary system will need to be in service) when designing the new system and determining the materials and components to be used [18]. System interfaces can be removed only after the new, temporary systems have been installed, tested, and begun to perform the functions of the legacy systems.

A critical analysis in the evaluation is the time to boil, or the time until fuel would be uncovered due to evaporative and steaming losses, in the event of a loss of power event. The results of this evaluation depend on many factors (such as physical dimensions of the pool, percent of capacity occupied by spent fuel, and age of the spent fuel), so a generic estimate of the limits cannot be provided. For reference, at one facility the evaporative loss rate from the SFP was 0.23 m^3 (60 gallons) per hour, and time to fuel becoming exposed due to evaporative losses was calculated to be four weeks. This same facility determined that the heat load of the SFP at that facility dropped by half within 18 months after permanent cessation of operations [18].

Although the thermal load decreases over time, SFP cooling remains a critical system. A dedicated auxiliary service water system to perform this function allows complete separation of the decay heat removal system from the rest of the facility and allows dismantling of legacy systems. Components from other systems may be repurposed to achieve this isolation (such as heat exchangers from obsolete or abandoned systems). The following key components must be included in the new, temporary system [18]:

- Heat exchanger with inlet and outlet isolation valves;
- System pressure monitoring equipment with indicators and annunciators in the control room;
- Radiation monitor downstream of the heat exchanger (periodic sampling for tritium, as well);
- A method for throttling the downstream isolation valve to ensure that the non-contaminated side of the heat exchanger is always maintained at a higher pressure than the SFP side (contamination control and mitigation measure); and
- SFP water makeup.

Earlier SFPI cooling systems relied on active cooling systems that required pumps, some of which had backup power to be used in the case of a transient. More recently, passive SFP systems, such as the one used at Gösgen nuclear power plant in Switzerland, can effectively cool SFP water for up to 72 hours [47]. A passive SFP cooling system consists of a wet cooling loop and a dry cooling tower. Passive systems' cooling capacity also limits the type of spent fuel that can be stored in the pool. Only fuel assemblies that have been cooled for several years are appropriate to be stored in pools with passive cooling systems.

As with the modification required of the SFP cooling water system, SFP electrical isolations must be implemented and new dedicated systems installed, including backup diesel power for the critical loads. Ancillary systems, such as fire protection, must be maintained while the SFPI is in service. As with other repowering-related projects, it is advised that all SFPI-related cables be color coded to avoid inadvertent events in the field [18].

Some facilities have created new, temporary motor control centers to provide power to the following:

- SFP cooling system pumps;
- Auxiliary service water system (heat sink for SFP cooling system);
- Heating, ventilation, and air conditioning components; and
- Liquid radioactive waste evaporator system.

Yankee Rowe installed a new 480 V transformer that was supplied from a 13.8 kV line. This plant repurposed a 175kW diesel generator set to supply backup power to SFPI systems [18].

The installation of a SFPI may be more complicated than establishing an ISFSI to store spent fuel at the facility. Additionally, the performance of any legacy systems that the SFPI uses must be evaluated as these systems may also have higher maintenance needs than newer systems. A major factor in these evaluations will be the anticipated service life for an SFPI: that is, the plan for when the fuel will be transferred to an ISFSI, to final storage at a repository, or sent to a reprocessing facility.

4.4.3 Transfer to Dry Fuel Storage

Completion of a decommissioning project requires the removal of the spent fuel to an off-site storage or reprocessing location, or to an on-site ISFSI. In addition to spent fuel, ISFSIs may also be used to store high activity waste, such as reactor internals.

A major consideration for when spent fuel can be transferred to an ISFSI is the time that the fuel bundle was removed from the reactor core. Fuel cannot be transferred to dry storage until decay heat levels are reduced to required levels. Bundles that have been stored for longer periods and are, therefore cooler, may be used as shielding for bundles of spent fuel that have more recently been removed from the core.

To meet off-site dose limits, fuel assemblies may be arranged in a cask with older bundles placed at the periphery to act as shielding for the more recent bundles in the center. This was the case at Kewaunee, where a loading pattern was adopted in which recently unloaded fuel assemblies of up to 1.8 kW were shielded by older fuel with a thermal rating of up to 0.8 kW [48].

Special cases, such as damaged, high-burnup, or underburned fuel can be stored in the casks, if precautions are taken. The bundles must also permit normal handling and retrieval from the cask and comply with criticality, thermal, and structural requirements [48].

4.4.4 Management of Cooling and Safety for Wet and Dry Spent Fuel Storage Systems

Requirements for successful long-term storage of spent fuel vary by method (wet or dry storage), although the ultimate goals are the same. Due to its passive design, dry storage of spent fuel in casks ultimately places fewer demands on the organization. This is a fundamental reason that many facilities that are required to manage their spent fuel in an interim on-site storage facility ultimately choose dry storage methods [10, 43].

Table 4-1 compares security, safety, and cooling methods between dry and wet storage systems.

Table 4-1
Comparison of security, safety, and cooling methods between dry (cask) storage and wet (pool) storage

Parameter	Dry Storage	Wet Storage
Security	Fuel is stored in canisters at a dedicated facility surrounded by multiple barriers. Video surveillance can augment security personnel tours. Security tours need not access contaminated areas, with the associated savings in time and costs.	Fuel is stored in a pool at a dedicated facility surrounded by multiple barriers. Video surveillance can augment security personnel tours. Security tours may require access to a contaminated area with time and cost implications.
Safety	Dry spent fuel storage is considered safe due to its passive design, which incorporates simple natural air circulation around the canister that is placed in a reinforced concrete structure.	Successful storage of spent fuel in pools is dependent on properly functioning cooling, water cleanup, and fire protection systems, as well as the integrity of the pool itself. The active systems may require redundancy and backup electrical systems. Some newer, independent wet storage systems allow for passive cooling of the pool for up to 72 hours in the event of a loss of power.
Cooling Method	Cooling of the multi-purpose canister that contains the fuel is through passive air circulation, so there are no active systems that may fail and potentially compromise safety.	Cooling of fuel in wet storage requires the integrity of the pool and properly functioning cooling and filtration systems. Passive cooling by natural circulation has been incorporated into the design of at least one independent, wet SFP system.

4.5 Primary References

The following documents serve as primary references on the topic of Site Preparations for Dismantlement:

[5] *Decommissioning Planning: Experiences from U.S. Utilities.* EPRI, Palo Alto, CA: 2006. 1013510.

[10] *Guidance for Transitioning from Operation to Decommissioning for Nuclear Power Plants.* EPRI, Palo Alto, CA: 2016. 3002007551.

[13] *Nuclear Plant Decommissioning Lessons Learned.* EPRI, Palo Alto, CA: 2010. 1021107.

[43] *Guidance for Establishing Safe Storage Conditions for Shutdown Nuclear Power Reactors.* EPRI, Palo Alto, CA: 2016. 3002008231.

Section 5: Decontamination

5.1 Decontamination (in Plant)

Appropriate decontamination efforts, in conjunction with proper dismantling techniques and an effective reuse and recycling program, can reduce the waste inventory thereby reducing costs [4]. Decontamination efforts focus on two general areas: mechanical decontamination of plant structures and chemical decontamination of plants systems such as the primary coolant loops and system components.

Specific objectives for any decontamination effort may include one or more of the following:

- Provide an overall reduction in personnel exposures;
- Minimize the volume of radioactive waste; and
- Free release SSCs so they can be recycled or reused.

Key to implementing a successful SSCs decontamination effort is a proper evaluation of the proposed method with regard to effects and goals, including the following [4]:

- Decontamination level to be achieved;
- Estimated dose from decontamination effort;
- Potential for airborne contamination (radiological and non-radiological);
- Likelihood for a successful decontamination campaign;
- Post-campaign contamination levels to be achieved;
- A cost–benefit analysis (such as the cost of the effort versus the savings achieved when disposing waste);
- Estimates of waste volumes to be generated, divided into categories: solid waste, radioactive waste, hazardous waste, and mixed waste;
- Applicability of the methodology to the material and the SSCs to be decontaminated;

- Potential negative effects of the decontamination method on the SSCs (especially important if the component is to be reused);
- Potential off-site and on-site effects associated with the decontamination campaign and the nature and cost of controls necessary to mitigate these effects; and
- Non-radiological hazards.

