BWR Decommissioning General Information and Experiences

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1 Introduction

Many BWR nuclear power plants have begun decommissioning activities after completing the licensed operating period of 30 to 40 years, with the final goal of obtaining license termination and getting the property released based on decommissioning regulations and guidelines. The power plants use a variety of strategies for dismantling systems, structures, and components (SSC), waste management, and deciding on the future use of the site. Typical activities include safely decommissioning of the plant, minimizing radioactive waste generation, fuel removal and storage, license termination and getting the site restored and released. In the US, it is expected that decommissioning be completed within a period of 60 years.

Radioactive waste management is a major part of the decommissioning cost; however, the experience shows that this cost is much less than the staffing costs. This fact is an incentive for management to optimize the length of the decommissioning period in order to lower and control costs.

During decommissioning, plant sites typically use one of three approaches [US NRC, 2015; EPRI 2006], Immediate Dismantling (DCON), Safe Enclosure (SAFSTOR) or Entombment (ENTOMB). Each approach has its benefits and disadvantages while a majority of plants have used the SAFSTOR approach.

During DCON, equipment, buildings and parts of the facility and site that contain radioactive contaminants are decontaminated from equipment and materials to a level that permits removal of regulatory control and are dismantled shortly after the cessation of operations [US NRC, 2015].

During SAFSTOR, a facility is left intact with fuel being removed and radioactive liquids have been drained from systems and components and then processed. Radionuclide decay occurs during the period of safe storage, thus reducing the quantity of contaminated and radioactive material [US NRC, 2015]. SAFSTOR is considered differed dismantling.

During ENTOMB, radioactive structures, systems, and components are encased in a structurally stable material like concrete. The entombed structure is appropriately maintained and continuous surveillance is performed until the radionuclides decay to a level that meets regulatory requirements for restricted release of the property. To date, no NRC licensed facilities have requested ENTOMB option [US NRC, 2015].

US reactors that have completed decommissioning and those that are in the process of decommissioning are listed in Table 1-1 and Table 1-2 respectively [NEI, 2016].

Table 1-1: US Reactors that have Completed Decommissioning [NEI, 2016].

Reactors that completed decommissioning (ISFSI-only or license terminated):	
Big Rock Point Fort St. Vrain Haddam Neck Maine Yankee Pathfinder	Rancho Seco Shippingport Shoreham Trojan Yankee Rowe
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Table 1-2: US Reactors in Decommissioning [NEI, 2016].

Reactors in decommissioning:	
Crystal River 3 Dresden 1 Fermi 1 GE ESADA Vallecitos GE Vallecitos BWR Humboldt Bay* Indian Point 1 Kewaunee LaCrosse*	Millstone 1 Peach Bottom 1 San Onofre 1 San Onofre 2* San Onofre 3* Three Mile Island 2 Vermont Yankee Zion 1* Zion 2*
*DECON process	
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The typical decommissioning time line used in the US is shown in Figure 1-1 [US NRC, 2015].

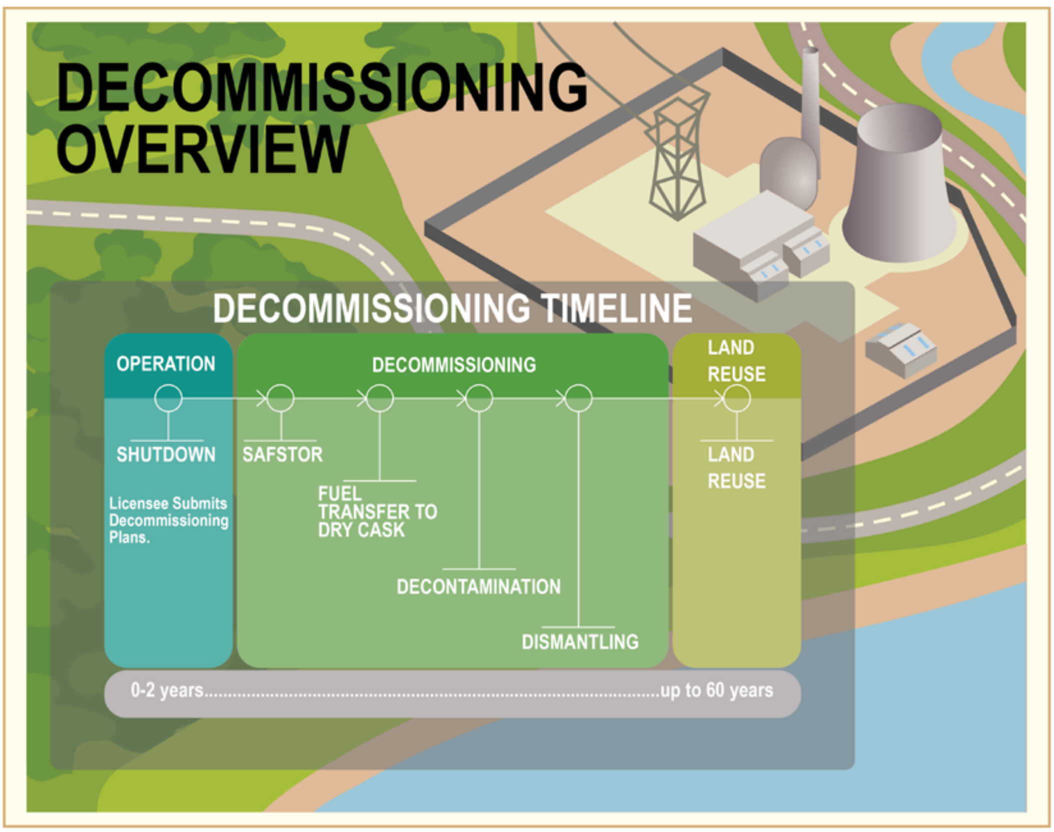

Figure 1-1: The typical decommissioning time line in the US [US NRC, 2015].

This report summarizes the publicly available BWR decommissioning general information and experiences along with salient features and practices employed in the decommissioning activity including potential costs involved. The report does not cover PWR, VVER, CANDU decommissioning or other non-BWR decommissioning activities including Nuclear Research Laboratories.

Some of the key items presented in the report, based on the US experience, include the following:

- Regulatory process of nuclear decommissioning
- General decommissioning guidelines

2 Regulatory Process of Nuclear Decommissioning

2.1 The Basic Approaches Available

The regulatory process codified as 10CFR 50.82 is described in three phases. The first phase begins when a licensee decides to permanently cease operation ends before major decommissioning activity begins or when the reactor is placed in storage mode. The second phase begins during major decommissioning activities including decontamination and dismantling. The third phase involves all remaining activities that lead to termination of the license [EPRI, 1998]. The licensee is expected to comply with NUREG-0586 [NUREG-0586, 1988] that describes the Generic Environmental Impact Statement (GEIS) when using any one of the methods DECON, SAFSTOR or ENTOMB.

