Chapter 9
Nuclear Facilities, Decommissioning of

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Glossary

Decommissioning	Nuclear decommissioning is a term used to describe the process of removing a nuclear facility or site safely from service and reducing residual radioactivity to a level that permits (1) release of the property for unrestricted use and termination of the license or (2) release of the property under restricted conditions and termination of the license. Although waste classification and management is an important aspect of decommissioning, the details of radioactive waste management and disposal are not addressed in this article.
Decontamination	The removal of undesired residual radioactivity from facilities, soils, or equipment, prior to the release of a site or facility and termination of a license. Also known as remediation, remedial action, and cleanup.
Exposure pathway	The route by which radioactivity travels through the environment to eventually cause radiation exposure to a person or group.
Financial assurance	A guarantee or other financial arrangement that ensures funds for decommissioning will be available when needed.

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Institutional controls	Administrative and physical measures to control access to a site and minimize disturbances to engineered measures established to control the residual radioactivity.
Monitoring	The measurement of radiation levels, concentrations, surface area concentrations, or quantities of radioactive material and the use of the results of these measurements to evaluate potential exposures and doses.
Nuclear fuel cycle	Consists of the different stages necessary to produce nuclear power. Specific stages include (1) the *front end* of the nuclear fuel cycle where uranium is mined and fuel is prepared, (2) the *service period* in which the fuel is used during reactor operation, and (3) the *back end*, which involves safe management, containment, and either reprocessing or disposal of spent nuclear fuel. Because uranium fuel is the most common type of nuclear fuel, this article focuses on the uranium nuclear fuel cycle.
Radiological survey	An evaluation of the radiological conditions and potential hazards at a site related to the production, use, transfer, release, disposal, or presence of radioactive material or other sources of radiation. Radiological surveys can be used to provide the basis for acquiring necessary technical information to develop, analyze, and select appropriate cleanup techniques.
Residual radioactivity	Radioactivity in structures, materials, soils, groundwater, and other media at a site resulting from activities under the licensee's control, excluding background radiation.

Definition of the Subject

The process of safely shutting down, dismantling, cleaning up, and monitoring nuclear facilities is collectively known as nuclear decommissioning. Nuclear power has been used as a source of energy for more than 50 years, and more than 500 nuclear reactors have been constructed and operated worldwide [1]. In addition to power plants, the nuclear fuel cycle requires different types of facilities to mine uranium, produce fresh nuclear fuel, and manage spent nuclear fuel and associated radioactive wastes after the fuel can no longer be effectively used to produce power. Many of the facilities associated with the nuclear fuel cycle that supports these reactors, as well as the reactors themselves, have either reached or are approaching the end of their planned service life. Also, some countries such as Belgium and Germany have initiated national policies to phase out nuclear power over time [2, 3]. Owners and operators of nuclear facilities, as well as government agencies responsible for their regulation, must evaluate economic and public policy considerations to determine whether to renew facility licenses or to permanently remove facilities from service, and decommission them to release the sites for other potential uses.

Definitions of nuclear decommissioning, radiological dose limits for site release, and even terminology can vary from country to country depending on the nature of the laws and regulations that govern the nuclear fuel cycle. The International Atomic Energy Agency (IAEA) defines decommissioning as "…the administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility" [4]. Similarly, the Nuclear Energy Agency (NEA) broadly defines decommissioning as covering "all of the administrative and technical actions associated with cessation of operation and withdrawal from service" [1]. The World Nuclear Association (WNA) defines the two main objectives of decommissioning as rendering the site permanently safe and restoring it, "as far as practicable," for reuse for nuclear or non-nuclear activities. Reuse can apply to different components of a nuclear facility, including land, water bodies, buildings, equipment, and materials [5].

Some early nuclear facilities were developed without explicit consideration of decommissioning, and these "legacy" sites continue to be identified and cleaned up – often at public expense. As it is currently practiced in most nations with a robust legal and regulatory framework, the decommissioning process begins when a facility is removed from service. Planning for decommissioning should begin at the design stage, before a facility enters operation [4, 6]. For example, early decisions about construction materials, site layout, spill prevention and control measures, waste management, and financial assurance can all influence decommissioning activities at the end of a facility's life cycle and may be made (or be required) before a facility receives an operating license. Similarly, some national nuclear regulatory programs require that decommissioning plans be submitted with the initial license application and periodically reevaluated and updated during the operating life of the facility [6, 7]. Decommissioning is generally considered complete when the facility is removed from regulatory control (e.g., the license is terminated) and the site is made available for reuse.

The processes and technologies are similar to those used for other industrial facilities, but because of the nature of the materials used in the nuclear fuel cycle, nuclear decommissioning tends to be a regulated process that requires special procedures to handle and dispose of radioactive materials safely. The specific methods used in nuclear decommissioning vary widely, depending on factors such as the type, size, age, operational history, and design of a given nuclear facility. National policies differ on detailed objectives, and individual countries are likely to have different issues of concern such as the future use of nuclear power, the continued availability of trained staff, socioeconomic effects on surrounding communities that may result from shutting down a large facility, and financial issues associated with funding decommissioning activities.

For these reasons, there is no unique or preferred "one size fits all" approach to the nuclear decommissioning process. The intent of this article is neither to endorse any particular approach, nor to describe all potential aspects of nuclear decommissioning in detail, but rather to provide a broad overview of generally applicable principles. Further, this article focuses on decommissioning facilities associated with the commercial-scale production of nuclear power. Other processes that use or generate nuclear materials such as military programs, nuclear medicine, and industrial operations that produce radioactive materials as a byproduct are beyond the intended scope of this discussion. The reader is referred to the references identified in the Bibliography for further information and more detailed discussion of the processes described here.

Introduction

In 2007, nuclear reactors provided slightly more than 14% of the world's electricity, with ranges as high as 76.8% in France [8]. Currently (July 2009), 436 nuclear power reactors are in operation, with 5 reactors in long-term shutdown and 48 new reactors under construction [9]. In addition to nuclear reactors, generating nuclear power requires different types of facilities to support the nuclear fuel cycle. For example, as of August 2003, the IAEA reported that there were 423 operating nuclear fuel cycle facilities, with 19 more under construction. Eventually, decisions will need to be made with regard to closing and decommissioning these facilities in a safe manner and potentially returning the land to other uses.

More than 50 years after the first nuclear power reactor went on line, many of the facilities associated with commercial-scale nuclear power generation are now approaching the end of their planned service life. For example, the European Union estimates that at least one-third of the 152 nuclear power plants operating in its member countries will need to be decommissioned by 2025 [2], and the IAEA reported that 297 nuclear fuel cycle facilities were shut down or in the process of being decommissioned worldwide as of August 2003 [4]. An even larger number of manufacturing and research facilities (about 1,600) that use radioactive material will need to be decommissioned "over the coming decades" [10].

At the same time, increased global energy demand, coupled with a growing concern about the effects of carbon emissions from traditional fuel sources, has sparked renewed interest in nuclear power generation. As an example, the U.S. Nuclear Regulatory Commission (USNRC), the agency responsible for licensing and regulating commercial nuclear activities in the United States, received a total of 17 applications to construct and operate 26 new commercial nuclear reactors during 2007–2008 [11]. Although some countries are deemphasizing nuclear power, other countries in Europe and Asia have indicated a renewed interest in nuclear power as a component of their overall energy portfolio [3, 8, 12].

Together, these developments indicate that all stages of the commercial nuclear fuel cycle will continue to be active or will be expanded in the foreseeable future. For this reason, methods to safely take these facilities out of service and decommission them will continue to be an important component of energy policy. It is these methods that are the subject of this article.

Although primarily developed for nuclear power plants, there are three basic types of alternative decommissioning strategies that may be applicable to other nuclear facilities:

- A strategy of immediate decontamination and dismantlement [1, 7] (also defined as DECON [11, 13]) begins soon after the nuclear facility closes.
- Safe storage [1], deferred or delayed decontamination [7], or SAFSTOR [14, 15] refer to decommissioning strategies where a nuclear facility is left intact after closing, placed in a stable condition, and maintained and monitored until subsequent dismantlement and decommissioning. Similarly, uranium production facilities (mines and mills) may be placed on standby status when uranium prices are low and deposits cannot be produced at a profit.
- A strategy of entombment [1, 7] or ENTOMB [14, 15] involves encasing radioactive materials onsite in a long-lived, structurally sound material such as concrete.

The first two strategies may also be combined. For example, some facilities at a site may be immediately dismantled while other structures are placed in safe storage. Generally, decommissioning activities are anticipated to be completed in a period of decades from the end of operations [14, 15].

Once the decommissioning strategy is selected for a given facility, general activities associated with nuclear decommissioning may include:

- Characterizing the features of the site and conducting radiological surveys to determine radiation background and residual radiation levels
- Developing a site-specific decommissioning plan
- Estimating cost
- Conducting safety and performance assessments
- Decontaminating structures, equipment, and components for reuse or recycling
- Dismantling and removing buildings, structures, and equipment from the site
- Remediating contaminated soils and groundwater
- Performing waste management and disposal
- Conducting final inspections and surveys
- Reclaiming disturbed lands
- Implementing active institutional controls and monitoring

Specific decommissioning activities and technologies are determined on a case-by-case basis and can depend on many things at a given site, such as the duration, type, and scale of operations; the geologic setting of the site; socioeconomic considerations; and the regulatory policies of the government. In addition, a key part of a decommissioning plan is estimating decommissioning costs to establish financial arrangements that ensure resources are available to complete the decommissioning process.