5.2 Chemical Decontamination of the Primary Coolant System and Components

Chemical decontamination is often performed early in a decommissioning project to lower dose to workers during subsequent dismantling of the facility.

For the decontamination of systems and equipment, processes such as Chemical Oxidation Reduction Decontamination (CORD) from Areva, Westinghouse's NITROX, and the EPRI-licensed Decontamination for Decommissioning (DfD) have been employed. A review of chemical decontamination experiences at decommissioning sites to date has led to the conclusion that it is difficult to compare results of FSD at different facilities because of variability amongst plants with regard to run time, systems, history of failed fuel, and decontamination scope [26]. A review of experiences using EPRI's DfD process yielded significant dose reduction (up to 92% dose savings) when used in projects ranging from decontamination of individual major components (e.g., heat exchangers and hold up tanks) to full system decontamination [49].

Permanently shut down facilities should perform a review to determine whether the facility would benefit from chemical decontamination efforts. The goal of the chemical decontamination project will depend on the system and its level of internal contamination. For primary systems, the chemical decontamination is performed to lower radiation levels for workers performing other decommissioning projects, as well as the effect of the chemical decontamination effort on shipping decontaminated systems for disposal. Chemical decontamination on components or subsystems may be performed with the goal of reducing contamination levels to the point that an individual component may be free released [4] or the waste classification reduced. In such cases, the target component would typically be decontaminated separately.

The evaluation that should be performed to provide adequate information to decision makers includes the following [4]:

- Recommendations on the feasibility of performing chemical decontamination on a given system relative to cost versus benefit;
- The scope of the chemical decontamination project for the system;
- A comparison of the available chemical decontamination methodologies;

- The potential effects of the chemical decontamination project on other decommissioning activities; and
- Benefit of the chemical decontamination compared to decay in storage if delayed decommissioning is the chosen strategy.

To estimate the dose reduction benefit of system chemical decontamination, planners must estimate the potential decontamination factor based on the system, isotope mix, and experience using the proposed chemical decontamination method. This evaluation should include consideration of the general area dose reduction factor, which also takes into account the dose to workers due to adjacent systems that either have not been or cannot be decontaminated. Planners must calculate the dose reduction factor for all areas adjacent to the system for which the decontamination is proposed to determine the true benefit of the decontamination project [4].

The base case for one licensee [16] was the total dose assuming that work proceeded without performing a full system chemical decontamination. The alternative case calculated the total dose after performing a chemical decontamination. Total doses for decommissioning were calculated as follows:

- Base case radiation exposure: 19.7 Sv (1,970 Rem)
- Alternative case radiation exposure: 9.35 Sv (935 Rem)

An additional step was undertaken by this licensee. The base case radiation exposure was compared to the NRC GEIS estimate for exposure required to decommission a PWR (11.2 Sv [1,115 Rem]) [20]. The NRC estimate includes the dose received during the transportation of waste to a repository. Because the base case estimated dose was significantly higher than the NRC GEIS estimate, the licensee decided to perform a chemical decontamination to lower the dose to workers.

Benefits of performing the chemical decontamination include the following:

- It is consistent with the ALARA philosophy to reduce personnel exposure to radiation.
- Project radioactive waste costs are reduced, and decommissioning activities can be performed more efficiently when dose rates and contamination levels are reduced.
- The site avoids the time and expense to prepare and receive approval of a plant-specific environmental impact statement from the NRC.

Lessons learned from full system decontamination projects performed after permanent shutdown include [16, 26]:

- Material conditions of plant components are key to the success of a full system decontamination. Full system decontamination should be undertaken as soon as possible after permanent shutdown to ensure that systems are still functional and that preventive and other maintenance is current. System failures add delays and cost to the full system decontamination and total decommissioning cost.
- Performing the full system decontamination early in the decommissioning project allows the site to use highly experienced staff to control the plant systems.
- Cooperation between the full system decontamination vendor and site staff is critical to a successful campaign.
- Use of cameras and telemetry to monitor equipment and personnel keeps personnel dose ALARA.
- Resin-loading needs to be closely monitored if the plant has significant transuranic activity in the oxide film.

5.3 Mechanical Decontamination of Plant Structures and Components

Due to costs associated with the disposal of large radiologically contaminated SSCs, physical decontamination may be used to mitigate the effects of disposal costs on the decommissioning budget. Decontaminated SSCs may be recycled or disposed in nonhazardous waste landfills, thereby significantly lowering costs. Mechanical methods for decontamination fall into two general categories [50]:

- Basic methods such as brushing, washing, scrubbing, or vacuuming; and
- Aggressive methods such as grinding, needle guns, concrete shaving, high-pressure liquids, high-pressure CO_2 pellets, and steel shot.

5.3.1 Concrete

Concrete decontamination can be a significant task during decommissioning due to the sheer volume of concrete used in commercial nuclear power plants [50]. This is especially true for facilities that do not have access to landfills that can accept radioactive concrete. Concrete can be contaminated by radionuclides in spills or leaks in the plant or through activation. For concrete that is not activated, with the exception of tritium, most contaminants will be found near the surface of concrete, making it possible to remediate the largest volume of the concrete simply by removing the contaminated outer layer.

5.3.1.1 Physical Removal of Contaminated Concrete

Contaminated concrete is commonly removed using mechanical means. These systems can be effective, although one must consider system weight, cost, effectiveness, and complexity [50]. Existing scabbling systems use abrasive grit or mechanical impact coupled with a vacuum system (to control contamination) to remove layers of concrete. Concrete wastes (grit in various waste sizes) are deposited in drums for disposal. Systems are heavy and are deployed using industrial forklifts, which also affects their ability to be deployed at elevation or where space is limited. Several mechanical removal technologies (such as piston-head scabbler and concrete spaller) were compared; costs ranged from U.S.$44/m^2 to U.S.$1,076/m^2 in 2000 [51].

In recent years, some companies have developed new systems in an attempt to address drawbacks to earlier systems such as weight, bulkiness, and generation of new waste streams. Examples of new technologies include using liquid nitrogen to ablate contaminated concrete [50] and similar use of lasers. The application of liquid nitrogen to ablate or scabble concrete has the following advantages:

- The density of pressurized liquid nitrogen is comparable to that of water.
- Nitrogen warms and becomes a gas at room temperature, so no liquid-phase waste is generated.
- The method will not generate mixed waste (assuming the substrate is not a mixed waste).
- If the aggregate used in the concrete is a silicate (such as quartz), there is potential that it may be free released as nonradioactive.

5.4 Primary References

The following documents serve as primary references on the topic of decontamination:

[26] *José Cabrera Nuclear Power Plant Full System Decontamination Experience Report.* EPRI, Palo Alto, CA: 2009. 1019230.

[49] *Experience in the Testing and Application of the EPRI DfD Process: Decontamination for Decommissioning of Reactor Coolant Systems and Plant Components*. EPRI, Palo Alto, CA: 1999. TR-112877.

[50] *Characterization and Remediation of Contaminated Concrete.* EPRI, Palo Alto, CA: 2015. 3002005412.

Section 6: Segmentation and Treatment of Large Components

Demolition and removal of SSCs is a major part of a decommissioning project. Various methodologies can be used, ranging from mechanical cutting of components to large-scale demolition [8]. Considerations for the choice of dismantling method depend on factors such as disposal options, dose, contamination levels, material being sectioned, and access to the component (that is, the effect of interferences on accessibility).