In the DECON method, the equipment, structures and parts of the facility and sites that contain radioactive contaminants are removed or decontaminated to a level that permits termination of the license shortly after cessation of operations. The removal of used nuclear fuel rods and equipment—which accounts for over 99 percent of the plant's radioactivity—lowers the radiation level in the facility and significantly reduces the potential exposure to workers during subsequent decommissioning operations. DECON can take up to five years or more [NEI, 2016]. DECON is an acceptable decommissioning method according to GEIS [EPRI, 1998].

In the SAFSTOR method, the facility is placed and maintained in a safe stable condition until subsequent decontamination and dismantling that permits license termination. During SAFSTOR, the facility remains intact, but the fuel is removed from the reactor vessel and radioactive liquids are drained from systems and components and then processed. Radioactive decay occurs during the SAFSTOR period, thereby reducing the quantity of radioactive material that needs to be disposed of during decontamination and dismantling activities. During this time, the main components of the plant remain in place, including the reactor vessel, fuel pools, turbine and other elements. The NRC continues to inspect the site and provides regulatory oversight of maintenance and security appropriate to the low risk profile of the site [NEI, 2016]. SAFSTOR is an acceptable decommissioning method according to GEIS [EPRI, 1998].

In the ENTOMB method, radioactive structures, systems and components are encased in a structurally strong and a long lasting material like concrete. The entombed structure is maintained with continued surveillance until the radioactivity decays to a level that permits license termination. However, this approach of license termination may not be feasible in many cases because the radionuclide concentrations might be such that unrestricted use may not be possible even after 100 years, unless it is demonstrated otherwise [EPRI, 1998].

Licensees may also choose a combination of DECON and SAFSTOR where a Plant could be partially decontaminated, stored and later decontaminated and dismantled. Lacrosse reactor in Wisconsin is an example which is in SAFSTOR and yet some systems and components that are not required for long-term safe storage of spent fuel are being dismantled [EPRI, 1998].

Several nuclear power plants in the US completed decommissioning in the 1990s without a viable option for disposing of their spent nuclear fuel, because the federal government did not construct a geologic repository as planned. Accordingly, the NRC implemented regulations allowing licensees to sell off part of their land once it meets NRC release criteria, while maintaining a small parcel under license for storing the spent fuel. These stand-alone facilities, called "independent spent fuel storage installations," remain under license and NRC regulation. Licensees are responsible for security and for maintaining insurance and funding for eventual decommissioning [US NRC, 2015].

The long-term management of the spent fuel is based primarily on two options -- wet storage using portions or all of the existing spent fuel pool and dry storage using an on-site Independent Spent Fuel Storage Installation (ISFSI). Both options are currently in use at decommission and operating sites.

If the DECON option is chosen, then the approach essentially mandated by schedule is wet storage in the spent fuel pool or spent fuel island, until the fuel can be offloaded into dry cask storage. Typical dry cask storage system licenses require a minimum of five years of spent fuel decay in spent fuel pools to reduce heat load prior to placement into dry cask storage. This requirement means that the spent fuel pool and associated systems are usually required for at least five years after final reactor shutdown [EPRI, 2006].

As more facilities complete decommissioning, the NRC is implementing "lessons learned" in order to improve the program and focus on the prevention of future legacy sites that are difficult to clean up. Applications for new reactors must now describe how design and operations will minimize contamination during the plant's operating life and facilitate eventual decommissioning. New regulations published in 2010 require plant operators to be more vigilant in preventing contamination during operations, and to clean up and monitor any contamination that does occur [US NRC, 2015].

2.2 Plant Closure Initial Phase Activities – Planning and Preparation

All documents associated with the decontamination and dismantling activities need to be prepared as a part of this phase.

A licensee who decides to permanently cease operation must submit written certification within 30 days to NRC in accordance with 10CFR 50.82a(1)(i). The licensee shall also submit certification in accordance with 10CFR 50.82a(1)(ii) once the fuel has been permanently removed from the reactor pressure vessel [EPRI, 1998]. Once these certifications are filed, 10CFR 50.82a(2) prohibits operation of the reactor and movement of fuel into the reactor vessel.

After docketing these certifications, the licensee may begin certain decommissioning activities, however, major decommissioning activities such as planned decontamination and dismantling is allowed to be performed after submitting a post shutdown activities report (PSDAR) within 2 years following cessation of plant operation in accordance with 10CFR 50.82a(4). The PSDAR has information on decommissioning schedule, work plans, operating procedures, milestones, costs and environmental impacts. The decommissioning activities also allow accessing the trust funds in a phased approach. Following the submittal of PSDAR and following the submittal of the license termination plan (LTP), the public has the opportunity to participate. Licensees may begin major decommissioning activities 90 days after submitting the PSDAR to NRC.

After receiving the report, the NRC publishes a notice of receipt in the Federal Register, makes the report available for public review and comment, and holds a public meeting in the vicinity of the plant to discuss the licensee's intentions [US NRC, 2015].

A Schematic of activities to be performed before clean-up is shown in Figure 2-1[US NRC, 2015].

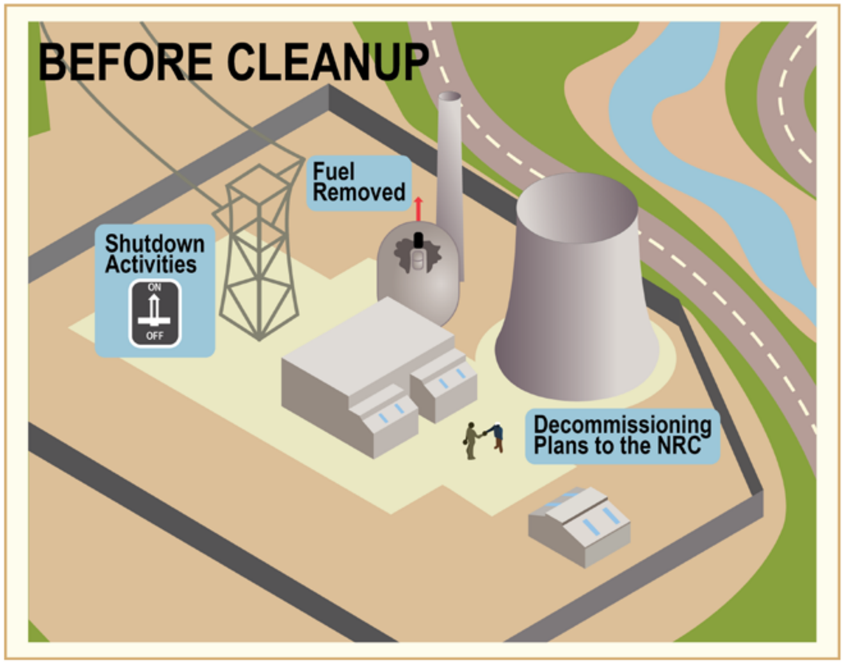

Figure 2-1: A Schematic of activities to be performed before clean-up [US NRC, 2015].

2.3 Major Decommissioning Phase Activities – Decontamination and Dismantling

Decommissioning activities are defined in 10CFR 50.2 as permanent removal or dismantling of major radioactive components such as, the reactor vessel and internals, large bore reactor coolant system piping and other large radioactive components. These activities can begin ninety days after the NRC receives the planning report, the owner can begin major decommissioning activities without specific NRC approval [US NRC, 2015].