Types of Nuclear Facilities

As described in the ”Introduction” section, generating electricity from nuclear power plants is only part of the nuclear fuel cycle [16] and decisions will need to be made with regard to the safe closure and decommissioning of each of these

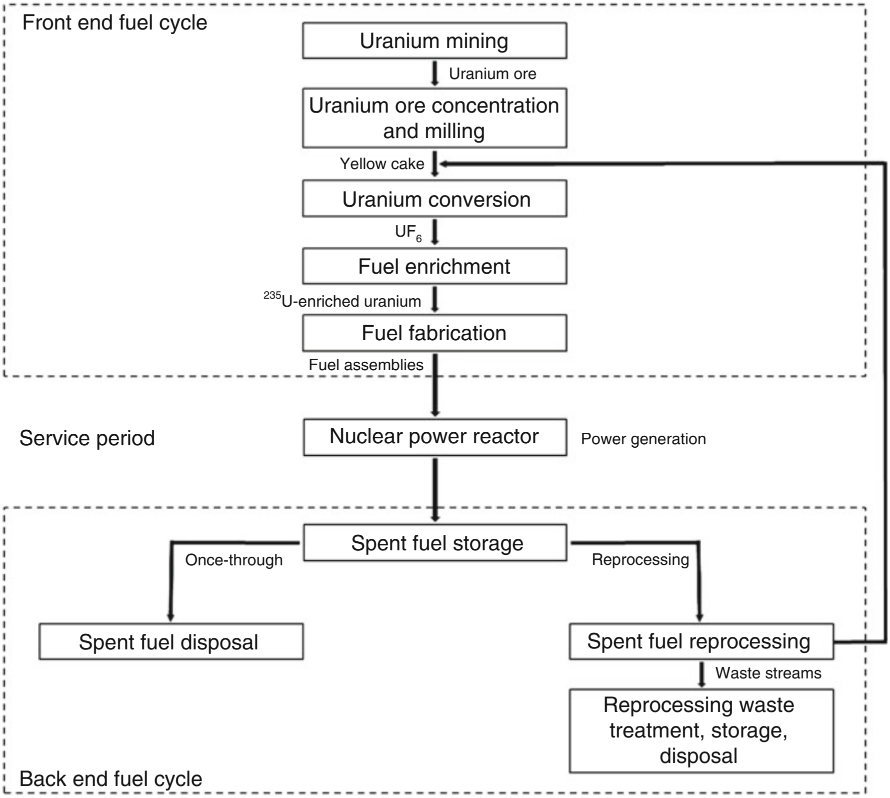

Fig. 9.1 Simplified diagram representing the nuclear (uranium) fuel cycle

facilities. To understand any unique aspects that will need to be addressed during nuclear decommissioning, it is important to describe the general nature of the activities that are conducted at each type of facility in the nuclear fuel cycle. Because uranium fuel is the most common type of nuclear fuel, this article focuses on the uranium nuclear fuel cycle (Fig. 9.1).

To support the nuclear fuel requirements of commercial power-generating facilities, there are facilities that

- Produce uranium by mining
- Mill ore to concentrate the uranium and package it for transportation
- Purify and transform the uranium concentrate into a form suitable for fuel manufacture through a process called uranium conversion
- Enrich the uranium in isotopes (^{235}U) that produce sustainable nuclear reactions
- Fabricate reactor fuel components and fuel assemblies

These facilities are part of the "front end" of the nuclear fuel cycle. Decommissioning issues for the front end of the fuel cycle are typically associated

Table 9.1 Material balance for the annual operation of a 1,000 MWe nuclear power reactor [17]

Type of nuclear facility	Material balance[a]
Mining	20,000 metric tons (22,000 t) of 1% uranium ore
Milling	230 metric tons (250 t) uranium oxide concentrate (U_3O_8) containing 195 metric tons (215 t) of uranium
Uranium conversion	288 metric tons (317 t) uranium hexafluoride (UF_6)
Fuel enrichment	35 metric tons (39 t) UF_6, containing 24 metric tons (27 t) enriched uranium (4% U-235), 11 metric tons (12 t) depleted uranium (0.25% U-235) tails
Fuel fabrication	27 metric tons (30 t) UO_2, containing 24 metric tons (30 t) enriched uranium
Reactor operation	8,640 million kilowatt-hour electricity at full output (assuming 100% load factor)
Spent nuclear fuel	27 metric tons (30 t) spent nuclear fuel containing 23 metric tons (25 t) uranium (0.8% U-235 as UO_2), 240 kg (529 lb) plutonium, 720 kg (1,587 lb) fission products, and transuranic elements

[a]Assuming enrichment to 4% U-235 with 0.25% tails assay; core load 72 metric tons (79 t) U, refueling so that 24 metric tons (26 t) U/year replaced; operation – 45,000 MWday/t (45 GWday/t) burn-up, 33% thermal efficiency

with naturally occurring radioactivity, such as uranium and radium, and hazards associated with the chemical processing of natural uranium-bearing ores [5].

After the nuclear fuel is used in a commercial reactor to produce electrical power during the service period, the management of the spent nuclear fuel at the "back end" of the nuclear fuel cycle can include facilities that

- Reprocess the fuel to extract nuclear materials and recycle uranium back into the front end of the fuel cycle
- Store or permanently dispose of spent nuclear fuel

At the back end of the fuel cycle, high-level sources of radioactivity and direct irradiation from spent nuclear fuel are decommissioning concerns in addition to natural radioactivity and chemical processing hazards [5]. An example of the typical material balance for the annual operation of a 1,000 Megawatt electric (MWe) nuclear power reactor [17] is included in Table 9.1.

Each of these facilities will require nuclear decommissioning at the end of its life cycle. Usually, the operator of a facility develops a decommissioning plan (see "Developing a Site-Specific Decommissioning Plan") to identify specific activities, estimate costs, and lay out a schedule [18–21]. The plan is submitted to the regulatory agency to ensure that it complies with the applicable regulations. Once it is approved, the initial decommissioning plan is periodically updated and becomes more detailed as the facility evolves during its operational life. At the end of the facility life cycle, the decommissioning plan serves as a blueprint for the nuclear decommissioning process. During decommissioning, the regulatory agency may periodically inspect the site to ensure that the decommissioning plan is being implemented correctly.

The following sections introduce the types of nuclear facilities associated with generating nuclear power and identify features that may influence nuclear decommissioning decisions and activities. The listing is not intended to be exhaustive, nor is it intended to provide a detailed discussion of the complex regulatory controls that may apply for a given type of nuclear facility. The reader is referred to the references identified in the Bibliography for further reading.

Front End Fuel Cycle Facilities

Uranium Mining

At the start of the nuclear fuel cycle, uranium mining focuses on extracting natural uranium ore from the earth. Uranium mining may be done through a conventional process of excavation by open pit or underground mining techniques. During excavation, uranium ore is segregated from waste rock or overburden, and shipped to a uranium mill for further processing (see "Uranium Milling"). Open pit and underground uranium mines are typically decommissioned and reclaimed in accordance with regulations applicable to the mining industry in general [22]. In many ways, decommissioning a uranium mine is subject to challenges similar to those faced in cleaning up mining operations for other resources such as coal and metals. For example, excavations may need to be backfilled, pit walls and disturbed surfaces recontoured, and revegetated to meet applicable mine reclamation standards. Groundwater contamination plumes with elevated levels of uranium and associated heavy metals (e.g., arsenic, selenium) need to be remediated and monitoring systems installed, as appropriate.

Alternatively, uranium recovery may be through a process called in situ leaching (ISL), where chemical fluids are injected through a series of wells into the subsurface to dissolve uranium from ore minerals. The now uranium-enriched solution is pumped back to the surface for subsequent extraction and processing [13, 22–24]. Decommissioning of ISL uranium facilities is different from cleaning up conventional uranium mining operations. For example, because there are no large-scale excavations associated with the ISL uranium recovery technology, surface land disturbance is much less than with conventional mining methods, and large amounts of waste rock are not generated. This can simplify the reclamation effort, but impacts to groundwater are potentially greater, and restoration of groundwater quality to premining levels tends to be a focus in decommissioning ISL facilities [13]. In addition, although the surface facilities such as well heads and pump houses necessary to support ISL uranium mining may be small compared to conventional operations, the well fields themselves may be very large. For example, the permitted areas for U.S. ISL operations in Wyoming and Texas may be as large as 6,500 ha (16,000 acres) and individual well fields may contain hundreds to thousands of wells [13].

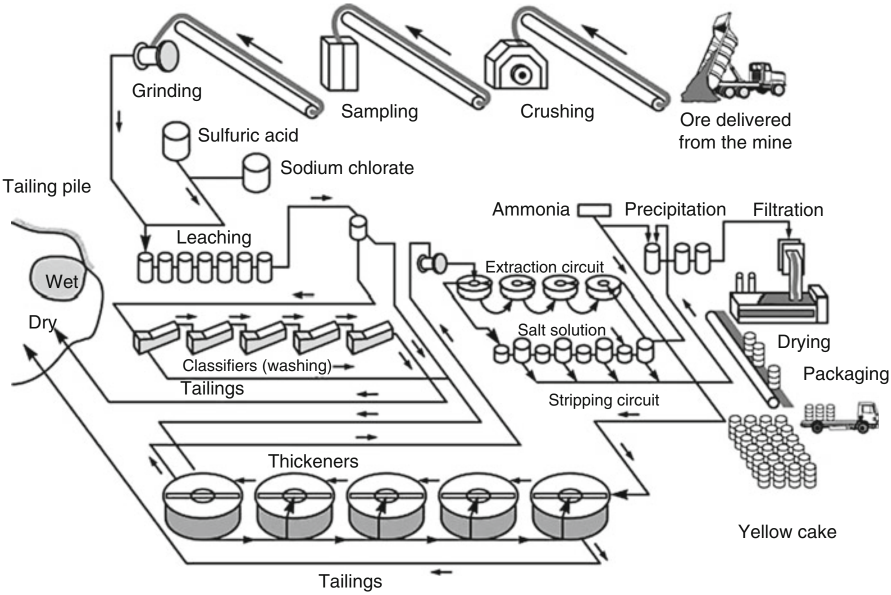

Fig. 9.2 A typical conventional uranium mill [22]

Uranium Milling

While varying depending on the deposit and the type of ore, uranium ores typically have a concentration of about 1% or less uranium (U_3O_8) by weight, although it can be as high as 20%. Decommissioning uranium milling facilities is generally concerned with naturally occurring radioactive elements such as uranium, thorium, and radium. For conventional uranium mining and milling operations (Fig. 9.2), uranium is concentrated through milling (crushing, grinding, separation) and subsequent chemical processing of the ore using alkaline or acid leaching solutions to produce a product called "yellow cake," a coarse powder that is approximately 70% or more U_3O_8 by weight. Milling operations are similar for ISL uranium, but because the mill input is uranium-bearing solutions instead of solid ore, the crushing and grinding, and leaching circuits are not necessary.

Depending on the economics of the operation, a mill may be colocated with a uranium mine, or it may be separate, charging a "toll" to accept and mill ore (conventional) or uranium-bearing solutions (ISL) from nearby uranium mines. Because of the throughput of uranium-bearing solutions and the handling of yellow cake, some of the buildings, pipes, and equipment in the mill may become radioactively contaminated with natural radioactive elements over time and will need to be decontaminated and/or disposed of during decommissioning. Spills and unintentional releases of uranium-rich solutions can lead to soil and groundwater contamination that may need to be remediated during decommissioning. In addition, during conventional milling, large quantities of waste solids are produced by the crushing, grinding, and leaching circuits. These waste solids, or "tailings," are placed in large impoundments that will also need to be decommissioned at the end of the mill's operational life. ISL facilities do not treat solid rock and therefore produce no tailings. Because these facilities handle large volumes of uranium-rich solutions, however, they may have one or more evaporation ponds that will eventually need to be decommissioned. Although specific activities will vary depending on size, age, operational conditions, and design, decommissioning of a uranium mill (both for conventional and ISL facilities) includes general activities described in the "General Methodologies for Decommissioning" section.