Examples of technologies used to section components include the following:

- Diamond wire to section the Fermi 1 reactor vessel and Rancho Seco steam generators and reactor head [52]
- Explosive charges to section a reactor building polar crane [8]
- A split-frame pipe lathe (clamshell) to section large-diameter piping [23]
- Reciprocating saws, carbide-tipped saws, and milling tools to section reactor internals [52]
- An abrasive water jet to section reactor internals [8]
- Thermal cutting techniques such as plasma arc and oxyacetylene cutting [54]

6.1 Segmentation of Irradiated Plant Components (Such as Reactor Internals)

One-piece disposal of large, highly irradiated components such as the reactor vessel and vessel internals is typically not practicable, and in many cases may not be permitted by the waste disposal authority. Thus, these components are generally segmented [53]. In addition to segmenting to meet waste acceptance and packaging requirements, segmentation is typically performed to segregate fractions of the components by waste classification. Activation levels may range from very highly active in regions closest to the core (activity concentrations greater than Class C (GTCC) levels by U.S. classification, or intermediate level waste (ILW) by IAEA classification), to no irradiation (surface contamination only). Very high activity waste is typically required to be managed similar to spent fuel, and thus stored in adapted dry storage canisters on the spent fuel storage installation (ISFSI).

6.1.1 Dismantling Reactor Internals

To minimize the amount of high activity waste generated (GTCC or ILW), segmentation of the reactor internals must be highly precise. Facilities recommend the following to ensure a successful reactor internals dismantling campaign [16, 18, 53]:

- Minimize the number of cuts required (cutting takes time and produces secondary waste);
- Evaluate the equipment to be used with regard to reliability and ease of use, particularly the cutting system and debris collection system;
- Develop a full-scale mockup and perform system checks to work out issues beforehand;
- Ensure that the cutting mast is stable for the most accurate cuts;
- Include radioactive waste department personnel in the planning stages of the project; and
- Maintain cavity cleanliness.

The following outlines the experience by one licensee's reactor internals segmentation campaign [22]. The intent of the campaign was to precisely determine which components would meet the definition of GTCC waste and, therefore, would be required to be stored in a cask on the ISFSI pad pending shipment to an ultimate repository. A vendor performed the reactor internals activation analysis and established the basis for determining the amount of material that had to be removed. Radiation protection field surveys were performed to corroborate the analysis, and another vendor performed the segmentation work in accordance with the licensee's approved plan.

Segmentation of the reactor internals was performed using remote-controlled abrasive water jet and metal disintegration machining devices. Segmented GTCC pieces were placed into licensee-designed canisters. Debris and fines from the dismantling process were captured, and pool clarity was maintained within project required specifications. The campaign resulted in the following project statistics:

- Time to complete: one year
- Craft hours: 59,500
- Personnel exposure: 0.224 Sv (22.4 Rem) of a budgeted 0.772 Sv (77.2 Rem)
- Lost time or recordable injuries: none

This demonstrates that successful planning allowed the project to efficiently identify, dismantle, and package the reactor internals GTCC waste into a minimal number of canisters. The project initially planned for two canisters; however, only one canister was needed for the project.

Licensees have encountered significant difficulties during various reactor internals sectioning projects. The challenges were mostly technology-specific and, in the case of abrasive water jet technology, attributed to the use of a system that was not technologically mature, although it had been used at other facilities [16].

6.1.2 Dismantling Reactor Vessels

Methods for sectioning reactor vessels include abrasive water jet as well as thermal and mechanical cutting. An evaluation of different methods of reactor vessel sectioning was performed by one licensee. The licensee evaluated the different segmentation options based on the following criteria [52]:

- Cutting speed which affects project duration and cost;
- Secondary waste generation which affects cost;
- Vapor generation;
- Accuracy;
- Depth of cut; and
- Contractor experience

Based on this evaluation, this licensee chose robotically controlled abrasive water jets to segment the reactor vessel. One drawback for this sectioning method was identified: this technology uses a water jet to which an abrasive (garnet, a silicate commonly used to coat sandpaper) was added. The wet garnet abrasive generated large volumes of a low-activity radioactive waste that caused some issues with collection and drying for disposal.

Other licensees have used underwater mechanical section of the reactor vessel, as well as reactor vessel internals, because of the following advantages: [53]

- Very little secondary waste is produced;
- Visibility is good; and
- Airborne contamination from gases released during sectioning is not an issue.

Current practice favors use of mechanical cutting techniques for both the reactor vessel and vessel internals, although thermal and abrasive water jet methods continue to be successfully employed.

6.2 Segmentation of Irradiated Concrete Structures

Concrete and the associated reinforcing steel represent the largest amount of waste generated, by volume and weight, at most decommissioning projects. For example, approximately 75,000 m^3 (2.65 million cubic feet) of concrete are used in the construction of the average commercial power reactor [50]. BWRs have the potential to generate more radioactively contaminated concrete waste than PWRs due to their larger radiological controls area (RCA), which is inherent in the design.

Concrete in the RCA may be surface contaminated by isotopes typically present in the reactor coolant (cobalt-60, cesium-137, etc.). Additionally, gaseous contaminants such as tritium and carbon-14 may diffuse deeper into the concrete. In areas near the core, concrete may be activated and thus volumetrically contaminated with radioisotopes such as calcium-45 and europium-152, as well as cobalt-60 and iron-55 in the associated reinforcing steel [50].Characterization of licensed material in concrete can be through any combination of direct sampling, modeling of sampling results, and surveys by technicians using traditional meters or in-field gamma spectroscopy systems. In general, characterizing concrete through surveys can be done only after the relative concentrations of the radionuclides present have been characterized through a formal sampling program.

Because of the potential for cross-contamination of adjacent areas when sectioning contaminated concrete, a method must be chosen that minimizes the spread of radioactive dust, or contains hazardous byproducts and debris during cutting activities. Diamond wire technology was successfully used to section large concrete components at one facility. This licensee cited the following benefits of diamond wire cutting technology over competitive technologies such as jackhammers and hoe rams [23, 50]:

- It creates little dust;
- It is a quiet technology; and
- It has little vibration (vibration can weaken the surrounding structure)

To further minimize the generation of contaminated dust and to keep the wire cool, water is added to the cutting surface. The slurry generated can be directed to drums for drying and then disposal.

6.3 Segmentation of Large Contaminated (Non-irradiated) Components

Large contaminated components (such as steam generators, moisture separators, reactor coolant pumps, or pressurizers) at nuclear plants usually must be at least partially dismantled to allow them to be transported to a disposal facility. Dismantling technologies are similar to those described elsewhere in this section (see also Reference [54]). Major considerations are contamination control and resealing the sections for transportation [16, 23].

Because of the size of these components, the project plan must be laid out in detail. Specific considerations include the following [23, 52]:

- Transportation requirements, such as interferences or transportation mode limits, which will determine the size of the sections;
- Cranes to be used for the lifts within and outside the containment;
- Insulation, piping, and interference removal;
- Use of techniques for reduction of internal contamination in the components;

- ALARA planning;
- Technology to be used to segment components;
- Cutting openings in containment;
- Planning lifts inside containment;
- Preparation and removal from containment; and
- Preparation of components for shipping.

Selection of the disposal facility for the large components will determine the transportation methods available. This, in turn, will determine the dimensional limits of the segments, as well as any weight limits.

6.4 Primary References

The following documents serve as primary references on the topic of Segmentation and Treatment of Large Components:

[13] *Nuclear Plant Decommissioning Lessons Learned*. EPRI, Palo Alto, CA: 2010. 1021107.

[23] *Trojan PWR Decommissioning. Large Component Removal Project.* EPRI, Palo Alto, CA: 1997. TR-107916.

[50] *Characterization and Remediation of Contaminated Concrete.* EPRI, Palo Alto, CA: 2015. 3002005412.

[53] *Recent United States and International Experiences in Reactor Vessel and Internals Segmentation.* EPRI, Palo Alto, CA: 2012. 1023024.

[54] *Characterization and Management of Cutting Debris during Plant Dismantlement*. EPRI, Palo Alto, CA: 2016. 3002005410.

Section 7: Dismantlement of Plant Systems and Small Components

In addition to large facility components, such as the reactor and concrete structures, smaller components, such as ventilation, cooling, and hydraulic systems must be dispositioned. Although such systems are generally smaller, and more easily sectioned and disposed, planning for dismantlement is important and should include:

- Sequencing the removal of SSCs to avoid impacts to systems that are still operational.
- Characterization to determine presence and levels of radioactive contamination as well as hazardous, or toxic, constituents of concern.
- Determining the technology to be used to dismantle the SSCs. Considerations are safety, cost, contamination control, speed, and experience with a given technology.
- Safety to personnel to guard against hazards specific to the dismantling technology chosen and other physical hazards associated with work on a given SSC, as well as possible exposure to radiation from the system being removed, or adjacent systems that are still operational.
- Waste generated by the dismantling technology chosen. For example, some cutting technologies generate large amounts of spent grit, potentially a new waste stream that may cause challenges to disposal management.