This phase includes the activities associated with the mobilization of workers to the site to perform the decontamination and dismantling activities. This will also include training and establishing work areas, safety controls and appropriate administrative areas.

A Schematic of activities to be performed during clean-up is shown in Figure 2-2 [US NRC, 2015].

3 General Decommissioning Guidelines

The intent is to decommission the facility so as to reduce the level of radioactivity remaining in the facility to residual levels that are suitable for unrestricted release in accordance with the criteria for decommissioning in 10CFR 20.1401 and 20.1402, and for NRC license termination pursuant to 10CFR 70.38. The level of radioactivity remaining need to be suitable for unrestricted release in a manner that will not require stabilization and long term surveillance programs [US NRC, 2014].

- Release criteria for building surfaces and soils need to be established and approved as a part of the development and approval of the Decommissioning Plan.
- Decommissioning activities need to include the cleaning and removal of radioactive and hazardous waste contamination that may be present on materials, equipment and structures. Cleaning effectiveness need to be assured by verification.
- A reasonable effort need to be made to eliminate residual contamination as part of the decommissioning activities in accordance with the provisions of "As Low As Reasonably Achievable" (ALARA).
- Radioactivity on equipment or surfaces should not be covered by paint, plating, or other covering material unless contamination levels are below the limits specified in Decommissioning Plan prior to applying the covering.
- The radioactivity on the interior surfaces of pipes, drain lines, and ductwork need to be determined by making measurements at traps, and other appropriate access points, provided that contamination at these locations is likely to be representative of contamination on the interior of the pipes, drain lines, or ductwork. Surfaces of premises, equipment, or scrap which are likely to be contaminated but are of such size, construction, or location that the surfaces are inaccessible for purposes of measurement will have to be presumed to be contaminated in excess of the limits.
- Special requests may be made to NRC to authorize the release of premises, equipment, or scrap having surfaces contaminated in excess of the limits specified. This may include, but may not be limited to, special circumstances such as razing of buildings or transferring of premises or equipment to another organization continuing work with radioactive materials.
- Radiation exposure limits need to be consistent with allowable limits specified in 10CFR 20.
- Shipments of radioactive materials associated with decommissioning need to conform to the applicable regulations of Title 49 Code of Federal Regulations for transporting hazardous materials.
- Prior to release for unrestricted use, a comprehensive radiation survey need to establish that contamination levels and dose rates are within the limits approved in the Decommissioning Plan.
- Independent reviews of the premises need to be made to verify that hazardous waste and radioactive contamination have been removed to acceptable levels and that the premises meet regulatory release limits.

4 Typical Decommissioning Action Plan

A typical decommissioning action plan involves a variety of steps that can be attended to while the plant is still operating. If approvals are obtained for some of these steps, it allows the licensee to implement decommissioning activities immediately after the cessation of plant operation and defueling of the reactor vessel [US NRC, 2014].

As an example, Oyster Creek BWR developed a number of specific decommissioning project plans while the plant was still operating. This allowed the decommissioning work to be identified, scheduled and accomplished in a timely manner.

Following is a list of steps involved in a decommissioning process action plan Figure 4-1 [EPRI, 1998].

- <u>Certification</u>: Prepare and submit certifications required by 10CFR 50.82 describing that a decision has been made to permanently cease operations and fuel has been permanently removed from the reactor.
- <u>Staffing Plan</u>: Adequate staffing plan is established with minimum staffing requirements to address emergency response, fire protection, security and certified fuel handlers
- <u>Technical Specifications</u>: Revise technical specifications for a defueled mode, and identify which ones are applicable during decommissioning since operational modes are no longer applicable. The applicable specifications may include, spent fuel pool operation, effluent monitoring and other administrative controls.
- <u>Accident Assessment</u>: Re-evaluate FSAR accident assessment so that it is applicable to a permanently shutdown defueled facility. Review potential accidents relating to fuel handling from spent fuel pool (SFP), cask drop, radioactive liquid release if applicable, as limiting events. As an example, one plant identified the resin container accident as the most limiting event while another identified mishandling of a feed and bleed heat exchanger as the most limiting event. In addition, fires associated with zircaloy fuel cladding should also be examined in this evaluation. The assessment should also include an engineering evaluation on SFP heat-up, evaporation rate and consequences of terminating SFP cooling. The revised FSAR accident analysis should be prepared to facilitate future use of 10 CFR 50.59 for decommissioning activities.
- <u>Emergency Plan</u>: Develop an emergency plan for a de-fueled situation using the already existing FSAR accident analysis as the basis. It should be possible to conclude that the release of radioactive material beyond the protected area is within the existing EPA protective action guidelines. This plan, in principle, should have a reduced number of emergency action levels and emergency classifications.
- <u>Security Plan</u>: The security plan needs to be adjusted to reflect the reduced requirements for a permanently defueled facility and focus on threats that could target spent fuel pool integrity. The plan should address the defueled security training and qualifications. In addition, the licensees may consider having an independent assessment of the proposed plan changes that may facilitate NRC review of the proposed plan.
- <u>Operations Training and Requalifications</u>: Redefine operations training and requalification that compliments shift staffing to maintain the defueled facility within technical specifications. With defueled condition, licensed Senior Reactor Operators are replaced with certified fuel handlers and equipment operators.
- <u>Relief Requests</u>: Since the facility is non-operational and defueled, operational rules do not apply. However, the licensee must seek relief from the regulator (e.g. NRC) for regulations not addressed by the new rule making.
- <u>UFSAR Update</u>: Maintain updates and review the FSAR. Updated FSAR must be filed with NRC at least every 24 months.
- <u>QA Program</u>: Modify and reduce the scope of the QA program appropriately to address the defuel condition. This may require systems functional review and review of remaining systems supporting spent fuel.
- <u>Fire Protection Program</u>: Examine the potential for fire hazards under defueled condition to maintain the spent fuel pool and minimize the spread of contamination with fewer energized systems in operation. Evaluate the need to reduce fire brigade staffing.
- <u>Site Characterization</u>: Site characterization requires identification of locations that require removal of contamination (remediation) in order to meet the criteria for license termination. A

5 General Decontamination, Cleaning Methods and Dismantling

Removal of radioactive material from contaminated surfaces can be accomplished [US NRC, 2014] in three ways: (1) physical cleaning of the surface, (2) using chemicals to dissolve surface films containing radioactive materials or (3) removing the surface of the structure itself (i.e. mechanical action).

5.1 Decontamination and Cleaning Methods

Physical cleaning methods include sweeping, vacuuming, hand wiping, sandblasting, and washing with various cleansing agents. Chemical decontamination methods use acid or basic solutions to dissolve residual contamination from surfaces. This technique is usually applied to wet processing systems, such as pumps, piping, and storage tanks. If physical cleaning and chemical decontamination techniques do not reduce contamination levels on equipment and/or building surfaces to acceptable radioactivity release levels, or are unfeasible, it will be necessary to either use more extensive methods, such as sandblasting or scraping that physically removes surface layers, or to remove the item for burial.