Uranium Conversion

Although natural uranium ores are concentrated and purified during milling to produce yellow cake, the uranium must be further purified and converted to a gas state to produce nuclear fuel. The nature of these chemical processes and the size and complexity of these uranium conversion facilities strongly influence the decommissioning process. Uranium conversion facilities are designed to remove impurities from the yellow cake and convert solid uranium into uranium hexafluoride (UF_6), the only uranium compound that exists as a gas at suitable temperatures [4, 17]. The UF_6 gas is then pressurized and cooled to a liquid state [4]. The liquid is stored in cylinders and allowed to solidify for shipment to a fuel enrichment plant (see "Fuel Enrichment"). Some uranium conversion facilities also recycle uranium scrap that may come from manufacturing facilities or other production plants [4].

The uranium conversion process involves strong acids and alkali agents to dissolve the yellow cake powder. As with mining and milling, the operational risks associated with uranium conversion are chemical as well as radiological, and the safe removal and disposal of hazardous chemicals used in the conversion process must be taken into consideration as part of the decommissioning process. Because it is predominantly an industrial chemical facility, the types of decommissioning issues for a uranium conversion facility are similar to those described in the "Uranium Milling" section for buildings, equipment, and land reclamation at uranium mills. No tailings are produced during uranium conversion. Groundwater and soil contamination from spills and leaks are possible and will need to be identified, remediated, and monitored in accordance with applicable regulations [19]. The size and complexity of uranium conversion plants can lead to significant decommissioning costs. For example, alternative decommissioning options for the 243-ha (600-acre) Sequoyah Fuels uranium conversion plant site in Gore, Oklahoma, varied from about US $19 to US $254 million (2006 dollar value), depending on the option selected for disposal of contaminated materials [25].

Fuel Enrichment

Natural uranium is composed of ^{238}U (99.274%) and ^{235}U (0.711%) and contains trace amounts of ^{234}U (<0.01%). Nuclear reactor fuel requires increasing (or enriching) the fissionable ^{235}U above these natural levels to sustain the nuclear reactions. During the fuel enrichment process, gaseous UF_6 is gradually enriched in ^{235}U to about 3–5% – levels that are sufficient for fabricating commercial reactor fuel [26, 27]. One product of the enrichment process of special concern during decommissioning is depleted uranium tails, where the ^{235}U content has been reduced to below natural levels (about 0.2–0.35%) [28]. This waste stream is commonly stored at the site in gas cylinders of UF_6, although it may also be converted to solid form such as uranium oxide. Depleted uranium emits low levels of radiation and is also a toxic heavy metal, so during decommissioning, this waste must be managed and disposed in accordance with both radiological and hazardous waste criteria [27, 29].

Gaseous diffusion is the process most widely used for nuclear fuel enrichment. The gaseous diffusion process takes advantage of the different diffusion rates that result from the slight differences in mass for ^{238}U and ^{235}U. Gaseous UF_6 is pumped through a permeable porous barrier media. The lower molecular weight ^{235}U has a higher diffusion rate and moves through the barrier media more readily than the higher molecular weight ^{238}U; the UF_6 gas that passes through the media is therefore slightly enriched in ^{235}U [30]. The process is repeated through many barriers until the desired enrichment levels are achieved.

These types of plants are large industrial facilities, with a footprint of about 300–600 ha (750–1,500 acres) that contains a large amount of piping and pumps required to move the UF_6 gas through the permeable barrier system [4]. During operations, the primary hazards in gaseous diffusion plants that may influence subsequent decommissioning include the chemical and radiological hazard of a UF_6 release [31]. There is also a potential for mishandling the enriched uranium, which could create a criticality accident (inadvertent nuclear chain reaction). Because these are large facilities, decontamination and decommissioning of inactive buildings and areas may occur while other parts of the facility continue to operate. Surveillance, maintenance, and security will continue for active parts of the facility. Depending on the operating history of the plant, including spills and unintentional releases, decommissioning and cleanup activities at fuel enrichment facilities may include assessing and remediating soil or groundwater and waste management activities, such as disposing of contaminated materials. The size and complexity of a gaseous diffusion plant can lead to large costs for full decommissioning of all facilities. For example, the U.S. Government Accountability Office (GAO) estimated that cleanup activities at three fuel enrichment plants (Paducah, Kentucky; Oak Ridge, Tennessee; Portsmouth, Ohio) cost US $2.7 billion (in 2004 dollars) from 1993 through 2003, and total costs through final decommissioning in 2044 would exceed revenues into the Uranium Enrichment Decontamination and Decommissioning Fund by about US $3.2–6.2 billion (in

2007 dollars) [32]. Newer technologies such as gas centrifuge and laser separation are being considered for the next generation of fuel enrichment facilities, and the decommissioning issues are likely to be different, with perhaps less waste generated during operation [26].

Fuel Fabrication

For a typical commercial light water reactor, nuclear fuel is the solid form of uranium oxide (UO_2). Fuel fabrication facilities use chemical processes to convert the ^{235}U-enriched UF_6 into UO_2 in the form of a fine powder [28]. Because many of the materials (such as UF_6) are the same, specific factors that may influence the decommissioning of fuel fabrication facilities will be similar to those identified for uranium conversion and fuel enrichment facilities (see "Uranium Conversion" and "Fuel Enrichment"). This powder is then compacted and sintered (heated at a high temperature to fuse the particles together) to produce fuel pellets. These pellets are loaded into metal tubes to produce fuel rods. Hardware is then used to configure the fuel rods into fuel assemblies of the appropriate dimensions and design for a nuclear power reactor. Although this article focuses on the uranium nuclear fuel cycle, other nuclear fuels can also be fabricated, including mixed oxide (MOX) fuels formed from combining uranium and plutonium oxides, thorium fuels based on the ^{232}Th decay chain with ^{233}U as the fissile fuel element, uranium metal alloy fuels, and microsphere fuel particles [28].

Heavy water (water that contains more than the natural proportion of the hydrogen isotope deuterium, ^{2}H) is used as a moderator in some types of nuclear reactors. Heavy water is extracted from normal water through several chemical processes, the most common of which is distillation through electrolysis or isotopic exchange [24].

Chemical, radiological, and criticality hazards at fuel fabrication facilities are similar to hazards at enrichment plants. Most at risk from these hazards are the plant workers. These facilities generally pose a low risk to the public.

Service Period: Nuclear Power Plants

As indicated, the three decommissioning strategies described in the "Introduction" section were initially developed for nuclear reactors and power plants. The principal concerns during the decommissioning of these reactors and power plants are the safe cessation of operation; the safe management, storage, and disposition of highly irradiated spent nuclear fuel; draining and treatment of water and other fluids from the reactor cooling systems; and the decontamination and disposal of equipment, materials, and other systems that may contain contamination or activation products at the site.

At a very basic level, most nuclear reactors operating today use the heat from the controlled fission of ^{235}U (and perhaps ^{239}Pu in the case of MOX fuel) to boil water that turns a turbine and produces electrical power. As described previously, there are 436 nuclear power reactors operating worldwide, with 48 new reactors under construction. In addition, there are 287 (as of August 2003) research and test reactors and critical assemblies (i.e., producing little or no power), predominantly located at research universities and government facilities, that are used for research, education, and training purposes [4, 33].

There is no single design that is representative of all reactors. Of the operating nuclear power reactors, about 400 are water cooled and moderated (Energy Information Administration, 2006) and are predominantly pressurized water reactors (PWR), boiling water reactors (BWR), and pressurized heavy water reactors (PHWR). For example, all of the 104 operating commercial nuclear reactors in the United States are either BWR (35 reactors) or PWR (69 reactors) types [34]. Other operating reactor types include gas-cooled reactors, graphite-moderated reactors, and fast breeder reactors.

Early prototype nuclear reactors are sometimes called Generation I reactors. The current nuclear reactor designs are sometimes called Generation II (large central nuclear power plants) and Generation III (advanced LWR) reactors [28, 35]. Current research and development efforts are focused on designing the next generation, or Generation IV reactors, with a goal to provide more efficient and safe nuclear power generation that is also more resistant to nuclear proliferation [28, 36–38]. In the United States, the Next Generation Nuclear Program initiated with the Energy Policy Act of 2005 focuses on developing a very-high-temperature gas-cooled reactor (VHTR) operating at temperatures greater than 950°C for the production of electricity, process heat, and hydrogen [37]. Other designs are also being considered for the next generation of nuclear reactors, predominantly those based on gas-cooled (such as pebble bed modular reactors), water-cooled (super-critical water-cooled reactors), and fast-spectrum technologies (cooled by sodium, lead, or inert gases) [28, 35].

The different current and future design types and sizes of reactors make decommissioning inherently a site- and reactor-specific process. Each current and future reactor design will have its own design-specific decommissioning requirements that must be taken into consideration.

Back End Fuel Cycle Facilities

After the nuclear fuel is irradiated in a reactor and the useful energy has been extracted, it is called spent nuclear fuel. The removal of spent nuclear fuel from the reactor is generally considered part of the transition from the operational phase of the power plant, and not as part of the decommissioning process. The back end of the nuclear fuel cycle consists of facilities that handle spent nuclear fuel. Currently, most commercial nuclear power is based on an open, or "once through" uranium fuel cycle, where the fuel is used in a power plant one time and then removed as spent nuclear fuel [39].

Fuel Reprocessing Facilities

When the spent nuclear fuel is removed from the reactor, it is predominantly composed of uranium oxide (96%), other actinides like plutonium and americium (1%), and other fission products such as cesium and strontium (3%) [30]. The spent nuclear fuel must be cooled both thermally and radioactively in a water-filled spent fuel pool and later placed in dry cask storage at the reactor site.

Fuel reprocessing facilities are designed to recover materials such as uranium and plutonium from irradiated spent nuclear fuel. After sufficient cooling, the spent nuclear fuel is dissolved using solvents and the usable components (mostly uranium and plutonium) are separated from waste materials such as other actinides and fission products [4, 40]. The recovered uranium and plutonium are recycled into the front end of the nuclear fuel cycle and refabricated to produce new nuclear fuel (such as MOX) or used for defense purposes. Waste materials, in the form of sludges, salt cake, or calcined wastes, and the reprocessing solutions are collected for disposal. Liquid wastes are generally not suitable for disposal, and decommissioning and cleanup may include vitrification to solidify waste solutions in the form of borosilicate glass.