7.1 Characterization of SSCs to Support Dismantling

Characterization of SSCs for radioactive contamination and hazardous constituents of concern should be performed during the site HSA and include characterization activities as described in Section 3. Proper advanced characterization of SSCs is key in determining Personnel Protective Equipment (PPE) requirements, ALARA controls, and disposal options. Planning the dismantling of a given system should not proceed if there is doubt about the adequacy of the characterization of the system, as unknowns can add significantly to project delays and unanticipated materials management costs.

7.2 Technology Options for Dismantling SSCs

Sectioning SSCs for transportation and disposal can be performed using methods as diverse as plasma arc, oxygen lance, rotary saw, clam-shell cutters, and abrasive water jet. Each method, whether a thermal or mechanical, has its advantages and disadvantages depending upon the specific application [54].

Rancho Seco Nuclear Generating Station (RSNGS) evaluated the different segmentation technologies in preparation of segmenting the plant's reactor vessel, as presented in Section 6.1. Some of the technologies evaluated by RSNGS were found to be appropriate for use in sectioning plant systems. The results of evaluations of relevant technologies are presented in Table 7-1 [55].

Table 7-1
Comparison of advantages and disadvantages for different sectioning technologies.

Sectioning Technology	Advantage	Disadvantage
Plasma Arc Current flowing through a tungsten electrode heats a gas, usually argon, hydrogen, or helium. The gas is accelerated to sonic velocity through a nozzle. This high velocity, high temperature gas (approx. 15,000 °F, 8316 °C) is used to cut the metal.	• Clean, accurate, cuts • Can be used with robotic arm • Generally limited to manual use • Can pierce holes for rigging	• 5-inch (12.7 cm) thickness limit • Generates potentially radioactive vapors • Secondary waste stream generated • Requires local exhaust hood for vapor control
Carbon Arc/Air Carbon Arc Current flowing through a carbon or graphite electrode melts the metal and the force of the arc, gravity, or pressurized air removes the molten metal.	• No thickness limit • Fast cutting • Can pierce holes for rigging	• Generates potentially radioactive vapor • Difficult to use with robotic arm due to electrode • Consumable electrode difficult to replace with robotic arm • Secondary waste generated • Requires local exhaust hood for vapor control
Oxygen Arc Current flowing through a tubular electrode creates a molten puddle of metal and pressurized oxygen is used to remove the metal. The electrode is consumed in the process.	• No thickness limit • Fast cutting • Can pierce holes for rigging	• Generates potentially radioactive vapor • Consumable electrode difficult to replace with robotic arm • Secondary waste generated • Requires local exhaust hood for vapor control

Table 7-1 (continued)
Comparison of advantages and disadvantages for different sectioning technologies.

Sectioning Technology	Advantage	Disadvantage
Oxy-Fuel Gas Oxygen and Fuel Gas, usually acetylene, is used to melt the metal and remove the molten metal.	• Equipment readily available (Manual)	• Is an ALARA concern if used manually • Generates potentially radioactive vapor • Limited to 10-inch (25.4 cm) thickness • Difficult to use with robotic arm • Secondary waste stream • Requires local exhaust hood for vapor control
Laser Laser uses a highly concentrated beam generated from the excitation of a laser material, CO_2, or ruby, to melt the material being cut. A high pressure inert gas stream removes the molten material.	• Accurate clean cut • No consumable electrode	• Limited material thickness approx. 0.75 inch (1.9 cm). • Generates potentially radioactive vapor • Requires local exhaust hood to vapor control
Mechanical/Rotary Saw A large mechanical saw is used to cut the material. Saw blade is moved by hydraulic, or mechanical, method.	• Does not generate vapor • Conceptually simple	• Material being cut must be held rigid • Slow cutting speed and may be unknown
Diamond Wire Cylindrical shaped pieces of industrial diamonds are threaded over a steel cable to form a continuous blade. The wire cuts the material by use of a hydraulic motor and a series of rubber faced pulleys attached to the material.	• Does not generate vapor • Good for cutting concrete	• Requires difficult setups to make horizontal cuts • Cutting speed is very slow • Needs starter holes cut by another method for feeding wire to the cutting surface

7.3 Safety Evaluation to Support Dismantling

Safety concerns when dismantling systems and small components include occupational safety issues such as exposure to heat, debris, working at elevation, workings being struck by objects that are being sectioned, or cuts and burns. ALARA concerns include direct radiation from adjacent systems, or exposure to airborne radioactivity as systems are being sectioned. Worker safety is a primary concern and plays a large role in choosing the best dismantling technology for a given project.

Furthermore, many plants were constructed when lead-containing paint was widely used and PCB paints were used in specialized applications. These paints may need to be removed (abatement) from areas where components are being sectioned to comply with regulatory requirements (prevent the generation of dioxin from PCBs) and/or eliminate, or at least reduce, worker exposure to hazardous or toxic material that could potentially be volatilized during section of components as well as to prevent cross-contamination of adjacent areas.

7.4 Waste Disposal Options for Debris from Dismantling Operations

Debris produced from the dismantling of plant systems and components has several disposal options depending on the base material (e.g., carbon steel, lead, or concrete) as well as the type and concentration of contamination.

Metal debris can generally be recycled if it passes clearance criteria for radioactivity even if it is coated with lead paint. If the paint on the debris contains PCBs it may need to be removed before the metal can be recycled, though the costs of stripping paints may lead to the decision of having the debris disposed in a licensed landfill.

Radiologically contaminated debris disposal options may be more limited and recycling may not be an option at all. Few landfills are licensed to accept radioactive debris and restrictions on land disposal of radioactive debris which is also contaminated with hazardous or toxic constituents of concern include treatment or encapsulation before it can be placed in the landfill.

Debris that will be landfilled may be comingled with non-debris material such as used sandblast grit, soiled rags, fasteners, …etc. which may be subject to a percentage-based quantity limit (e.g., not to exceed a certain percentage by weight or volume of the debris) which is set by disposal facility in the Waste Acceptance Criteria documentation.

7.5 Primary References

The following documents serve as primary references on the topic of Dismantling of Plant Systems and Small Components:

[54] *Characterization and Management of Cutting Debris during Plant Dismantlement*. EPRI, Palo Alto, CA: 2015. 3002005410.

[55] *Rancho Seco Vessel Segmentation Experience Report.* EPRI, Palo Alto, CA: 2008. 1015501.

Section 8: Demolition of Large Contaminated Structures

8.1 Contaminated Building Demolition

Structures that are completely outside the RCA, and unlikely to be contaminated with licensed material, can generally be demolished using techniques similar to those used for other industrial facilities. Confirmatory characterization of such facilities must be undertaken to ensure that undocumented leaks or spills of licensed material did not occur. Once radioactive contamination has been confirmed not to be present, the primary contamination concern for these buildings is the potential presence of hazardous, toxic, or regulated substances (e.g., asbestos, etc.) that require systems, structures, or components to be sampled and characterized to ensure proper management and disposal of regulated materials. Ideally, the results from building characterization for radioactive and nonradioactive constituents should be considered together in the development of building management and demolition plans, although the characterization efforts may be completed in separate phases.

Buildings that formed RCA boundaries require additional steps to ensure that contamination is not spread during their demolition. Based on the Historical Site Assessment and characterization surveys, distribution of licensed material within these structures should be well understood. The degree of contamination in these buildings, as well as an inventory of regulated materials, will assist in determining factors for management planning such as contamination control, exposure control, and methods employed to dismantle the buildings. Several methods have been used to dismantle potentially contaminated buildings, including hoe rams, torches, and shaped charges (explosives).

Licensees have successfully used explosives (shaped charges) to dismantle the reactor building, including some major SSCs within the RCA. For these organizations, explosive demolition was a viable method that increased the speed (threefold to fivefold) at which the facility is decommissioned. Using explosives on site warrants extra measures, such as strict control over the explosives [8].