Removal of contamination from sealed porous surfaces, such as painted walls and floors, asphalt, tank exteriors, and other surfaces, will be accomplished using a variety of techniques. For removable contamination, vacuuming or simple sweeping compounds are often effective. For more fixed contamination, various cleaning compounds combined with hand wiping, hand scrubbing, and/or power scrubbing techniques can be utilized.

Degreasing agents may be used to remove contamination films from surfaces. Organic solvents have an advantage of not being corrosive to equipment and electrical connections.

Variable pressure, high or low-velocity liquid jets can be effective for some types of decontamination work. The device can be operated by one person, at pressures up to 30,000 psi, using a hand-held jet lance. Typical tools and equipment used for dismantlement and decontamination are as follows:

Oxyacetylene Torch, Guillotine Pipe Saw, Tube Cutter, Ratcheting Pipe Cutter, Reciprocating Saw, Nibbler Assorted Tools (Impact Wrenches, Bolt Cutters, etc.), High-Velocity Liquid Jet, Low-Velocity Liquid Jet, Hydraulic Concrete Surface Spalling Device, Concrete Drills, Electric/Pneumatic Hammers, Portable A Frames, Portable Wash Tanks, Portable Greenhouse Erection Kit, Portable Spray Cleaning Booth, Portable Power Brushes, Portable Abrasive Blasting Unit.

A variety of other mechanical technologies used in dismantlement and management of low level, intermediate level and high level radwaste are listed by Cuomo [Cuomo, 2002].

Chemical techniques use diluted or concentrated solvents which come in contact with the radioactive substances to be dissolved. The dissolution may also cause the dissolution of part of the base material or simply of the radioactive deposit film on the surface. This last approach is adopted when there is an interest in maintaining the integrity of the base metal such as in the case of operating plants, where the decontamination is applied only to reduce worker doses during maintenance activities. Chemical decontamination is applied by a continuous flushing in intact piping, creating a closed loop, and it is preferred for areas where access is difficult and for decontaminating the internal surfaces of piping. Chemical decontamination can be also successfully used for large areas such as floors and walls [Cuomo, 2002]. Chemical solutions identified as decontamination agents and compatible with the available waste treatment processes and with materials used in the system may be used during decontamination. Consideration need to be given to cost and environmental impact.

Concrete surfaces in the plant which are contaminated to a depth of a few centimetres and that cannot be cleaned to an acceptable release level by surface wiping or washing techniques need to be physically removed and packaged for disposal. Several criteria need to be considered in selecting a concrete removal method. The selected method need to facilitate control of airborne contamination and minimize the potential for personnel exposure to radioactivity. The size and weight of removed materials need to be controlled to facilitate packaging and shipping for disposal [US NRC, 2014].

6 Radiological and Industrial Safety

During decommissioning activities, worker exposures and potential release pathways need to be controlled and monitored in accordance with internal procedures, license conditions and regulatory requirements [US NRC, 2014].

The criticality accident alarm system (CAAS), which provides real-time monitoring wherever spent nuclear material (SNM) is handled or stored on the plant site, need to be operationally maintained to assure that the system will provide an alarm in the unlikely event a criticality occurs. The CAAS need to remain active as long as the monitoring system is needed. An interim emergency response plan needs to be prepared prior to the start of the decommissioning activities.

Another safety system that will be essential during decontamination is the fire alarm system with fire alarm boxes strategically placed throughout the site. After being triggered, the system currently sends out a coded alarm that identifies the area of the fire. Activities during decommissioning such as cutting, dismantling and non-routine trash accumulation makes this safety system essential.

Necessary environmental monitoring programs established during the operation of the plant need to continue during the decommissioning activities to assure that contaminants are being contained. Samples are typically taken at the stack release points, from soil around the site, at the discharge point, and from wells around the site. These samples need to be analysed for specific contaminants. A history of data has been generated to provide a reference point for the evaluation of the effectiveness of the environmental monitoring program during decommissioning.

Radiation exposure to employees need to be monitored through existing programs, such as issuance of personnel monitoring devices, air sampling of airborne contamination, and routine bioassays. These programs need to be continued to meet the regulatory requirements specified in 10CFR 20.

Workers who are trained in radiation protection practices and contamination control techniques should perform decontamination activities. Protective clothing needs to be made available in sufficient quantities to allow for personnel contamination control. Various types of respirators need to be available to provide the degree of protection necessary for the decontamination job being performed, ranging from half-mask respirators to supplied air hoods or masks.

For jobs requiring dismantlement of heavily contaminated items, isolation tents with portable blowers and high efficiency particulate air (HEPA) filters may be utilized. Tenting techniques may also be employed for decontamination activities where significant dusting potential exists.

7 Waste Management

Radioisotopes with a half-life of more than ten days may contribute to radioactive waste. The waste needs to be kept safe until the process of decay reduces the radioactivity levels of the materials. For storage and disposal, it is usually classified into different types (very low level-VLLW, low level-LLW, intermediate level-ILW and high level-HLW radioactive waste) according to risks and decay time (Table 7-1).

Table 7-1: Radioactive waste classification. Source: Adapted from [IAEA, 2009].

	Very Low Level Waste (VLLW)	Low Level Waste (LLW)	Intermediate Level Waste (ILW)	High Level Waste (HLW)
Radioactivity	Contains very limited concentrations of long-lived radioactive isotopes with activity concentrations usually above the clearance levels	Contains limited concentrations of long-lived radioactive isotopes but has high radioactivity	Contains long-lived radioactive isotopes that will not decay to a level of activity concentration acceptable for near surface disposal	Contains levels of activity concentration high enough to generate significant quantities of heat by radioactive decay or with large amounts of long-lived radioactive isotopes
Examples of waste sources	Concrete rubble, soil	Clothing, glass, building materials	Fuel rod casings, reactor vessel part	Debris of spent fuel
Isolation	Engineered surface landfill	Near surface disposal at depth up to 30 meters	Shallow disposal at depth from a few tens to a few hundred meters	Deep geological formations
Need shielding	No	No	Yes	Yes
Need cooling	No	No	No	Yes

Most of the high level radioactive material that finally contributes to high level radioactive waste is the spent fuel regularly removed from operating reactors. A typical 1000-MWe reactor produces about 27 tonnes of this waste per year [WNA, 2011a]. The amount of spent fuel produced by the world's reactors is barely enough to fill two Olympic size swimming pools every year. Although the volumes are relatively small, high level waste contains 95 per cent of the radioactivity in waste from the nuclear power industry. It will need to be kept isolated for thousands of years [UNEP, 2012].

According to current waste management practices, high level waste will ultimately require disposal in deep geological formations. Establishment of such sites has been delayed, partly related to costs, partly to public opposition to proposed sites [WNA, 2011b].