Because of the high radiological dose rates and contamination levels associated with irradiated spent nuclear fuel, human access is limited for major parts of the facility. This leads to decontamination and decommissioning that is more complicated than facilities such as uranium mills and fuel fabrication facilities at the front end of the nuclear fuel cycle. Facilities tend to be very large, and large volumes of liquid wastes are produced and stored for subsequent disposal.

Examples of fuel reprocessing facilities in the United States include U.S. Department of Energy (USDOE) facilities at Hanford, Washington, and the Savannah River site in South Carolina. The only commercial fuel reprocessing facility in the United States, located at West Valley, New York, ceased operations in 1972. The Carter administration elected to defer reprocessing of commercial nuclear fuel in 1977, and there are no commercial fuel reprocessing facilities currently operating in the United States. The USDOE has completed vitrification of the liquid wastes at West Valley, storing the borosilicate glass logs on site [41, 42]. Decommissioning activities at West Valley are ongoing. Large reprocessing facilities are also located at Sellafield in the United Kingdom and La Hague in France.

Waste Management and Disposal

As with many aspects of nuclear decommissioning, the nature and amount of waste produced during cleanup activities will depend on the age and size of a given facility, as well as the nature and history of operations at the site. As described in IAEA [43], four different types of waste or "waste streams," each with different disposal options, are typically produced during nuclear decommissioning. The first three are types that include radioactive waste:

- Primary waste is generated during dismantling activities and may include internal plant components such as a reactor pressure vessel and associated piping, equipment such as pumps and valves, special facilities such as glove boxes and radiation hot cells, and building materials. These components of the primary waste streams may be radioactive through activation by both short- and long-lived radionuclides during plant operations, or by surface contamination. Primary wastes can include a variety of materials, but typically metal and concrete rubble are the largest component by volume of this waste stream [43].
- Secondary wastes are generated during different steps in decontamination and dismantling. These may include solutions, absorbents, and filters used to treat surfaces to reduce radioactive contamination.
- Tools and equipment, such as cutting equipment and protective gear for personnel use during decontamination and dismantling, may become contaminated. To minimize costs and waste volumes, some equipment may be decontaminated so that it can continue to be used.

In addition to these radioactive wastes, decommissioning can potentially produce large volumes of non-radioactive wastes, such as construction debris, sanitary wastes, hazardous chemicals, and asbestos. These wastes are similar to those that might be encountered during the decommissioning of a typical, nonnuclear industrial facility. Some of these materials like furniture, nonirradiated scrap metal, and office equipment can be reused and recycled. The remainder of this waste stream typically has a well-established disposal path through municipal landfills and sanitary disposal systems.

Radioactive waste can occur in a variety of forms, including gases, liquids, and solids, with radiological characteristics that depend on the concentration and half-lives of the different radionuclides. For these reasons, classification of waste is particularly important, as it will determine the methods to be used in handling, segregating, conditioning, packaging, and transporting wastes. Waste classification also establishes the applicable acceptance criteria for different waste storage and disposal options, which in turn can have a strong effect on decommissioning planning and implementation, and ultimately, the total cost of decommissioning [43].

Although it varies from country to country, classification of radioactive waste is typically based on some combination of the types of processes from which the waste was generated, the radionuclide content of the waste, the timing of the waste generation (e.g., legacy wastes generated prior to developing a robust licensing process), as well as chemical, physical, and biological properties of the waste [30, 43, 44]. The following sections provide general descriptions based on waste classifications proposed in IAEA [45]. Note, however, that specific classification of waste streams and the methods for their management, treatment, and disposal are defined by the policies, laws, and regulations that a nation applies to commercial-scale nuclear power generation and subsequent nuclear decommissioning and waste management activities. For these reasons, waste classification is complex and may vary from country to country [44]; the descriptions presented here are for informational purposes only and are not an endorsement of a particular radioactive waste classification system.

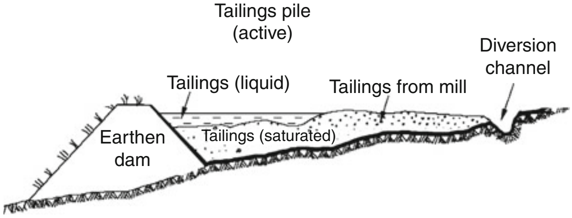

Fig. 9.3 Schematic cross section of a tailings impoundment [22]

Uranium Mill Tailings and Groundwater Restoration

For conventional mining and milling operations, processing the ore results in a waste stream of solid waste material, sands, fine-grained slurries (sometimes called slimes), and processing liquids. These materials are collectively referred to as tailings and are pumped from the mill to a tailings impoundment for disposal (see Figs. 9.2 and 9.3).

Generally, there are a number of tailings impoundments and evaporation ponds at each mill site [22], and the total volume can be quite large. The amount and nature of the tailings, however, depend on the capacity of the mill and the length of time the facility is in operation. For example, the former Climax Uranium Company mill in Grand Junction, Colorado, produced 2 million metric tons (2.2 million tons) of tailings that were placed in a 46-ha (114-acre) tailings impoundment [46]. The nature of the material in each impoundment or pond varies, depending on which part of the mill process produced the tailings. In addition, with the approval of the regulatory agency, operators may use tailings impoundments for onsite disposal of wastes associated with decommissioning and dismantling buildings, structures, and equipment, as well as for soils, pond liners, and sludges that have been radiologically contaminated.

Tailings have become a major focus in regulating active uranium mining and milling operations, as well as cleaning up legacy tailings from older, inactive sites. For example, in 1978, the U.S. Congress enacted the Uranium Mill Tailings Radiation Control Act (UMTRCA) to provide government funds to clean up and stabilize tailings from inactive legacy mills [22]. In a 1995 summary study of UMTRCA sites, the USDOE noted that tailings reclamation was the costliest aspect of the decommissioning process for conventional uranium mills [22]. During reclamation planning, the operator typically uses computer models to evaluate geotechnical stability. Although site-specific tailings reclamation methods are established in a reclamation plan that is evaluated for compliance with the government regulations that govern the cleanup [22, 24, 47, 48], general steps include:

- Shaping and recontouring the tailings pile and installing drainage diversion systems to minimize erosion hazards from surface runoff.
- Allowing the tailings to settle and dehydrate.
- Establishing survey monuments so that settling can be monitored.

- Installing a low permeability engineered cover to minimize water infiltration into the pile and radon emissions from the tailings. Generally this cover consists of clays and/or geotextiles.
- Installing a final cover for erosion protection.
- Establishing a monitoring system to ensure that the design and construction of the reclaimed tailings work as expected. Long-term stewardship during a period of institutional controls may include active measures to maintain and repair the tailings covers.

For active operations, regulations typically call for lining tailings impoundments and installing monitoring systems to prevent migration of contaminants (e.g., radionuclides and associated heavy metals) from the tailings into underlying aquifers [24, 48]. For older and inactive operations, however, the tailings impoundments may not be lined. This can lead to contaminants leaching into the underlying groundwater system over time; these contaminants need to be remediated when the tailings are reclaimed. Depending on the importance of local groundwater resources to nearby communities and the site and design of the impoundment, the level of effort needed to clean up groundwater may be extensive and long term.

Because uranium milling at an ISL facility does not produce tailings, the amount of material at the surface to be decommissioned and ultimately reclaimed is significantly less. Because there are no large tailings impoundments associated with ISL facilities, contaminated decommissioning wastes (e.g., equipment, building components, soils, evaporation pond sludges, and liners) must either be transported to a licensed disposal facility, or an onsite disposal cell will need to be built.

The ISL process does, however, alter groundwater chemistry in the production well fields. After uranium extraction from the ore deposit is no longer economically feasible, the groundwater quality is restored to pre-extraction conditions through a series of treatment steps [13, 49]. As with tailings reclamation, site-specific methods are determined with approval of the regulatory agency, but general steps for groundwater restoration include:

- Groundwater sweep, where groundwater is pumped from the production zone to draw in surrounding natural groundwater. The pumped groundwater may be treated to remove contaminants and reinjected.
- Reverse osmosis, where groundwater is pumped from the production zone and passed through a pressurized, semipermeable membrane (reverse osmosis) system to remove dissolved chemicals. The cleaner water is then reinjected, and the more concentrated brines are pumped to evaporation ponds or disposed of by injection in deep wells.
- Stabilization, where chemicals such as hydrogen sulfide may be injected into the production zone to establish chemical conditions that cause dissolved chemicals to precipitate out as minerals.
- Monitoring, where the groundwater quality is tested to ensure that conditions have stabilized and meet the restoration criteria.

Groundwater restoration occurs when the economics for producing a well field are no longer favorable. Because ISL facilities typically have more than one well field, it is common for groundwater restoration to begin in one well field while other well fields are still actively producing uranium [13, 49].

After groundwater restoration, the physical components of the well field are then restored. Piping, well casing, and pipeline materials are hauled to a licensed disposal facility. Surface facilities such as tanks and buildings are dismantled, removed, and disposed. Pumps are removed for reuse in other well fields, and the wells are filled with cement, plugged, and abandoned. Any soils contaminated by well field spills are removed and disposed, and the disturbed land is graded, recontoured, and revegetated.

Spent Nuclear Fuel and High-Level Waste

As described previously in "Fuel Reprocessing Facilities" section, after the economic energy has been extracted from nuclear fuel, the fuel is removed from the reactor. At this point, it is referred to as spent nuclear fuel. Spent nuclear fuel is highly radioactive because of the decay of fission and activation products that result from the nuclear reactions that occur when the fuel is inside the reactor core. Although it is no longer hot enough to generate electricity, it is well above ambient temperatures.

For these reasons, spent nuclear fuel must be carefully handled, stored, and shielded to provide both radiation protection to workers and the public, and to manage the thermal heat generated by the cooling fuel. In most cases, spent nuclear fuel is stored at or near the reactor, either in dedicated spent fuel pools that use water to provide both cooling and radiation protection or in air-cooled concrete and steel dry casks [13].

As described in "Fuel Reprocessing Facilities" section, after spent nuclear fuel has been cooled and radioactivity has decreased through decay of short-lived radionuclides, spent nuclear fuel may be reprocessed. The fuel reprocessing process typically produces a liquid waste stream that contains fission and activation products that remain after potentially valuable radioactive elements such as plutonium and uranium are removed. This liquid waste stream is typically stored in large tanks for subsequent treatment. Treatment may include processing the liquid wastes into different forms such as sludges, salt cake, or a calcined solid. These forms still produce radiation and must be shielded to provide protection to workers. Current practice in countries such as France, Japan, the United Kingdom, and the United States involves using high temperature furnaces to vitrify liquid wastes into a solid glass waste form.