Another licensee, based on their evaluation of project costs, solely used hoe rams to demolish the reactor building [16]. They stated that licensees that used explosives to demolish their reactor building also needed to use hoe rams to cut openings in the side of the reactor building to weaken the structure enough to then use explosives to bring the rest of the building down. By continuing the process with hoe rams, including using an armored excavator and hoe ram to take out the final concrete piers, this licensee's final demolition cost was less than that for explosive demolition and just as safe. This is the most common approach to building demolition.

The use of mechanical or explosive means of demolition requires area and objective-specific financial, engineering and safety analysis to arrive at the most cost-effective, practical and safe approach for particular structures at each site.

8.2 Dismantling Concrete Structures at Multi-Unit Sites with Operating Reactors

Although dismantling concrete structures at single-unit sites has challenges, those issues are magnified at sites that still have additional operating reactors. System interfaces at multiple unit sites can involve all the units, posing an increased risk to the unit systems that are still operating as decommissioning proceeds at the facility being dismantled. Financial evaluation of the between-unit integration aspects of decommissioning should be conducted well in advance, as some licensees have found the integration process is too expensive, and therefore delayed decommissioning until both plants were ready for permanent shut down.

The following case of multi-unit staged decommissioning illustrates some of the challenges involved and how the use of a QA risk-weighted, performance-based model was beneficial to a successful outcome. In this case, the licensee with a multi-unit site decided to implement prompt decommissioning after managing one of the reactors as a permanently shut down reactor in delayed decommissioning for several years [22]. This licensee successfully managed a complex project to remove a concrete containment building while two other reactors were still operating within several hundred feet of the permanently shut down reactor. Furthermore, as an additional complicating factor, the site's fuel storage building was adjacent to the concrete building that was scheduled for demolition.

The structure to be removed was a concrete building that was 46 m (151 ft) in diameter and 28 m (93 ft) tall, with 0.9 m (3 ft) thick walls. The building was installed around the original steel containment as a seismic category A reinforced structure, heavily reinforced with steel. An engineering analysis was performed, and it was determined that the demolition could proceed under certain constraints. The primary concern was protection of the adjacent fuel storage building during demolition of the seismic category A reinforced structure.

To safely dismantle the concrete building, the building wall was divided into four zones, each with its own requirements under which dismantling activities could occur. Before the dismantling activities were initiated, safe load paths were established to ensure that heavy lifts were not conducted over or adjacent to the fuel storage building or spent fuel modules. This licensee identified that successful completion of the project was due in part to QA's independent oversight of the project. QA used a risk-weighted, performance-based model to evaluate work and provide focus on critical phases of the job.

8.3 Primary References

The following documents serve as primary references on the topic Demolition of Large Contaminated Structures.

[8] *Maine Yankee Decommissioning Experience Report. Detailed Experiences 1997–2004.* EPRI, Palo Alto, CA: 2005. 1011734.

[16] *Connecticut Yankee Decommissioning Experience Report. Detailed Experiences 1996–2006*. EPRI, Palo Alto, CA: 2006. 1013511.

[22] *San Onofre Nuclear Generating Station—Unit 1 Decommissioning Experience Report. Detailed Experiences 1999—2008*. EPRI, Palo Alto, CA: 2008. 1016773.

[50] *Characterization and Remediation of Contaminated Concrete.* EPRI, Palo Alto, CA: 2015. 3002005412.

Section 9: Management of Decommissioning Wastes

9.1 Decommissioning Wastes

Management of decommissioning wastes is a major aspect of decommissioning projects [56]. The availability of waste disposal options is the primary criteria in determining disposal costs, and hence the decommissioning budget. Since disposal facility capacity has decreased with time, disposal costs have risen and availability of facilities has decreased with time. For these reasons, some licensees have opted for immediate dismantling to ensure that treatment, storage, and disposal facilities, which are a limited commodity in most countries, are available for receiving all likely waste streams [18].

The decommissioning of a nuclear facility generates a wide variety of waste streams with different chemical, physical, and radiological characteristics. Reasonable estimates of disposal costs depend on an accurate assessment of the volume and/or weight of these waste streams, and should be established as early in the site characterization process as is feasible. This section of the report focuses on decommissioning wastes, excluding spent fuel, which is discussed separately (see Section 4.4).

The types of wastes that can be generated include non-radioactive, radioactive, non-hazardous, hazardous, or mixed-hazard wastes (such as wastes exhibiting both hazardous and radiological characteristics). Furthermore, a decommissioning site generates solid-, liquid-, and mixed-phase wastes (a combination of solids and liquids, not to be confused with mixed waste).

Radioactive wastes are separated into the following categories [57]:

- Low-level waste (LLW)
- Intermediate-level waste (ILW)
- High-level waste (HLW)

In the United States, LLW can be further divided into four classes [58]:

- Class A (the lowest level)
- Class B
- Class C
- Greater Than Class C (GTCC) which is ultimately the responsibility of the federal government

Both radiological and non-radiological wastes at decommissioning sites must also be evaluated for non-radiological contaminants that may contain hazardous (such as heavy metals or spent solvents), toxic (such as polychlorinated biphenyls [PCBs]) or regulated (e.g., asbestos) constituents that drive management and/or disposal. In some instances, the presence of a non-radiological regulated material alone may dictate options for management or disposal. In other instances, the presence of a hazardous or regulated constituent may not impact disposal unless the condition, or concentration, of the constituent triggers a regulatory management threshold. If waste stream characteristics trigger regulatory criteria for management as both hazardous and radiological waste, the waste must be managed according to other regulations appropriate for mixed wastes. Generally, the presence of hazardous or toxic constituents of concern complicates waste handling, limits disposal options, and increases costs. Therefore, minimizing the generation of mixed wastes through cross-contamination during decommissioning is highly desirable.

Hazardous elements and regulated compounds can be found in a variety of decommissioning wastes from buildings and structures such as paint, caulk, insulation, floor and ceiling tiles, gaskets, used oil, sludges, or dry active wastes. Due to the age of many nuclear facilities and the lack of regulations in the past regarding materials that are now designated as hazardous or toxic elements and compounds, the presence of these constituents of concern should be anticipated in many waste streams associated with older buildings and structures (see Reference [44] for discussion on this topic).

9.1.1 Waste Disposal Options

One of the first tasks regarding waste management at any site is the evaluation of disposal options. This is in large part dictated by the availability of a treatment, storage, and disposal facility for each waste stream. The disposal options available to a licensee for wastes generated by a decommissioning project can be quite limited, especially if the waste is characterized as mixed waste.

Disposal options for liquid radioactive wastes depend on factors such as total activity, the radionuclides present, whether the liquid is aqueous or non-aqueous, and volume of waste. Disposal options for liquid wastes include combustion and solidification, stabilization, and placement in a licensed landfill. Non-aqueous liquids, such as oils and spent solvents, usually must be characterized and shipped to a licensed vendor for treatment.

In most countries, disposal of bulk solid waste may require encapsulation or solidification before being placed in a licensed disposal facility. Debris, being solid and stable, may have alternate requirements that are easier to achieve; therefore, more disposal options may be available. Depending on the treatment, storage, and disposal facility and the characteristics of the debris, the debris may be required to be encapsulated before disposal.

Some decommissioning wastes are amenable to recycling, and this approach should be used if a processor is available. Metals such as lead or steel can be recycled, even if slightly contaminated, to produce shielding, waste drums, or other components for use at nuclear facilities [56]. Plant decommissioning of building and structures can generate large volumes of non-impacted concrete, including the foundations that can sometimes remain in place, and a large portion of the non-impacted asphalt, brick or concrete may be rubblized and re-used to fill foundations, structural voids or as fill in regrading [15].

Table 9-1 provides an overview of general waste management options used in various countries [59], and it shows the variability in approaches to managing LLW, ILW, and HLW. Another category, very-low-level waste (VLLW), which is less active than LLW, is also managed in several different ways in Europe. Spain, Sweden, and the United Kingdom implement free release (clearance) and allow surface disposal of VLLW. These countries also permit recycling, or reuse, to minimize waste. German regulations allow clearance and recycling and conditional disposal of some slightly radioactive wastes in landfills, but Germany does not recognize the VLLW category. French laws do not allow clearance, but France manages slightly contaminated or indeterminate wastes as VLLW at licensed facilities. In the United States, local and state regulations may dictate requirements for recycling and re-use of non-radiological solid wastes.