After the spent fuel is removed, decommissioning produces only small amounts of high level waste (HLW), most of which is nuclear fuel debris left behind after the last fuel was removed from the reactor. However, decommissioning typically generates two-thirds of all the very low, low and intermediate level waste (VLLW, LLW and ILW) produced during a reactor's lifetime. Dismantling a 1000-MWe reactor generates around 10 000 m^3 of VLLW, LLW and ILW, but that amount may be greatly reduced with proper management and use of robots to more selectively to separate the more radioactive parts from the rest [McCombie, 2010]. This waste can include large amounts of construction materials, along with steel reactor vessel equipment, chemical sludges, control rods, and other types of material that have been in close proximity to reactor fuel. The radioactivity of the waste generated during decommissioning will usually be negligible within a few decades. Nevertheless, this waste requires safe handling, storage and disposal until that time [UNEP, 2012].

8 Final Release

As areas/buildings are being decontaminated, contamination surveys need to be made to determine the degree to which decontamination has been effective. Upon completion of all decommissioning activities a final site survey need to be performed to determine the level of residual material. It is intended to demonstrate that applicable limits have been achieved, and that the premises may be released for unrestricted use [US NRC, 2014].

Once public concerns are addressed, the NRC will terminate the license if all work has followed the approved license termination plan and the final radiation survey shows that the site is suitable for release. Most plans envision releasing the site to the public for unrestricted use, meaning any residual radiation would be below NRC's limits of 25 millirem (0.25 mSv) per year. This completes the decommissioning process [NEI, 2016].

A detailed survey report need to be prepared which identifies the premises, describes the scope of the survey, and reports the findings of the survey in specified units. A copy of this survey report needs to be submitted to the NRC and the State requesting release of the site for unrestricted use.

9 Decommissioning Funds and Cost Estimates

Before a nuclear power plant begins operations, the licensee must establish or obtain a financial mechanism – such as a trust fund or a guarantee from its parent company – to ensure there will be sufficient money to pay for the ultimate decommissioning of the facility [US NRC, 2015].

Each nuclear power plant licensee must report to the NRC every two years the status of its decommissioning funding for each reactor or share of a reactor that it owns. The report must estimate the minimum amount needed for decommissioning by using the formulas found in 10 CFR 50.75(c). Licensees may alternatively determine a site-specific funding estimate, provided that amount is greater than the generic decommissioning estimate. Although there are many factors that affect reactor decommissioning costs, generally they range from $300 million to $400 million. Approximately 70 percent of licensees are authorized to accumulate decommissioning funds over the operating life of their plants. These owners – generally traditional, rate-regulated electric utilities or indirectly regulated generation companies – are not required today to have all of the funds needed for decommissioning. The remaining licensees must provide financial assurance through other methods such as prepaid decommissioning funds and/or a surety method or guarantee. The staff performs an independent analysis of each of these reports to determine whether licensees are providing reasonable "decommissioning funding assurance" for radiological decommissioning of the reactor at the permanent termination of operation.

In the case of BWRs, approximately 33% of the cost goes for dismantling while about 23% goes toward waste treatment and disposal, and the weight of radioactive waste arising from decommissioning activities is below 10 tonnes per MWe [OECD/NEA, 2003].

10 Power Reactor Shutdown and Decommissioning Status in the United States

Decommissioning status, as of May 2015, for shutdown of NRC licensed reactors in shown in Table 10-1 [US NRC, 2015].

Table 10-1: Decommissioning Status for Shutdown of NRC-Licensed Power Reactors (As of May 2015)

Reactor	Type	Location	Ceased Operations	Status	Fuel Onsite
Big Rock Point	BWR	Charlevoix, MI	8/29/97	ISFSI Only*	Yes
Crystal River 3	PWR	Crystal River, FL	2/20/13	SAFSTOR	Yes
Dresden 1	BWR	Morris, IL	10/31/78	SAFSTOR	Yes
Fermi 1	Fast Breeder	Monroe Co., MI	9/22/72	SAFSTOR	No
Fort St.Vrain	HTGR	Platteville, CO	8/18/89	ISFSI Only	Yes
GE VBWR	BWR	Alameda Co., CA	12/9/63	SAFSTOR	No
Haddam Neck	PWR	Haddam Neck, CT	12/9/96	ISFSI Only	Yes
Humboldt Bay 3	BWR	Eureka, CA	7/2/76	DECON	Yes
Indian Point 1	PWR	Buchanan, NY	10/31/74	SAFSTOR	Yes
Kewaunee	PWR	Carlton, WI	5/7/13	SAFSTOR	Yes
LaCrosse	BWR	LaCrosse, WI	4/30/87	DECON	Yes
Maine Yankee	PWR	Wiscasset, ME	12/6/96	ISFSI Only	Yes
Millstone 1	BWR	Waterford, CT	7/21/88	SAFSTOR	Yes
N.S. Savannah	PWR	Norfolk, VA	11/70	SAFSTOR	No
Pathfinder	Superheat BWR	Sioux Falls, SD	9/16/67	License Terminated	No
Peach Bottom 1	HTGR	York Co., PA	10/31/74	SAFSTOR	No
Rancho Seco	PWR	Sacramento, CA	6/7/89	ISFSI Only**	Yes
San Onofre 1	PWR	San Clemente, CA	11/30/92	SAFSTOR	Yes
San Onofre 2&3	PWR	San Clemente, CA	6/12/13	SAFSTOR	Yes
Saxton	PWR	Saxton, PA	5/1/72	License Terminated	No
Shippingport	PWR	Shipping Port, PA	10/1/82	License Terminated	No
Shoreham	BWR	Suffolk Co., NY	6/28/89	License Terminated	No
Three Mile Island 2	PWR	Middletown, PA	3/28/79	SAFSTOR***	No
Trojan	PWR	Portland, OR	11/9/92	ISFSI Only	Yes
Vermont Yankee	BWR	Vernon, VT	12/29/15	SAFSTOR	Yes
Yankee Rowe	PWR	Franklin Co., MA	10/1/91	ISFSI Only	Yes
Zion 1 & 2	PWR	Zion, IL	2/21/97 9/19/96	DECON	Yes

[shaded] Decommissioning completed

* An independent spent fuel storage installation (ISFSI) is a stand-alone facility within the plant boundary constructed for the interim storage of spent nuclear fuel. ISFSI Only means the plant license has been reduced to include only the spent fuel storage facility.

** Rancho Seco has a low-level waste storage facility in addition to its ISFSI.

*** Post-defueling monitored storage (PDMS).

11 US BWR Decommissioning Details

Big Rock Point

Big Rock Point was Michigan's first nuclear power plant and the nation's fifth. It also produced Cobalt-60 for the medical industry from 1971 to 1982.

Ground was broken on July 20, 1960. Construction was completed in 29 months at a cost of $27.7 million. Its license from the Nuclear Regulatory Commission was issued on August 29, 1962. The reactor first went critical on September 27 and the first electricity was generated on December 8, 1962.