In most countries in Europe, Asia, and North America, the ultimate disposal path for spent nuclear fuel and reprocessing high-level radioactive waste (HLW) is permanent geologic disposal in an underground repository [50]. At present, a large number of different geologic settings are under consideration. No country has licensed and constructed a geologic repository, however, and spent nuclear fuel and reprocessing HLW are typically managed through onsite interim storage.

Intermediate-Level Waste

Intermediate-level radioactive waste (ILW) is defined in IAEA [45] as "... waste which, because of its radionuclide content requires shielding but needs little or no provision for heat dissipation during its handling and transportation." This waste may be further classified into components consisting of short-lived radionuclides that will decay to low levels during a period on the order of hundreds of years in which institutional controls such as fencing or access restrictions can be considered to be effective in minimizing radiological dose [45]. Conversely, long-lived ILW is dominated by radionuclides that will not decay to sufficiently low levels. The ILW classification is not used in the United States.

In the United States, a transuranic (TRU) waste stream includes man-made alpha radiation-emitting radionuclides with an atomic number greater than that of uranium (i.e., 92) and a half-life longer than 20 years [51]. TRU is produced during reactor fuel assembly, weapons fabrication, and fuel chemical processing operations [15]. Specifically, TRU is that portion of the waste stream that is not classified as spent nuclear fuel, HLW, or low-level radioactive waste (LLW) [30, 51].

A wide variety of storage options exists for the storage and disposal of ILW and TRU. Storage may be through retrievable burial, underground bunkers, concrete caissons, aboveground concrete pads, and inside buildings [30]. Since 1999 in the United States, the USDOE has been disposing TRU waste in a bedded salt deposit about 700 m (2,300 ft) below the ground surface at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico [30].

Low-Level Waste

LLW has low radionuclide content. Similar to ILW, IAEA [45, 52] suggests that LLW be further divided on the basis of whether it consists predominantly of short-lived or long-lived radionuclides. LLW tends to be defined by what it is not (i.e., not HLW, ILW, or TRU) rather than what it is, so it can include a broad range of materials and radioactivity levels [30, 51]. For example, LLW may contain small amounts of radioactivity spread through a large volume of material or it may contain sufficiently high levels of radioactivity to require shielding for its safe handling [15, 30, 53]. LLW wastes generated during nuclear decommissioning may involve a wide range of materials including rags, papers, filters, ion exchange resins, discarded protective clothing, contaminated soils and construction rubble, piping, and tanks.

Because of the generally low levels of radioactivity, LLW is typically disposed using near-surface burial. Depending on its physical and chemical properties, LLW may be packaged in drums, casks, special boxes, or other sealed containers [30]. Contaminated soil and construction debris may be disposed directly into the cell without a container. Some large components such as pipes and tanks may be cut up or flattened to reduce the volume.

LLW disposal facilities may be either commercial or government operations, although commercial facilities are still typically governed by government regulation. Similar to municipal landfills, LLW disposal cell designs may include a liner, and an engineered cover system may be installed to reduce water infiltration into the underlying groundwater system [15]. Monitoring systems and institutional controls are installed to ensure waste isolation (air, water, and soil) and to limit access to the disposal facility [51].

Hazardous and Mixed Wastes

Depending on their age and size, decommissioning of nuclear facilities may involve management and disposal of hazardous wastes that result from the processes employed during facility operations, or from building standards used during the initial construction of the plant. For example, hazardous chemicals such as acidic, alkaline, and organic solutions used during uranium milling or fuel reprocessing may require special handling, treatment, and segregation prior to disposal. In addition, hazardous materials such as asbestos may be encountered when older buildings are dismantled and may require special treatment and disposal. If these hazardous wastes are free from radioactive contamination, their ultimate disposal path would be based on hazardous waste regulations.

Radioactive wastes may also be mixed with hazardous wastes. The management and disposal of these wastes can be complicated, as there may be more than one agency with jurisdiction and more than one set of waste handling criteria may apply. For example, in the United States, the U.S. Environmental Protection Agency (USEPA) has authority over hazardous waste through the Resource Conservation and Recovery Act, and the USNRC and USDOE have regulatory authority over radioactive wastes through the Atomic Energy Act. In this case, the management and disposal options to be considered for decommissioning wastes may need to comply with both hazardous and radiation safety requirements [54].

Uncontaminated Wastes

As with other industrial operations, nuclear facilities may also produce wastes that contain little or no radioactive contamination. If the radioactivity of these wastes falls below levels established by the applicable regulations and statutes, they may require no additional nuclear regulatory control. Also, as described in "Safety and Performance Assessment" section, some decommissioning wastes can be decontaminated below the applicable "clearance" levels and released from regulatory control [55]. IAEA [45] identifies these as "exempt" wastes and notes that they can be disposed of using conventional methods and systems.

As structures are dismantled and steel, concrete, and other surfaces (e.g., parking lots) are removed, large volumes of construction debris may be generated during nuclear facility decommissioning. Because some of these structures are not associated with nuclear-related activities, construction debris of this nature may meet the requirements of exempt waste. The specific levels of radioactivity that establish the criteria to be used in identifying exempt wastes will typically differ from country to country. As a result, the volume of exempt waste and disposal paths will also vary.

General Methodologies for Decommissioning

Specific decommissioning activities and technologies, as well as the sequence of their application, will vary depending on size, age, operational conditions, and design of a nuclear facility, and on the regulatory framework that governs decommissioning. As indicated previously, this article provides a general discussion of typical decommissioning activities. This discussion is not a recommendation of particular approaches or technologies, and the reader is referred to the references identified in the Bibliography for further reading.

Developing a Site-Specific Decommissioning Plan

Nuclear decommissioning is perhaps most effective when the process is laid out in a decommissioning plan. For the lead organization (either commercial or government) with responsibility for decommissioning, the plan provides the opportunity to develop a strategy that, among other things, identifies specific decommissioning issues at a given site, determines the types of processes and methodologies to be used, specifies the desired end state of the facility, and establishes the schedules and financing mechanisms for decommissioning. For large, complex commercial nuclear fuel cycle facilities such as a power plant or a fuel enrichment plant, the decommissioning plan is an extensive document that is supported by a large number of underlying technical and policy reports and references. Although the specific contents of a decommissioning plan can depend on the type of facility, the regulatory framework, and other policy issues, some of the general topics to be covered include [18]:

- Facility Description and Operational History
- Radiological Status
- Alternate Decommissioning Strategies and Selection of a Preferred Alternative
- Project Management
- Decommissioning Activities
- Surveillance and Maintenance During Decommissioning
- Waste Management
- Cost Estimate and Funding Mechanisms
- Safety and Performance Assessment

- Environmental Impact Assessment
- Health and Safety for Workers and the Public
- Quality Assurance
- Emergency Planning
- Physical Security and Safeguards
- Final Radiation Survey

Typically, a site-specific decommissioning plan is developed and refined in stages. An initial plan describing major structures, systems, and features is developed as the facility is designed and constructed. The initial plan is designed to provide basic information and establish project baselines prior to facility startup. The initial decommissioning plan is also intended to provide a framework for cost estimates (see "Estimates of Decommissioning Costs") to ensure that the necessary funds will be in place to cover decommissioning when the facility ceases operation. During the operational life of the facility, the initial decommissioning plan is periodically updated to reflect the operator's experience and understanding of the site. As with any large industrial facility, nuclear facilities may change as technology or regulatory oversight develops, or as the economics of the plant change. As the plant approaches the end of its operational life, the decommissioning plan becomes more detailed. The final decommissioning plan is developed just prior to a facility ceasing operations. The regulatory agency typically reviews this plan and must approve it before the operator can implement the decommissioning strategy [18]. Once the decommissioning plan is approved, it then becomes the basis for subsequent activities, although it may continue to be revised throughout a decommissioning process that can extend over decades.

Site Characterization

Site characterization provides the context for nuclear decommissioning. Ideally, site characterization includes a description of the size and location of the facility, buildings and systems, and the operational history of the site, as well as a description of spills or other releases that may affect the decommissioning process. Nonradiological hazardous process chemicals and other materials like asbestos that require special treatment and disposal may also be identified in the site characterization survey.

One objective in undertaking site characterization is to establish the preoperational baselines and background values that may be used to determine criteria for successful decommissioning. For example, an understanding of background water quality is used to establish site-specific levels for groundwater restoration, as well as action levels for monitoring. Site characterization should identify the geographical and geological context of the facility in relationship to important resources for the area such as critical habitat or historical and cultural areas. In addition, site characterization may include a discussion of the socioeconomic impacts of the facility, because this may be an important consideration in selecting among different decommissioning strategies [1]. The site characterization and radiological surveys are intended to be of sufficient detail to provide data for planning the decommissioning effort, including selection of specific remediation techniques, establishing decommissioning schedules, estimating costs and waste volumes, and identifying important health and safety considerations to be considered during decommissioning [20].

For the purposes of nuclear decommissioning, site characterization pays special attention to the radiological status of the site, focusing on establishing the extent to which buildings, systems, equipment, soils, and water may contain residual activity [18]. These radiological "hot spots" can be determined using historical information (e.g., location of historic spills, known storage locations, sites identified by ongoing monitoring during operations), conducting surveys with radiation detection equipment, and collecting soil and water samples for subsequent analysis [18, 20, 56, 57].

A key component of site characterization is locating and maintaining existing records [58, 59]. A lack of information on past activities has been a special challenge for decommissioning Cold War legacy sites.

Selecting a Decommissioning Strategy

The reasons for taking a nuclear facility out of service may be based on economics, national policy decisions about the suitability of nuclear power, safety, or obsolescent technology [60]. As described in "Introduction" section, decommissioning strategies for nuclear facilities generally fall into one of three categories:

- A strategy of immediate decontamination and dismantlement [1, 7, 61, 62] (also defined as DECON [14, 15]) begins soon after the nuclear facility closes. For nuclear reactors, spent nuclear fuel is removed, stored, and cooled, pending permanent disposal or reprocessing, and equipment, buildings, structures, and portions of the facility that contain radioactive contaminants are either removed or decontaminated to meet regulatory requirements for releasing the property. In general, this strategy imposes the largest requirements for resources (funding) and personnel in the short term. It takes advantage of the existence of a trained workforce with experience in operating the facility.
- Safe storage [1, 61], deferred or delayed decontamination [7, 62], or SAFSTOR [14, 15], refer to decommissioning strategies where a nuclear facility is left intact after closing, placed in a stable condition, and maintained and monitored until subsequent dismantlement and decommissioning. One purpose in choosing this strategy is to allow radioactivity to decay during a period of safe storage, perhaps on the order of decades, potentially reducing the radiological hazards and the quantity of nuclear waste that must be disposed. This strategy may also benefit from continuing developments in decommissioning technology and waste management options.