9.1.2 Regulatory Requirements

Regulations determine how the wastes are characterized, classified and managed. The degree of sampling required relative to the volume of waste to be disposed is also often determined by regulation, but also by the treatment and disposal facility receiving the waste, which may have other operational criteria (such as limits of substances in emissions from the waste combustion or destruction) that must be met.

Licensees must understand the regulations in their country that apply to the different wastes that will be generated during decommissioning. If plans require that wastes be sent for treatment or disposed in another country, the regulations for international transport must be understood, as well as additional requirements of the country in which the waste treatment and disposal will take place. In some countries or regions, individual states impose requirements that are more restrictive than those at the federal or regional/state level. Finally, criteria for hazardous or radioactive constituents can vary between regulations for waste characterization, transportation of hazardous materials, or personnel exposure levels.

The European Union has a set of requirements for the various aspects of managing radioactive waste; the requirements are provided in a Council Directive published in 2011 [60]. This document lists requirements of the European Union member states to generate their own regulatory framework to regulate nuclear power, including the management of radioactive waste. Table 9-2 provides an overview of agencies that regulate radioactive waste in several countries.

Table 9-1
Radioactive waste management options for select countries

Country	Disposal Options	Waste Management Options
Belgium	• Near-surface disposal at nuclear facilities for LLW • Studies are under way (2016) for deep storage of ILW and HLW as well as spent fuel	• LLW and ILW storage: Belgoprocess, Dessel • HLW (vitrified): Belgoprocess, Dessel • Spent fuel: At the nuclear facility
Canada	• Near-surface disposal for LLW and ILW. • Studies are under way (2016) for deep storage of ILW and HLW as well as spent fuel	• LLW and ILW from all Ontario reactors at the "Western Waste Management Facility" • Spent nuclear fuel from Bruce Power at the "Western Waste Management Facility" • Spent nuclear fuel from Pickering at the Pickering Waste Management Facility • Spent nuclear fuel from Darlington at the Darlington Waste Management Facility
Finland	• Near-surface disposal for LLW and ILW • Deep geological repository for HLW	• Construction of rock characterization facility began in 2004 • Operation of deep geological repository to commence in 2020
France	• LLW and ILW in shallow or surface disposal at several sites • HLW and spent fuel in deep geological repositories	• One deep geological repository to be constructed and operational in 2025 and two further repositories planned
Germany	• Interim storage at nuclear facilities • Long-term subsurface disposal for radioactive waste and spent fuel	• Konrad (former iron-ore mine) for radioactive wastes with "negligible" heat generation • Gorleben Salt Dome for radioactive waste, currently being evaluated for HLW
Japan	• Near-surface disposal for LLW and ILW • Deep geological disposal of vitrified residues from spent fuel reprocessing	• LLW at Japan Nuclear Fuel Ltd. at Rokkashomura • Deep geological repository in planning stages (Nuclear Waste Management Organization)

Table 9-1 (continued)
Radioactive waste management options for select countries

Country	Disposal Options	Waste Management Options
Sweden	• Underground storage of LLW and ILW • Spent fuel stored in pools (Interim storage facility) • Deep geological repository to be built	• LLW and ILW stored under the Baltic near Forsmark plant at SFR • Spent fuel stored in pools located in a cavern at a central storage facility near Oskarshamn plant • Östhammer deep geological repository to be located near Forsmark plant
United Kingdom	• LLW at near-surface repository • HLW from reprocessing stored in vitrified form • ILW and HLW to be stored in deep geological repository	• LLW stored at Drigg (Cumbria) since 1958 • HLW currently stored at Sellafield until cooled (est. 50 years) • Currently planning for location of deep geological repository
United States	• LLW in near-surface repositories managed by private companies • Interim storage of spent fuel and GTCC wastes at the nuclear facilities in dry storage installations (a few facilities use wet [pool] storage) • Deep geological repository for spent fuel and GTCC wastes	• Several LLW facilities in various states • Spent fuel and GTCC at the nuclear facilities pending deep geological repository or reprocessing • No plans since Yucca Mountain, Nevada, not to be used

Source: World Nuclear Association [59]; 2016 data

Table 9-2
Radioactive waste regulators for select countries

Country	Regulators
Belgium	• Federal Agency for Nuclear Control (FANC) • Belgian Agency for Management of Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS)
Canada	• Canadian Nuclear Safety Commission (CNSC)—regulator for federal facilities • Natural Resources Canada—responsible for radioactive waste management
Finland	• Radiation and Nuclear Safety Authority (STUK)—regulator • Ministry of Employment and the Economy—responsible for radioactive waste management
France	• French nuclear safety authority (Autorité de Sûreté Nucléaire [ASN])—regulator • Ministry for Ecology, Energy, Sustainable Development and Town and Country Planning (Le ministère de l'Écologie, de l'Énergie, du Développement durable et de l'Aménagement du territoire)—responsible for radioactive waste management
Germany	• Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU])
Japan	• Nuclear Regulatory Authority • Japan Atomic Energy Commission • Ministry of Economy, Trade and Industry—responsible for radioactive waste
Sweden	• Swedish Radiation Safety Authority
United Kingdom	• Health and Safety Executive's Nuclear Directorate—regulator • Environment Agency—regulator • Scottish Environmental Protection Agency—regulator • Department for Energy and Climate Change—responsible for radioactive waste
United States	• Nuclear Regulatory Commission • Environmental Protection Agency • Department of Energy

Source: World Nuclear Association [59]

9.1.3 Waste Management Plan

A decommissioning waste management plan should include the following [56]:

- A characterization sampling, materials classification and waste inventory plan;
- Waste disposal means and methods;
- A strategy to establish a process for determining whether SSCs should be decontaminated or disposed;
- A decision point should be established to determine whether *in situ* decontamination benefits—such as reduced occupational dose, ease of dismantling, or less expensive disposal options—are greater than dismantling and disposal of the contaminated SSCs;
- Options and plans generation, staging, packaging and transport including trucking frequencies and transportation routes;
- A method for staging and short-term storage of wastes on site;
- An evaluation of how the decommissioning project sequence will affect waste management; and
- Contingency plans for situations in which waste is generated at a rate greater than it can be shipped for disposal.

The first step in developing an effective waste management plan for plant decommissioning is to complete a comprehensive characterization of building, systems and structures that will support identification and classification of waste types, locations, estimated volumes and evaluation of management and disposal options. Key elements of an effective characterization plan include a comprehensive summary of applicable regulatory requirements influencing waste identification and classification, sample distribution requirements, sample types, sampling methodologies, minimum sample size, sample preservation requirements, lower limits of detection that influence the minimum sample size and Quality Assurance requirements.

9.2 Reduction, Treatment, Packaging, and Shipping of Decommissioning Wastes

It is imperative to accurately characterize the volume of each waste stream generated at a decommissioning facility because of the costs associated with handling these wastes and their disposition. Furthermore, because radioactive, and especially mixed, wastes have fewer and more expensive disposal options, efforts such as decontamination or volume reduction may be cost effective. Many disposal sites determine costs by waste volume, so compaction of low-density radioactive waste may be advisable.

Because of the limited waste disposal options and costs associated with radioactive and hazardous wastes, licensees should consider methods for volume reduction. The question of whether it is more cost-effective to perform the compaction at the facility or contract the work to an off-site vendor should be evaluated. One licensee evaluated the cost of installing equipment for compacting asbestos waste on site and concluded that, after all regulatory requirements were met, the costs would exceed those to have the material sent to a licensed vendor for compaction before disposal [18].

Decommissioning of a nuclear facility will produce a large quantity of slightly contaminated concrete debris. One licensee estimated that approximately 136 million kg (350 million lbs) of debris would be generated during the decommissioning project. Experience has shown that when the site demolishes large concrete structures such as the turbine building, reactor building, and radioactive waste building, debris is generated at a greater rate than it can be shipped off site for disposal [16].