The 75 MWe reactor was scrammed for the last time at 10:33 a.m. EDT on August 29, 1997, after 35 years of safe and successful operation. The last fuel was removed from the core on September 20, 1997. Decontamination of the reactor vessel, primary coolant system, reactor water clean-up system, the shutdown cooling system and the steam drum was completed using standard decontamination approaches in 1999. The chemical used was fluoroboric acid to dissolve contamination (mostly Co-60). The process effectively removed 96% of the contamination [Tompkins, 2006]. Following the primary system decontamination, the average post-decon contact dose rates were 10 mRem/hr. A total of 406 Curies of gamma emitting radionuclides (83% of which is Co-60) was removed by cation exchange resins [EPRI, 2004].

The 235,000-pound (107,000 kg) reactor vessel (9.1 m tall and 2.7 m diameter) was removed on August 25, 2003 and shipped to Barnwell, South Carolina on October 7, 2003.

The license termination plan (LTP) was developed based on NUREG-1700 and references 5 to 13 listed therein [NUREG-1700, 1998]. The NRC License Termination Rule [10CFR 20.1402] defines the standard for unrestricted release of a site as that no average member of a group receive a post closure dose of more than 25 mrem/yr Total Effective Dose Equivalent (TEDE) from all dose pathways (i.e. contaminated soil, concrete and groundwater) [EPRI, 2008].

All of Big Rock Point's 500-acre (200 ha) has been torn down. Other than eight spent fuel casks and the spherical containment structure, there are no signs that the site was home to a nuclear power plant.

Decommissioning costs totalled $390 million at the time.

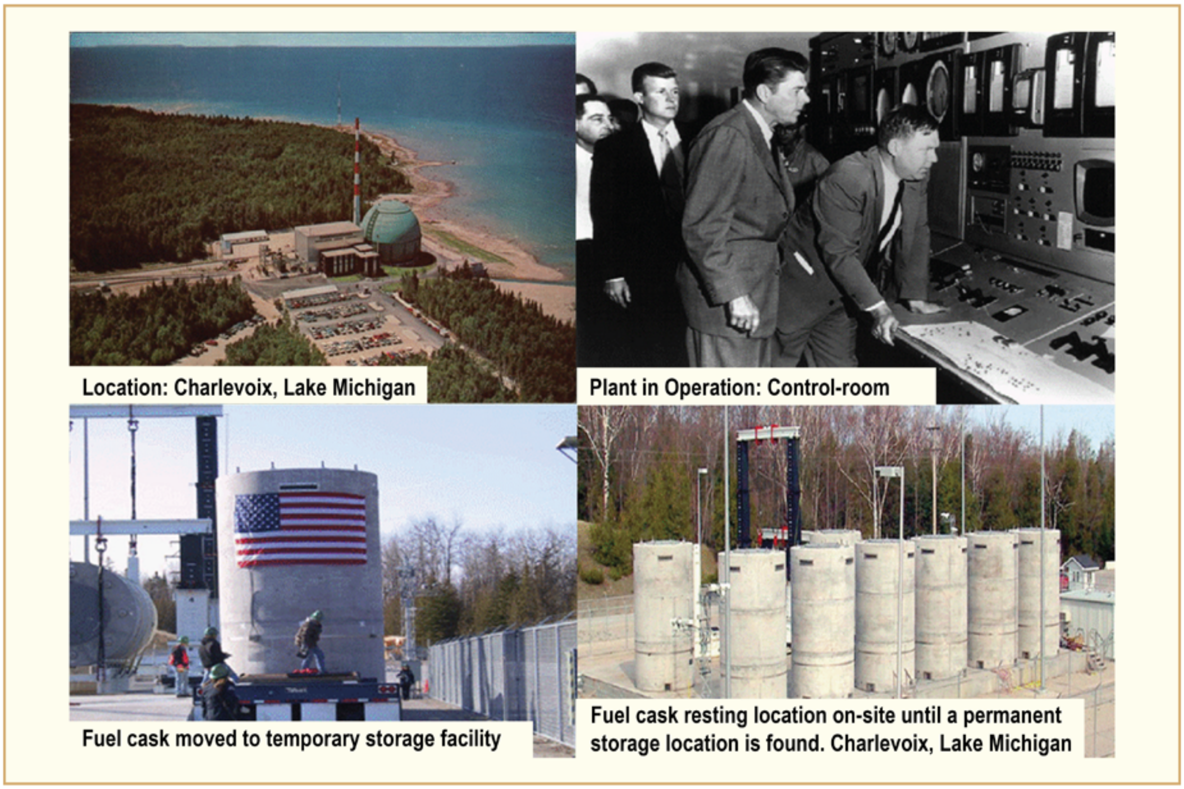

Figure 11-1: A brief history of Big Rock Point plant from operation to dry fuel cask storage [Internet Sources, 2017].

At Big Rock Point Plant, the work scheduled in 1999 included the following [Powers & Petrosky, 1999]:

- Reactor vessel characterization
- Installation of an alternate liquid radwaste system
- Dismantlement of the control room
- Establishment of a spent fuel pool monitoring station
- Completion of the spent fuel pool cooling skid
- Chemical decontamination of chromated systems
- Condenser removal
- Feedwater heater removal
- Condensate tank removal
- Switchyard dismantlement
- Control rod drive room dismantlement

Other activities performed in decommissioning and decontamination of Big Rock Point (BRP) Plant has been reported by Carraway and Wills [Carraway & Wills, 2001].

The unique approach of BRP decommissioning approach is the application of the regulation in 10CFR 20.2002, "Method for obtaining approval of proposed disposal practices". This regulation allows licensees to apply to the commission to dispose of licensed material like concrete that is within dose limits, into a state of Michigan landfill with considerable cost savings as opposed to a NRC licensed landfill [EPRI, 2004].

The general soil contamination levels at the site was low, with few locations indicating maximum concentrations of Cs-137 and Co-60 at 31 pCi/kg and 106 pCi/kg (1.147 Bq/kg and 3.922 Bq/kg) [EPRI, 2004].

12 Technical Advances and Research Activities in Decommissioning and Decontamination

The extensive activities performed by EPRI in collaboration with many organizations on technical advances, completed research activities and new research activities are summarized in a separate reference [Bushart, 2008]. The reference provides information and reference sources on reports on decommissioning and decontamination experience along with lessons learned, waste storage, remediation of contaminated soil and concrete, nuclear plant ground water monitoring, reactor vessel segmentation, ground water protection guidelines, radioactive waste handling, and radionuclide separation and removal techniques.

Many EPRI report references dealing with nuclear plant decontamination and decommissioning appear in EPRI reports, 1) on Decommissioning Planning [EPRI, 2006], 2) on Power Reactor Decommissioning Experience [EPRI, 2008] and 3) on Decommissioning and Remediation [EPRI, 2012].

13 NPP Decontamination and Decommissioning Status in Germany

Germany's decision to phase out nuclear energy for commercial power generation in 2011 followed the Fukushima Daiichi incident. All eight NPPs, which were shut down in 2011, applied for a decommissioning license [Brendebach, 2016]. Decommissioning includes post-operating activities such as defueling, licensing etc., and then 10 to 13 years for dismantling [Thomauske et al., 2016]. The decision as to which decommissioning strategy to implement is taken by the operator. Most operators have opted for immediate dismantling [Brendebach, 2016].