This approach places a premium on knowledge management, as the operations workforce may not be available when decommissioning begins years after the end of operations. This decommissioning strategy may be the only option if there are insufficient funds available to cover the costs of immediate decontamination and dismantlement, or if some aspects of the regulatory framework, such as a spent nuclear fuel disposal site, are not available when operations cease [7, 63]. Safe storage may allow one part of a large facility to be closed while the rest of the facility completes its life cycle. For example, one reactor unit at a nuclear power plant may be closed and the fuel removed while the remaining reactor units continue to produce electricity. When the decision is made to close the remaining portions, all of the components can then be decommissioned together, with accompanying potential benefits from optimizing the use of staff and specialized equipment for decommissioning. An example of this approach is the Peach Bottom Unit 1 reactor in York County, Pennsylvania, which was shut down in 1974 and placed in SAFSTOR. Reactor Units 2 and 3 continue to operate and are scheduled for shutdown in 2034, at which point final decommissioning will begin [64].

- A strategy of entombment [1, 7, 61, 62] or ENTOMB [14, 15] involves encasing radioactive materials onsite in a long-lived, structurally sound material such as concrete. The entombment structures are maintained and monitored as appropriate, with institutional controls (e.g., fencing, security personnel) to limit access. For some facilities, the intent of entombment is permanent encapsulation [7], and computer models are used to simulate performance for thousands of years [19]. Because entombment effectively creates a surface waste disposal site, it is not generally a suitable decommissioning strategy for facilities associated with fuel enrichment, fuel fabrication, and fuel reprocessing [62]. In addition, an entombment strategy may also limit the options for releasing the site for reuse.

The first two decommissioning strategies may also be combined. For example, some facilities at a site may be immediately dismantled while other structures are placed in safe storage. For large sites like fuel enrichment plants, nuclear decommissioning activities may be occurring at some facilities at the same time as active operations [4]. Generally, it is anticipated that decommissioning activities will be completed in a period of decades from the end of operations [14].

Because of the wide variety of nuclear facilities, there is no unique approach to decontamination and decommissioning. Several factors may be considered in selecting the decommissioning strategy [1, 7, 62] for a specific site, including:

- The status of the policies and regulatory framework that establish, among other things, the national direction of the nuclear industry and legal requirements for nuclear decommissioning
- The financial costs (both direct and indirect) associated with a given decommissioning strategy and the amount of funding available
- The availability of waste management and disposal facilities for the types and volumes of waste to be generated during decommissioning
- Risks to health and safety of both workers and members of the public

- Potential environmental impacts associated with a given decommissioning strategy
- Knowledge management concerns and the availability of trained and experienced personnel to conduct the decommissioning activities
- The desired end state for the site, and potential socioeconomic impacts to local communities and other stakeholders, including options for release and reuse of the site after decommissioning is complete

These factors need to be considered within the context of the specific site before selecting the preferred alternative. As described previously, the reasons for selecting one alternative as opposed to another should be discussed in the decommissioning plan.

Estimates of Decommissioning Costs

The facility owner is generally responsible for ensuring that there are sufficient resources to cover activities associated with decommissioning a nuclear facility. These activities may include decontamination, decommissioning, reclamation, and groundwater restoration, as well as surveillance and monitoring that may be necessary for long-term stewardship. Cleanup of government facilities and legacy sites that were established prior to the development of a regulatory framework for nuclear decommissioning are generally the responsibility of the national (or state/provincial) governments. Funds for these government responsibilities may be raised by general appropriations (taxes) or user fees imposed on the beneficiaries of nuclear power.

Methods used to accumulate and manage funds for decommissioning commercial nuclear facilities vary from country to country [1]. One common method to establish a decommissioning fund is to impose a requirement that a portion of business revenues be set aside for decommissioning and waste management. Typically, the types of financial mechanisms that are acceptable for estimating, creating, and maintaining a decommissioning fund are either established by the regulatory agency responsible for the facility license or directly by legislation [1, 21].

In countries with a robust regulatory framework, the owner/operator is commonly required to present estimates for the cost of decommissioning activities as part of the license application. A detailed discussion of estimating decommissioning costs is contained in USNRC [21]. In general, cost estimates are specific to the size, type, and location of the facility, and they incorporate assumptions about:

- The transition between operations and facility shutdown, and the work associated with that process, such as postoperational cleanout
- The definition for the end state of the decommissioning process (e.g., unrestricted release, restricted release)

Table 9.2 Estimated costs associated with decommissioning different nuclear facilities [4]

Type of nuclear facility	Estimated decommissioning cost (min to max [median] in US $ million, 2003 value)	Operational life (years)	Time to decommission (years)
Uranium milling	0.800	25	1
Uranium conversion/ recovery	150	30	3
Uranium enrichment	600	30	10
Fuel fabrication	250	30	2
Nuclear power reactor[a]	250–500 (350)	40	10 (after 5-year transition period)
Fuel reprocessing	800	30	15
Industrial facilities	0.050–3 (0.200)	20	1

[a]Cost estimates for decommissioning nuclear power reactors do not include the processing of operational waste, removal and disposition of spent nuclear fuel, the draining of operational systems, or the development of a waste disposal facility

- The availability and suitability of established approaches to decommissioning methods versus the need for unique and perhaps untested technologies
- Availability and capacity of facilities for managing or disposing of residual spent fuel and radioactive waste

Once the regulatory agency or governing body evaluates and accepts the proposed cost estimates, the type and amount of the financial surety (e.g., letter of credit, prepaid cash, government bond) is established and administered in accordance with government regulations. The regulatory agency (as in Canada, United States, and Sweden) or a waste management body (as in Belgium and Spain) then reviews the fund on a regular basis, generally between 1 and 5 years [1, 21]. As identified during the review, the decommissioning fund may be updated and the amount adjusted either upwards or downwards to account for inflation, changes in technology, or completed decommissioning activities.

As noted previously, the actual costs of nuclear decommissioning can vary substantially. The IAEA provided estimates for median decommissioning costs associated with various types of nuclear facilities based on a combination of expert judgment and decommissioning experience and using assumptions with respect to operating life and time to decommission [4]. These estimates (in US $, 2003 value) are summarized in Table 9.2. Because the cost of decommissioning will depend strongly on site-specific issues such as local geology, facility age and design, and operational history, the actual costs for a given site may fall outside these ranges.

The estimates reported in IAEA [4] are general in nature and are not intended to bound all potential costs, particularly for very large government facilities. One general conclusion that can be made from these estimates is that management of spent nuclear fuel and radioactive wastes can represent a significant proportion of the total costs of decommissioning. For example, estimated costs for decommissioning the Sequoyah Fuels uranium conversion site near Gore, Oklahoma, varied from US $19 million for the no-action alternative of long-term stewardship, to about US $36 million for onsite disposal of most contaminated wastes, to as much as US $254 million for transportation and offsite disposal of all contaminated wastes [25]. These cost issues indicate the importance of accurately characterizing a site and identifying appropriate opportunities to decontaminate, recycle, and reuse materials.

Safety and Performance Assessment

Safety is among the highest priority issues in nuclear decommissioning. Safety assessments, typically developed by both operators and regulators, are engineering analyses that involve calculations and computer simulations to evaluate potential radiological doses. The purpose of the safety assessment is to identify and evaluate potential hazards to ensure that nuclear decommissioning can be done in a manner that is safe for workers, members of the public, and the environment [65].

In general, the safety assessment should be systematic and be linked to relevant safety criteria, taking into consideration potential radiological doses to workers and members of the public, discharges to the environment, and exposure to chemical and other nonradiological hazards [18, 57, 65, 66]. To meet these objectives, a safety assessment consists of:

- Estimates of system performance for all the situations selected
- Evaluation of the level of confidence in the estimated performance
- Overall assessment of compliance with safety requirements

The standards and criteria to be used in developing these assessments vary from country to country depending on the regulatory framework that is in place. Also, the nature of the safety assessment may vary depending on the complexity of the decommissioning strategy needed for a given nuclear facility. A general framework proposed by the IAEA [64] includes:

- The scope of the assessment, based on the physical state of the nuclear facility
- The objectives of the assessment
- The applicable safety requirements and criteria to be used in evaluating potential exposures to workers, members of the public, and the environment
- Outputs from the safety assessment, generally in the form of doses that can be compared to the relevant safety requirements and criteria
- A description of the approach used to implement the safety assessment, whether through simplified calculations or complicated computer models, and a discussion of how the approach is appropriate to the magnitude and time frames of the potential hazards
- Time frames for all phases of the decommissioning activities considered in the safety assessment

- A definition of all phases of nuclear decommissioning and the anticipated end points for each phase
- A definition of the final end state of the facility that is anticipated after all decommissioning activities are complete

In practice, a safety assessment starts with a description of the facility and all of the anticipated decommissioning activities that comprise the decommissioning strategy (see "Selecting a Decommissioning Strategy"). To evaluate off-normal scenarios, a safety assessment also includes identification of potential hazards and initiating events (both natural events such as earthquakes and human-made events such as fire), and potential exposure pathways. These are screened, usually on the basis of probability of their occurrence and the resulting consequence should they occur. Plausible scenarios are developed and used in the engineering analysis to quantify the likelihood and magnitude of potential radiological and safety consequences. In addition, the safety assessment should identify relevant experience and lessons learned from the decommissioning of similar facilities, if available.

For disposing of longer lived radionuclides, some regulatory frameworks and decommissioning strategies use a performance assessment that provides a quantitative evaluation of potential releases of long-lived radionuclides over time periods of hundreds to thousands of years or longer. Similar to safety assessments, but with a much longer time horizon, performance assessments typically involve computer simulations based on site-specific features, events, and processes (biological, physical, and chemical) that may affect the long-term performance of engineered barrier systems. A performance assessment also simulates the release of radionuclides from any engineered barrier system and their subsequent migration through the geosphere surrounding the facility. Finally, future potential radiological doses may be calculated for a hypothetical receptor group located away from the facility [38]. Because of the long time frame, it is not possible to include all potential conditions that might affect performance, so simplified models, or abstractions, are used to simulate important aspects of the engineered and geological systems. This can introduce uncertainty into the calculations that should be characterized and evaluated to determine whether there is sufficient confidence that the applicable regulatory criteria will be met [19, 38].

In essence, the idea of safety and performance assessments is intended to answer these questions: What can go wrong? How likely is it? What are the consequences? [38]. Where there is uncertainty in conceptual models of the system or in the model parameters, simplifying assumptions should be chosen in such a way that ensures the models will be transparent, conservative, and not underestimate potential radiological doses. Statistical analysis and sensitivity studies can help to characterize the nature and relative importance of the uncertainty. Depending on the results of the safety and/or performance assessment, the planned decommissioning activities may be modified to reduce risks, or compensate for uncertainty or limited information [66].