Concrete can be partially decontaminated to allow the bulk of the material to pass free release criteria, which is desirable because of the cost savings associated with dispositioning non-radioactive concrete. Successful decontamination techniques include scabbling, high-pressure washing, and shaving. In some cases, contamination is limited to coatings that had been applied to the concrete or it may be present only within 2 to 5 cm (1 to 2 in.) of the surface. However, in the case of activation products in bio-shields or tritium contamination, the bulk of the concrete is contaminated, and removal of surficial layers is not effective [50].

Most of this debris will be sent to licensed facilities for land disposal in engineered cells. These facilities are generally quite a distance (thousands of kilometers [miles] is not uncommon) from the decommissioning site, so transportation becomes a major issue from a time and cost perspective. However, if the contamination levels of the debris are sufficiently low, materials may qualify for disposal at some controlled landfills nearer to the site, thereby increasing the rate of disposal and lowering transportation costs. Sites should explore the latter option because the savings could be substantial.

Shipping options vary depending on the location of the decommissioning site. The most efficient option to ship radioactive debris is by rail because the volume and weight limits are much higher than for trucks. However, some sites do not have adequate rail access, so waste may have to be shipped by truck to a transfer station where it can be loaded onto rail cars. Depending on the waste profile, waste management at the transfer station could require the transfer facility to be licensed. Because of extremely low contamination levels in debris from one site, the licensee was able to use a transfer facility that did not possess a license to handle radioactive material. When that transfer facility was used, the licensee had the radiation protection technicians survey the facility at least weekly to ensure that it had not become contaminated.

Waste form also plays a role in disposal costs. For example, in the U.S., disposal facilities will charge less for materials that can be used for fill around debris, so it may be economical to have some of the concrete debris crushed into gravel size and remove the rebar for recycling, as appropriate, before disposal, or for use on site as fill in filling building voids or regrading as part of site restoration.

9.3 Recycling of Decommissioning Wastes

Recycling of decommissioning waste can provide considerable cost savings. Although recycling options are more plentiful for non-radioactive wastes, some facilities will recycle some radioactive wastes such as steel and lead. It may be appropriate to attempt to decontaminate metals to allow components to be recycled. Methods that have been successfully implemented to decontaminate metal SSCs and debris include the following [56]:

- *In situ* chemical decontamination.
- Post-dismantling decontamination in specialized enclosures with air filtration, as appropriate, to minimize the spread of contamination, using the following:
  - High-pressure water;
  - Grit blast; and
  - Dry ice (CO_2) beads.
- Removal of surface contamination (planing) on bulk lead.

Care should be taken that components with the potential for activation products be evaluated to ensure that decontamination by surficial removal of contamination is adequate to allow for free release or clearance (as applicable).

Evaluation of contamination in SSCs and debris can be performed by facility radiation protection personnel as part of their clearance duties. However, the workload during decommissioning can be quite high at times, leading management to hire more qualified, temporary staff or consider off-site processing at a central facility or a vendor site [56].

In Spain, a method-based approach was used to assay hundreds of metric tons of scrap metal for free release. The Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual (MARSAME) method–based survey design was used to reduce the amount of contaminated metal scrap and debris to be disposed as radioactive waste [61]. The project resulted in 692 metric tons (763 tons) of metal debris being cleared for recycling and 0.54 metric tons (0.6 tons) being sent for disposal as radioactive waste. Based on data quality objectives established, measurement times using a collimated high-purity germanium detector were 300 seconds for each measurement; that is, less than one hour per container and 600 seconds for each surface activity measurement. The total cost for the project was €3.7 million, compared to a cost of €6.9 million for sending all the metal debris for disposal as radioactive waste [61].

9.4 Primary References

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Section 10: Site Remediation and Release

The goal of a facility decommissioning project is to remediate the contaminated SSCs and media (e.g., contaminated soils or groundwater) on the property so that radiological conditions required for license termination are met. At NRC licensed power reactors, regulation requires that no member of the critical group receive a post-closure dose of more than 0.25 mSv per year (25 mrem/yr) Total Effective Dose Equivalent (TEDE) from all dose pathways [62]. There is an additional requirement that an evaluation be performed to determine the level of effort or additional remediation that may be necessary to meet the ALARA requirements. Each facility, however, has its own release standards that must be met because state or local standards may be lower than federal levels (e.g., Massachusetts requires licensees meet a TEDE of 10 mrem/yr). International standards differ from those of the United States, with the European Union using the IAEA release dose limit of 0.3 mSv per year (30 mrem/yr), although the limits may vary among member states of the European Union [63].

After the release criteria for a facility have been negotiated, site remediation must be undertaken to meet that limit. Remediation actions include removal of SSCs, soils, bedrock, and groundwater, as appropriate. Some SSCs may undergo decontamination to achieve release criteria limits. Upon completion of remediation activities, the Final Status Survey (FSS) is conducted to verify the effectiveness of the remediation in meeting license termination criteria to allow the regulatory authority to terminate the license.

10.1 Establishing Site Release Criteria

Dose rate–based release criteria have an inherent complication: one cannot measure the TEDE; rather, it must be determined based on the following:

- Source term;
- Exposure scenario; and
- Exposure pathways.

The licensee must first establish the end use of the property in coordination with the current/future owner after license termination. This end use is referred to, for the purpose of license termination, as the *exposure scenario*. Exposure scenarios vary from continued use as a nuclear facility (least restrictive) to nonnuclear industrial use, to resident farmer (the most restrictive). Bear in mind that the release criteria annual dose stays constant; however, the number and type of exposure pathways and the duration of exposure each year vary depending on the exposure scenario [64].

Significant exposure pathways for the critical group can include any, or all, of the following [64, 65]:

- External dose from direct exposure to contamination in soil;
- Internal dose due to inhalation of radionuclides;
- Internal dose from ingestion:
  - Vegetables grown in contaminated soil or irrigated with contaminated water;
  - Milk and meat from livestock grazing on the property;
  - Contaminated drinking water (surface water or groundwater, as appropriate);
  - Fish and other aquatic life from contaminated surface water such as a pond on site; and
  - Inadvertent ingestion of contaminated soils.

For the resident farmer scenario, any of these pathways whereby contamination is transferred to the critical receptors and is a source of dose may be active. These pathways must be evaluated for the facility to determine which ones are credible. Other possible exposure scenarios, based on the end use of the site, are the following [65]:

- Suburban resident;
- Industrial worker; or
- Recreational.

These exposure scenarios differ from the resident farmer in that the exposed individuals spend less time on site, and fewer exposure pathways are applicable. Table 10-1 shows how different exposure pathways are typically considered, depending on the exposure scenario. This is a generic evaluation; all pathways should be evaluated at a specific site for a specific exposure scenario. Conditions at that site may not meet the general assumptions and provide a basis for further consideration of pathway elimination.

Table 10-1
Exposure pathways to consider for residual radioactivity exposure scenarios

Pathway	Resident Farmer	Suburban Resident	Industrial Worker	Recreationist
External gamma	Yes	Yes	Yes	Yes
Dust inhalation	Yes	Yes	Yes	Yes
Ingestion, vegetation	Yes	Yes	No	No
Ingestion, meat	Yes	No	No	Yes
Ingestion, fish	Yes	No	No	Yes
Ingestion, soil	Yes	Yes	Yes	Yes
Ingestion, milk	Yes	No	No	No
Ingestion, water	Yes	No	No	No

Source: *User's Manual for RESRAD Version 6* [65]

Because of the different characteristics of radionuclides in the environment, in large part due to their chemical attributes, the source term must be well characterized for the site. This includes nuclides and their abundance, form, and distribution. Because the total effective dose equivalent (TEDE) cannot be measured, but must be calculated, activity limits for the different radionuclides by contaminated medium must be determined. A standard for performing these calculations is software developed at the Argonne National Laboratory (RESRAD). The RESRAD software can be used to calculate these activity limits, referred to as *derived concentration guideline levels* (DCGLs), by performing a backward calculation [64]. The concept, in general, is that the total dose limit (TEDE) is distributed among the existing exposure pathways to calculate a concentration limit. These DCGLs are then used in field surveys to determine whether the required post-remediation levels have been achieved to support license termination.