A legislated schedule for plant closures shut eight reactor blocks in March 2011 with all NPPs to be closed during the period 2011 – 2022. Figure 13-1 shows the phase out program in terms of generation capacity. Nine plants in decommissioning (three yet to finish); nine in post operations shut down pending decontamination and decommissioning (D&D); and eight plants still operating. Few have reached "green field" status [Thomauske et al., 2016].

The German Atomic Energy Act allows either immediate dismantlement or dismantlement after safe enclosure of a nuclear facility. No entombment (near surface disposal) is allowed. The operator of the nuclear facility is fully responsible for the decommissioning and dismantlement of the facility. The operator decides on the decommissioning strategy, the scope of the license to be applied for and the time frame of the decommissioning project. The operator is also responsible for the safety of the facility and any precautionary measures to be taken. The decommissioning activities are subject to intensive regulatory supervision involving the on-site presence of technical experts [Imielski, 2014].

The NPP decommissioning program is expected to proceed as follows:

- Continuing work at Obrigheim (KWO), Würgassen and Stade
- Philippsburg 1 (KKP1) and Neckarwestheim 1 (GKN1) will see the beginning of dismantling work by 2017
- Isar 1 (KKI1) and Biblis A and B are expected to follow soon
- Other reactors that were shut down in 2011 will follow decommissioning as soon as licensing, resources and finances are available

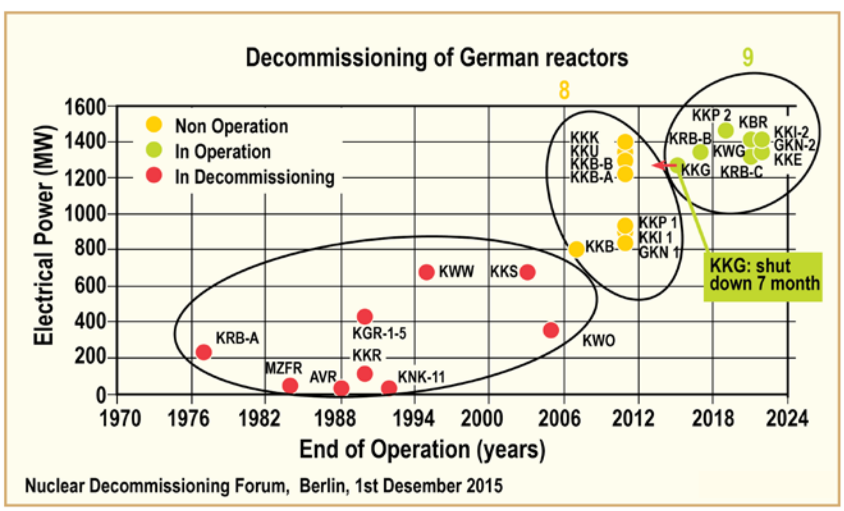

Figure 13-1: Nuclear power plant closures in Germany [Thomauske et al., 2016].

An overview of the currently on going decommissioning projects in Germany is shown in Table 13-1. In most cases decommissioning is in progress while the fuel elements are still stored in the cooling ponds until a site is found for long-term storage of fuel elements and other waste.

Table 13-1: Overview of Decommissioning Projects in Germany [Imielski, 2014]

Name	Abbrev.	Reactor type	Power MW_e	Date of application
Lingen	KWL	BWR	252	15.12.2008*
Isar-1	KKI 1	BWR	912	04.05.2012
Unterweser	KKU	BWR	1410	04.05.2012**
Biblis-A	KWB A	PWR	1225	06.08.2012
Biblis-B	KWB B	PWR	1300	06.08.2012
Brunsbüttel	KKB	BWR	806	01.11.2012
Neckarwestheim-1	GKN 1	PWR	840	24.04.2013
Philippsburg-1	KKP 1	BWR	926	24.04.2013
Krümmel	KKK	BWR	1402	–
Grafenrheinfeld	KKG	PWR	1345	28.03.2014

* Dismantling after safe enclosure
**Application changed on 20.12.2013

The projected decommissioning schedule for German NPPs is shown in Figure 13-2 if the Utilities adhere to the legislated closure program.

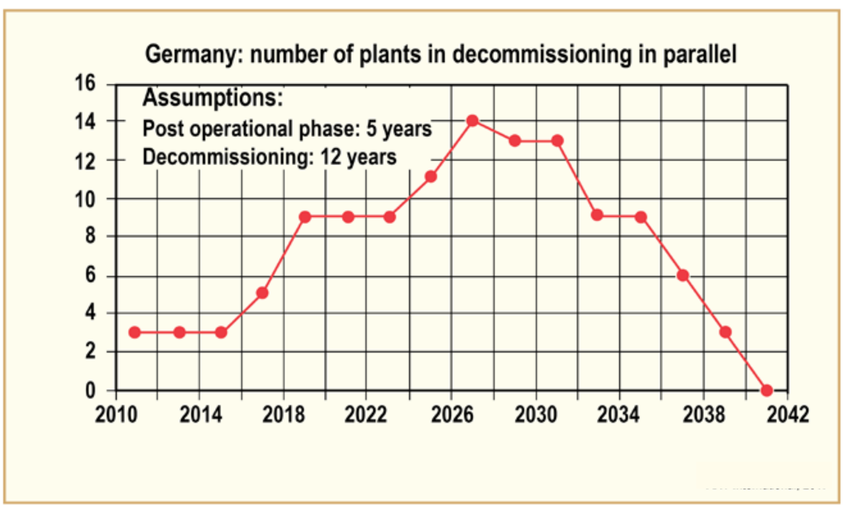

Figure 13-2: Decommissioning Time table for German NPPs [Thomauske et al., 2016].

In the German regulatory system, the German Atomic Energy Act allows either immediate dismantlement or dismantling after safe enclosure of a nuclear facility. No entombment or near surface disposal is allowed. The operator of the nuclear facility has the full responsibility for its decommissioning activities. Decommissioning and dismantling can be subjected to one or more licenses. Furthermore, decommissioning activities are subjected to intensive regulatory supervision involving technical experts and on-site presence of personnel during the course of the project [Imielski, 2014].

A broad process overview to be followed for NPP decommissioning according to German regulatory system is shown Figure 13-3.

14 NPP Decontamination and Decommissioning Status in Sweden

The shutdown of Barsebäck 1 & 2 dual unit BWRs (640 MWe each) occurred in 1999 and 2005 respectively. Transport of spent fuel elements was completed in 2006. Beginnings of decommissioning activities are planned in 2020. Delays are due to the availability of radioactive waste disposal for back end solution in 2020. Current activities include, service operation of the Plant, materials characterization, decommissioning planning according to Swedish "rip and ship" approach, communication with the management and financing via an external fund [Ehlert, 2012].