Decontaminating Structures, Equipment, and Components for Reuse or Recycling

The objectives of decontamination include reducing the potential radiological exposure of workers and members of the public during decommissioning; minimizing the volume of radioactive waste; and increasing the potential for reusing and recycling equipment, material, and land at the site of a nuclear facility [67].

Although specific technologies to be used during decommissioning activities will vary depending on size, age, operational conditions, and design, general decontamination methods include [68–70]:

- Chemical methods that use agents such as acids, oxidants, or chemical foams and gels to remove contamination fixed to surfaces. The nature of the chemical agent may be determined based on the properties of the surface to be decontaminated. Chemical decontamination methods may generate a liquid waste stream that requires further treatment to remove radioactive wastes (and generate subsequent secondary waste streams).
- Mechanical methods that rely on cutting, grinding, or other physical techniques to remove contaminated surfaces or layers.

The techniques used for decontamination will vary by material and from site to site, depending on issues such as the operational history of the facility, the level of contamination, and the type of material to be decontaminated [67, 69]. For example, chemical decontamination methods may not be appropriate for porous materials such as concrete, where fluids may migrate into the material.

In addition to technical feasibility, other considerations in selecting decontamination techniques may include the applicable clearance criteria and the potential doses to workers or members of the public to reach these levels. The selection process may also include evaluating the cost of decontamination versus the cost of disposal without decontamination, taking into account estimates of the volume, nature, category, and activity of any primary and secondary wastes that might result. For example, decontamination methods should be selected in such a way as to minimize the amounts of secondary wastes (e.g., cutting fluids or washdown fluids) produced. It is also important to ensure that selected decontamination methods are compatible with and do not compromise existing or planned key treatment, conditioning, storage, and disposal systems [67]. For example, high-pressure jets may not be an appropriate method for cleaning liquid waste storage tanks that are decades old and have experienced some corrosion.

Dismantling and Removing Buildings, Structures, and Equipment from the Site

Equipment removed from buildings (Fig. 9.4) during the cleanup process is typically categorized as (1) salable for unrestricted use after radiation checks and

Fig. 9.4 A steam generator is removed from a reactor building [76]

Fig. 9.5 Demolition of a reactor containment building [76]

decontamination; (2) potentially contaminated, but may be salvageable for sale to other nuclear facilities; and (3) contaminated and must be disposed. The responsible regulatory authority generally establishes the levels of contamination for these different categories.

Dismantling and removing buildings, foundations, structures, and equipment from a nuclear facility is sometimes referred to as "construction in reverse," and similar types of heavy equipment (e.g., trucks, cranes, earthmoving equipment) are used during dismantling (see Figs. 9.4 and 9.5). In addition, cutting equipment and even demolition explosives may be needed to break large structures down into smaller pieces that can be handled and transported more easily (Figs. 9.5 and 9.6). For high-radiation areas, remote techniques such as underwater cutting may be necessary to provide for worker radiation protection [67].

Where salvage is not economically or technically feasible, larger pieces of equipment (e.g., pipes, tanks) may be cut up and flattened, and building materials reduced to rubble to minimize waste volume and make handling for subsequent disposal easier. How much volume needs to be reduced may depend on the

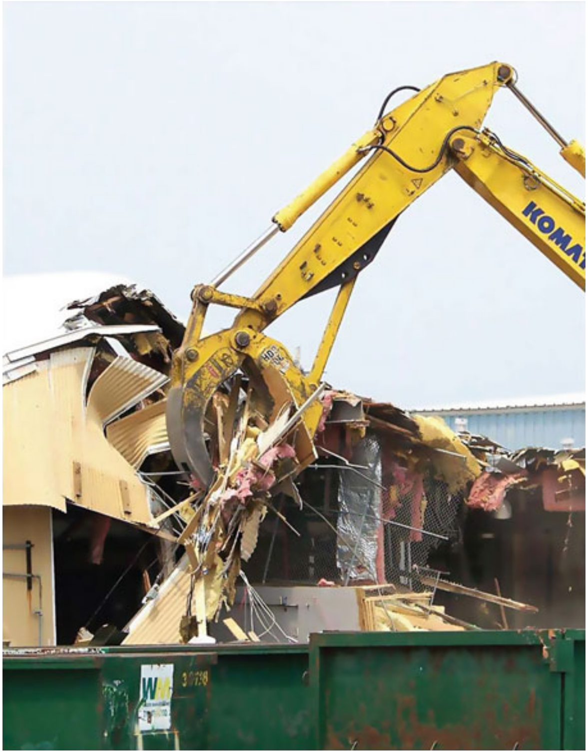

Fig. 9.6 Dismantling industrial buildings at a nuclear facility [42]

available waste disposal capacity and regulations that govern transportation and disposal. Pavement in roads and parking lots may also be removed for disposal as construction debris.

Remediating Contaminated Soils and Groundwater

Remediating residual radioactivity in soils and water generally uses technologies that are well established in the environmental industry. Evaluating and selecting a specific technique is an important part of decommissioning and depends on many site-specific issues such as the physical and chemical state of the residual radioactive material, the availability of equipment and a trained workforce, the availability of appropriate waste disposal capacity, and stakeholder sentiment. The following discussion is intended only as a brief summary of commonly available methods for remediation.

The most common remediation method used for contaminated soils involves excavating the soil for disposal in a LLW facility (Fig. 9.7). If the contamination layer is not deep, this may be an economically viable approach. If the contamination is widespread, however, the volume of material to be disposed in this fashion may be

Fig. 9.7 Removing uncontaminated soil and debris for offsite disposal [42]

quite large and may increase the costs of waste disposal. Alternatively, the soil may be excavated and treated using physical and chemical separation techniques to isolate and reduce the volume of contaminated material [27]. For example, in some cases, residual radioactivity may be more closely associated with fine clay-sized particles in the soil that can be separated by using screens or other physical separation methods. Chemical extraction methods use solutions such as organic acids to bind to the contamination and remove it from the soil. After separation of the contaminated and uncontaminated soil fractions, the uncontaminated soils are used as clean fill, and contaminated soils are treated further or processed for disposal. If chemical methods are used, the leachate may be treated to remove the dissolved radionuclides to meet water standards.

Contaminated surface water and groundwater typically require treatment to meet applicable standards. Widely available technologies for contaminated groundwater include pumping and treating to pull the contaminant plume back toward the extraction well. The contaminated water is then treated through a process such as ion exchange and is either injected back into the aquifer or discharged to a suitable surface water disposal system. A more recent technology for treating contaminated groundwater is the construction of a passive permeable reactive barrier or slurry wall system (Fig. 9.8). Built below the ground surface so that they intercept the groundwater plume, the reactive materials in the barrier are selected to chemically react with the contaminants and immobilize them in the subsurface. Reactive materials that may be used to remove uranium from groundwater include different

Fig. 9.8 Building a slurry wall to remediate contaminated groundwater [42]

forms of iron, such as metallic (zero-valent) or amorphous ferrihydrite [27]. The contamination will remain in place until the barrier is excavated, and barrier longevity and long-term performance are important engineering issues.

Other technologies rely on in place or in situ methods to reduce or immobilize soil and water contamination. For soils, contamination may be reduced or immobilized through mixing in amendments such as apatite or phosphate that will chemically react with the contamination. Alternatively, soil contamination may be immobilized in place by grouting or capping. Bioremediation is a collection of more recent technologies that use biological organisms to preferentially extract or otherwise break down toxic and radiological contamination from both soils and groundwater [71]. For example, sunflowers have been demonstrated to take up uranium from waste at a site in Ashtabula, Ohio, and at a small pond contaminated with uranium near the Chernobyl nuclear power plant site in Pripyat, Ukraine [27, 71].

In addition to active remediation technologies, monitored natural attenuation of contaminated soils and groundwater may be also be applicable, if it can be demonstrated to meet applicable criteria in a reasonable timeframe [72]. This method relies on monitoring soils and groundwater while the natural physical, chemical, or biological processes already occurring at the site contain and reduce volume, mass, and toxicity of the contamination in place. Where site conditions such as soil type and groundwater flow are favorable, monitored natural attenuation can be an attractive option because it is typically less disruptive and costly than more active remediation measures. However, because it can be perceived by stakeholders as "doing nothing," monitored natural attenuation is generally proposed as one part of a broader remediation strategy and combined with active remediation measures [72]. For example, a contamination source may be excavated and removed while monitored natural attenuation is implemented for the associated groundwater contaminant plume.

Waste Management and Disposal

As described in "Waste Management and Disposal" section, decommissioning wastes can fall into several different classes. Waste classification ultimately depends on the type of historical operations at the site and will influence the decommissioning strategy and waste management options that are selected for a facility. Once the physical, chemical, and radiological properties are characterized and the waste is classified and the applicable criteria are determined, the basic options for waste management are either onsite storage/disposal or transport offsite to an approved waste disposal facility.

For nuclear power plants, one of the final phases of operations before decommissioning is to remove the fuel from the reactor (defuel) and place the spent nuclear fuel in interim storage, either in pools or dry casks. This step would be necessary regardless of the decommissioning strategy selected [69]. As they are generated during operations, other wastes may be collected, segregated, chemically adjusted, and decontaminated onsite, and then placed in temporary monitored storage onsite until a final disposition path is determined [44]. A partial list of examples of the types of wastes that may be encountered during the decommissioning of nuclear facilities is presented in Table 9.3.

Waste may be treated to prepare it for final disposal. Treatment concepts include volume reduction and separation and removal of radionuclides and other hazardous wastes [44]. Some treatment options include incineration or compaction to reduce volume, and evaporation or ion exchange to remove radionuclides from liquid wastes. Some of these techniques can generate secondary wastes such as liquids, sludges, and filters that need to be managed as well.