10.2 Remediation of Land Areas

If facility-related radionuclides are found in soils and rock, they generally must be removed, or remediated, to achieve the DCGL for license termination. The amount of effort required depends on the radionuclides, their abundance and distribution, and the DCGL that must be attained. Alternatively, a deed restriction could be pursued to limit use (eliminate exposure pathways) and support a restricted site closure, but such restrictions generally require approval from regulators and public stakeholders.

Two techniques for remediating land areas have been used. The first method is to begin removal without prior characterization and perform continual surveys of materials during removal in the field until results indicate that materials above the DCGL are no longer present [16]. During use of this approach at one site, ultimately, 33,000 m^3 (1.17 million ft^3) of rock and soil were required to be removed and disposed as radioactive waste before DCGLs were met at the excavation boundary. Alternatively, advanced characterization prior to removal and the use of geostatistics to estimate waste volumes, as well as the vertical and lateral extent of contaminants in the subsurface can be completed in advance of removal actions. This approach allows managers to estimate remediation and disposal costs, as well as manpower and equipment costs, in the remediation planning phase prior to execution.

Basic techniques available for remediating soils include the following [66]:

- Immobilization using the following methods:
  - Stabilization (grouting);
  - Solidification (*ex situ* vitrification); and
  - Containment (engineered barriers).
- Extraction:
  - Soil washing; and
  - Solvent extraction
- Destruction:
  - Thermal processes; and
  - Oxidative techniques.

10.3 Remediation of Surface Waters and Sediments

Contamination of surface waters can be challenging whether the system is lentic or lotic. Lentic systems (such as ponds and lakes) are natural sinks and relatively high-water residency (low turnover) compared to lotic systems (such as streams and rivers). Lentic systems act as natural sinks and can sequester contaminants in their sediments. Lotic systems (such as streams and rivers), with their low residency time, tend to flush and dilute contaminants, although there is a risk that the contaminants may be re-concentrated if water velocity decreases.

Because surface waters are commonly used as a source of water for drinking, cooking, or cleaning, stakeholder concerns are usually quite high if surface waters become contaminated with radionuclides from a leak, or spill, in excess of the legal allowable limits. Because of the difficulty in remediating radionuclides from surface waters, containing the source physically or hydrologically may be the only recourse.

Sediment contamination due to leaks or spills are often handled in a similar fashion as is done with soils or bedrock via removal actions. Other options include stabilization and monitored natural attenuation. By their nature, sedimentary deposits are sinks and will sequester contaminants. The primary risk comes from the potential for the sediments to be disturbed or if redox conditions allow any radionuclides that are present to become mobilized and migrate.

10.4 Remediation of Groundwater

Groundwater contamination at nuclear facilities can occur while the facility is operational and during decommissioning as a consequence of leaks or spills of licensed material. If groundwater monitoring at the facility was not required during the operational phase, or if the groundwater monitoring well network was required only at the site boundary to ensure that a contaminant plume was not migrating off site, the first indication of an issue may be discovered during the HSA.

To illustrate the value of having an on-site groundwater monitoring program, one should consider the following example. One site discovered groundwater contamination during decommissioning that added U.S.$35 million in transportation and disposal costs to the project to remediate the contaminated soils, bedrock, and groundwater. Ancillary costs for the remediation activities were on the order of U.S.$15 million. If the contamination had been discovered when it first occurred, the situation could have been mitigated at that time to limit the extent of contamination [16]. Early detection of plant-related radionuclides can only occur if the site has an adequate on-site groundwater monitoring program.

Most NPPs are located in relatively close proximity to a surface water body which generally acts as a receiving water body for discharge of groundwater. Therefore, radiological impacts to groundwater may migrate along relatively short flow paths and discharge to surface water where few if any potential receptors may exist. Depending on the concentrations of radionuclides in groundwater and groundwater/surface water interactions, discharge to surface water may result in dilution to levels below thresholds of concern, allowing for a monitored natural attenuation (MNA) remedy for groundwater.

Remediation of groundwater contamination may be one of the more challenging aspects of a decommissioning project; however, that depends on the radionuclides, their respective activity, the size of the plume relative to the facility size, and site geological and hydrogeological characteristics. The chemical characteristics of radioisotopes determine the degree to which they will disperse in the environment. Tritium (hydrogen-3) and strontium-90 will be quickly transported away from the source in groundwater due to their low partitioning coefficient (K_d), whereas cesium-137 will bind with clays in the soil. This portioning of the different radionuclides in a contaminant plume can affect the characterization of the plume, as well as its effective remediation.

Groundwater remediation can take several forms, ranging from monitored natural attenuation to pumping and treatment. The appropriate response depends on radionuclides and hydrogeology, as well as regulatory requirements and stakeholder negotiations.

10.5 Final Status Survey

The FSS is performed after site remediation has been completed. The FSS determines whether the residual radioactivity in the survey unit complies with the radiological release criteria [68]. It is a standard method that uses field surveys and statistics to determine whether the remediation activities have been successful.

The FSS is the final step in the sequence that begins with the HSA. This process is described in MARSSIM, which is the standard for this research [69].

The MARSSIM method has the following advantages over earlier survey methods [69]:

- Use of dose- or risk-based release criteria, which are converted to derived concentration guideline levels;
- Use of data quality objectives;
- Use of methodology and scan sensitivity for FSS design to identify potential hot spots;
- Use of nonparametric statistics in the hypothesis-testing framework; and
- Use of international guides (such as ISO-7503 [70]) to generate technically defensible surface activity measurements.

DCGLs are limits that are generally translated to thresholds that can be compared to field measurements such as surveys or from discrete samples, as appropriate. DCGLs are translated from regulatory and negotiated final dose-based site limits through pathway analysis.

A MARSSIM-based survey design includes the following [69]:

- Recommends the use of nonparametric statistics;
- Begins with the identification of the radionuclides of concern and determination of whether any of those might be present in the background;
- Divides the site into one of three classes, which can be further divided into survey units [69]:
    - Class 1. Areas that either currently have, or may have had prior to remediation, contamination from radionuclides of concern above release criteria. These areas are likely to have some residual contamination (>DCGLs).
    - Class 2. Areas that either currently have, or might have had prior to remediation, contamination from radionuclides of concern but below release criteria (<DCGLs).
    - Class 3. Areas that were part of the facility's industrial area but are unlikely to contain any residual radioactivity or only a small fraction of the release criteria (<<DCGLs).

One of the largest FSS efforts performed was at the Oak Ridge K-31 and K-33 gaseous diffusion plants. This effort required more than four years to complete. Because the facility was to be reused, the final disposition scenario was industrial use, with the appropriate reductions in exposure pathways and the effects of that on DGCLs [71]. Lessons learned included the following:

- Characterization of the facility must be integrated into the decommissioning project at the start.
- Background activity levels and instrument sensitivity vary throughout the project. Mechanisms to assess those changes, as well as the technical bases, should be established before the start of the survey.
- Databases should be used to manage data for the project. Data to be maintained include survey metadata as well as data from the actual surveys.

An issue when developing the FSS is the determination of "non-impacted" areas on the site. An example of such an evaluation was performed for the Yankee Nuclear Power Station (Yankee Rowe) decommissioning project [18]. Yankee Rowe was one of the first commercial nuclear power plants in the United States. Although it was located on an 890-hectare (2200-acre) site in Massachusetts, the plant itself only occupied 4 hectares (10 acres) of the site. A project was undertaken to determine the boundary between the non-impacted area and the affected area (Class 3). For this evaluation, the following steps were initially performed:

- Review of the annual Radiological Environmental Monitoring Program reports;
- Review of past site use history and aerial photographs;
- Estimates of possible plant-related radionuclide concentrations in soils, based on data from permitted radioactive gaseous effluents; and
- Review of soils data from early scoping surveys.

To support the assessment based on the review of various lines of historical data, 30 samples and measurements were taken in the survey unit designated as "non-impacted" as a confirmation step. The results of these surveys showed that no plant-related radioisotopes were found in the non-impacted areas, with the exception of cesium-137. The cesium-137 values were consistent with those found in the background survey area, so the occurrence of the cesium-137 in the non-impacted areas was attributed to fallout from nuclear weapons testing [18].

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