Radioactive wastes may also be conditioned to produce a form that is more suited for handling, transportation, storage, and disposal. Low-level and intermediate-level wastes may be immobilized by mixing with grouts, cements, and bitumen, while liquid high-level wastes from fuel reprocessing may be vitrified into a glass waste form or otherwise modified to produce a solid waste form. These wastes are placed in packages or specially designed containers for interim storage, transportation, and subsequent offsite disposal (Fig. 9.9). This may be at a licensed disposal site, a specially constructed disposal cell, or an existing tailings impoundment that

Table 9.3 Partial list of the types of waste materials for different nuclear facilities

Type of nuclear facility	Examples of waste materials
Uranium mine	Waste rock Fuels and lubricants Contaminated soils and groundwaters
Uranium mill	Drums Insoluble waste and filter materials Liquid effluent Tailings and sludges Liquid nitrates Ion exchange resins Tanks, pipes, and equipment Contaminated soils and groundwater
Uranium conversion	Solid CaF_2 CaF_2 sludges with/without minor uranium Non-radiological chemical waste Tanks, pipes, and equipment Contaminated soils and groundwaters
Uranium enrichment	Depleted uranium tails Tanks, pipes, and equipment Contaminated soils and groundwaters
Fuel fabrication	Uranium scrap material Filters Wash water and decontamination/cleaning solutions Waste oils Spent acids and solvents Equipment Contaminated soils and groundwaters
Nuclear power plants	Reactor vessel and internal components Coolant system equipment and components Activated concretes and steels Evaporator concentrates Tanks, pipes, and equipment Contaminated debris and soils
Spent fuel reprocessing	Filters Activated and contaminated metal components Spent solvents, decontamination and metal cleaning agents Fuel cladding Laboratory analytical equipment and solutions Tanks, pipes, and equipment Contaminated debris, soils, and groundwater

is being reclaimed and used as a disposal cell. The materials must meet waste acceptance criteria for the disposal facility.

Alternatively, waste may be disposed in place with monitoring and an engineered system for long-term disposal [42]. Onsite waste management,

Fig. 9.9 Low-level radioactive waste packages for offsite disposal [42]

including a decommissioning strategy of entombment, must comply with applicable regulations for near- surface storage and disposal facilities [62]. In this case, a performance assessment (see "Safety and Performance Assessment") may be used to evaluate both engineered and natural barrier performance over long times. Depending on the nature of the waste and the site-specific conditions, different design options (backfill, concrete vaults, engineered covers) may be evaluated along with a combination of long-term monitoring and institutional controls [44]. Institutional controls such as fencing, signage, and physical security are generally assumed to be effective only for a period on the order of hundreds of years, while the performance of engineered and natural barriers is evaluated over periods as long as 10,000 years [19, 20].

Conducting Final Inspections and Surveys

During decommissioning, the national regulatory agency will typically conduct onsite reviews and inspections to ensure that the approved decommissioning plan is being followed [19] and the decommissioning activities are being conducted in a safe manner that complies with applicable regulations. After decommissioning is complete, there should be a final survey to evaluate the residual radioactivity that remains at the site. The specific goal of this survey is to determine the extent to which the site complies with the criteria set by the governing regulatory authority for subsequent reuse and/or release of the site [57, 67] – one of the objectives of decommissioning (see "Definition of the Subject").

This survey may be carried out in phases, as decommissioning work is completed, to enable parts of the site to be released from regulatory control. The final survey data are submitted to the regulatory authority, including a description of the applicable reuse/release criteria, the methods and procedures used, and the measurement results. Typically, the sampling and surveys will be focused on areas such as previous waste burial sites or spill locations identified as contaminated during the site characterization survey. These areas are sometimes called Class 1 areas [57], and sampling and surveys will be more extensive. Areas that are less likely to be contaminated, called Class 2 and Class 3 areas, receive lesser surveying and sample coverage. The results typically include an analysis to demonstrate the statistical significance of the results as compared to natural background radiation levels [20, 56, 57, 67].

Reclaiming Disturbed Land

After decommissioning and dismantlement of buildings and structures is complete, the decommissioning strategy may call for reclaiming disturbed land to preoperational condition. This is generally accomplished by adding clean topsoil, installing drainage and erosion controls if necessary, regrading and recontouring the surface to match the surrounding topography, and revegetating with native vegetation (Fig. 9.10). In addition, land reclamation efforts should include monitoring to ensure that drainage and erosion controls are functioning as intended, revegetated areas are stable, and invasive species have not become established. Many of these techniques are similar to those used to reclaim surface mines [73].

The amount of disturbed land to potentially reclaim can vary significantly for different nuclear facilities, especially conventional uranium mining and milling operations that produce significant quantities of waste rock and tailings covering tens to hundreds of hectares (acres). The type of reclamation will depend, in part, on the intended use of the land once the license is terminated. For example, a site intended for unrestricted release as a recreation area may have a more extensive land reclamation program than a site that will ultimately be released for future industrial uses.

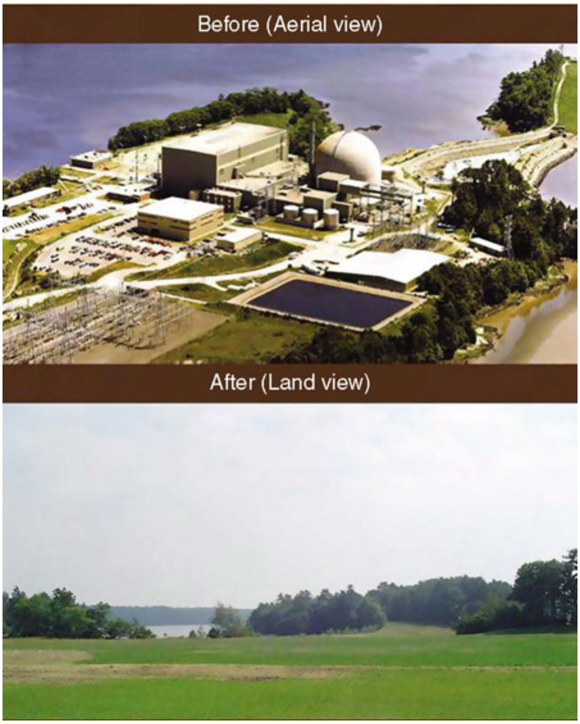

Fig. 9.10 Reclamation and revegetation of site after decommissioning a commercial nuclear power plant [77]

Status of Decontamination and Decommissioning

Because commercial nuclear fuel cycle facilities and nuclear power plants are governed at the national level using different policy, statutory, and regulatory frameworks, the status of nuclear decommissioning around the world is difficult to estimate [4]. A brief summary based on the estimates of international nuclear organizations such as the IAEA, NEA, and WNA is provided here and in Table 9.4.

- The leading countries for uranium production include Canada, Kazakhstan, and Australia, followed by Namibia, Russia, Niger, Uzbekistan, and the United States [40]. Uranium has been mined for decades, and some of the older mines are small and not well documented. The WNA estimates that more than 100 mines have been "retired from operations," although decommissioning is not complete at all of them [5].
- Uranium mills exist in countries with known uranium ore reserves. As of August 2003, the IAEA reported that 294 uranium mills were operating worldwide, with 231 plants shut down or in decommissioning and 149 fully decommissioned. Eight additional uranium mills were under construction [4].
- Uranium conversion plants to produce UF_6 operate in the United States, Canada, France, United Kingdom, China, and Russia. As of August 2003, the IAEA

Table 9.4 Decommissioning status for nuclear fuel cycle facilities as of August 2003 ([4], Table 9.3)

Type of nuclear facility	Operating	Under construction	Shut down /being commissioned	Decommissioned
Uranium milling	294	8	231	149
Uranium conversion/recovery	29	1	14	2
Uranium enrichment	21	2	7	5
Fuel fabrication/heavy water production	66	5	27	23
Fuel reprocessing	13	3	18	13

reports that 29 uranium conversion facilities were operating worldwide, with 14 plants shut down or in decommissioning and 2 fully decommissioned. One additional uranium conversion facility was under construction [4].

- Major enrichment plants are operated in the United States, France, and Russia, with smaller plants located in the United Kingdom, Netherlands, Germany, Japan, and China [28]. As of August 2003, the IAEA reports that 21 fuel enrichment facilities were operating worldwide, with 7 plants shut down or in decommissioning and 5 fully decommissioned. Two additional fuel enrichment plants were under construction [4].
- Fuel fabrication and/or heavy water production facilities operate in most countries with nuclear programs. As of August 2003, the IAEA reports that 66 fuel enrichment and heavy water production facilities were operating worldwide, with 27 plants shut down or in decommissioning and 23 fully decommissioned. Five additional fuel enrichment plants were under construction [4].
- At present, 436 commercial nuclear reactors are operating worldwide in many countries in North America, Europe, and Asia [9]. A total of 112 nuclear reactors have been placed in long-term shut down, and 14 have been completely decommissioned [4, 9]. Russia has the largest number of research and test reactors, followed by the United States, Japan, France, Germany, and China. In addition, research and test reactors are also located in developing countries in Africa, South America, and Asia. After peaking in the mid-1970s at about 370 reactors in 55 countries, the number of research and test reactors worldwide has declined sharply. As of August 2003, the IAEA reported that there were about 287 research and test reactors and critical assemblies in operation worldwide, with 8 more under construction. A total of 214 research and test reactors were shut down or being decommissioned, and 173 were reported as being decommissioned [4].
- As of August 2003, the IAEA reports that 13 fuel reprocessing plants were operating worldwide, with 18 plants shut down or in decommissioning and 13 fully decommissioned. Three additional fuel reprocessing plants were under construction [4].

Future Directions

As noted previously, interest in commercial nuclear power has been revived as a result of concerns with carbon emissions from traditional fossil fuels. As a result, many nations have reported an increase in proposed construction projects for new reactors. Although many of these proposed projects will use current Generation II and III reactor designs, there are research and development programs focused on designing the Next Generation IV reactors [37].

The different current and future design types and sizes of reactors will make decommissioning inherently a site- and reactor-specific process. Each current and future reactor design will have its own design-specific decommissioning requirements that must be taken into consideration. In addition, changes in reactor design or the use of nuclear fuels based on MOX or thorium may lead to different fuel requirements that will change the nature of decommissioning at the front end of the nuclear fuel cycle.

Much of the decommissioning experience gained to date is focused on an open, or "once through" uranium fuel cycle. Current programs such as the Global Nuclear Energy Partnership are evaluating the potential of a closed fuel cycle, where fuel is reprocessed and used more than once to generate power [39]. This approach, along with changes in ongoing nuclear reactor operations, would change the amount and characteristics of spent nuclear fuel for handling, storage, and disposal. In addition, closing the fuel cycle would require new nuclear fuel cycle facilities and change the waste streams produced at the back end of the fuel cycle. For these reasons, a change from an open to a closed nuclear fuel cycle may need new waste disposal options that will influence the selection of the decommissioning strategy for these types of facilities.

Although new decontamination techniques are continually being developed [27, 69], existing technology that has been previously applied with demonstrated success may continue to be preferred by stakeholders (members of the public, government agencies) to an untried method, particularly if trained staff and specialized equipment are readily available. As decommissioning costs and potential benefits are better understood, newer techniques may be applied more. In addition, many nations are looking at extending the service life of existing nuclear facilities and reactors. At the same time, the nuclear workforce is aging, placing a premium on knowledge management and recordkeeping to ensure valuable information and experience is not lost [58, 74, 75]. Decommissioning decisions are perhaps many decades in the future, but should be taken into consideration as designs are developed for advanced reactors and the nuclear facilities that support them.

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