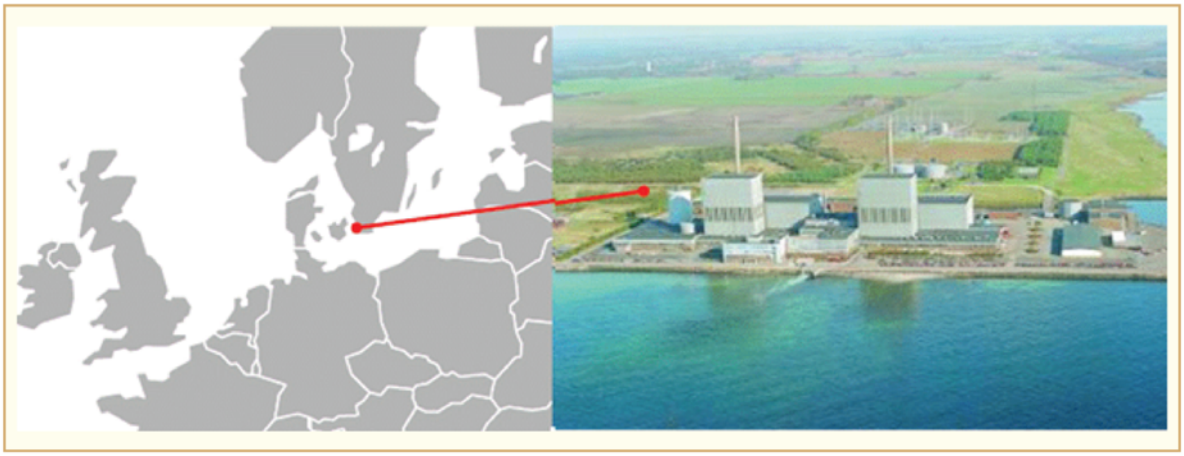

Figure 14-1: Barsebäck 1 & 2 BWR NPP locations in Sweden [Ehlert, 2012]. Adapted from E-ON presentation.

In addition to the already shutdown 2 Barsebäck units, other BWRs in Sweden include the 3 units at Forsmark, 3 units at Oskarshamn and one unit at Ringhals. When these units are systematically shutdown, they would have a final repository for operational waste (SFR) and an interim storage facility for spent fuel (CLAB), managed by the Swedish Nuclear Fuel and Waste Management Company (SKB). The approach of decommissioning waste management is shown in Figure 14-2 [Oskarsson, 2016].

The estimated time line for decommissioning of Ringhals Unit 1 (BWR) and Ringhals Unit 2 (PWR) is shown in Figure 14-3 [Oskarsson, 2016].

During decommissioning, optimization of logistics is crucial because of the large number of multiple story buildings and structures involved, large volumes of concrete, more than 100 km of pipes and tubes, and more than 100,000 components. In addition, all decommissioning and demolition activities have to be performed without affecting electricity supply to the site. From a radiological standpoint, how, when and where to handle radioactive waste (short and long lived) is also critically important. Furthermore, arguments can be made to remove large structures like RPV without segmentation, which is complex, time consuming and provides lower dose [Oskarsson, 2016].

15 NPP Decontamination and Decommissioning Status in Japan

The decommissioning of nuclear power plants is currently gaining increased momentum in Japan. However, since decommissioning has, in many cases, only started after the Fukushima nuclear accidents, most projects are not yet very advanced. Several uncertainties and unsolved problems, such as the method for the retrieval of the fuel debris from the damaged reactors of the Fukushima Daiichi NPPs and the management of the radioactive waste, threaten to lead to serious delays and increased costs. Despite these issues, several new projects were announced in early 2015, while the future of other nuclear power plants remains uncertain [Schmittem, 2016].

Figure 15-1 shows the location of the Japanese power reactors, including the ones that are expected to undergo decommissioning, the total being 15.

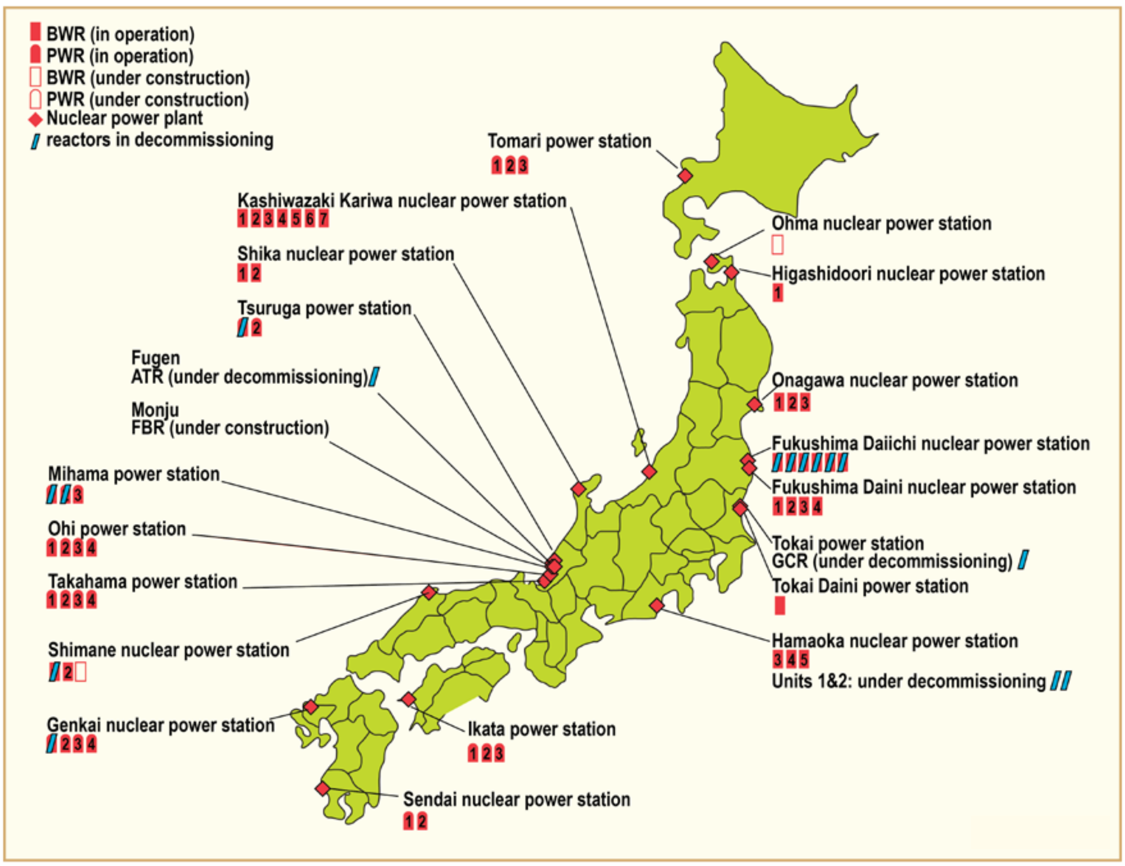

Figure 15-1: The power reactor map of Japan including the ones that are expected to undergo decommissioning (indicated in blue). Figure adapted from [Schmittem, 2016].

Details of the operable nuclear reactors in Japan are shown in Table 15-1.

Table 15-1: Operable reactor status in Japan [Schmittem, 2016].

						as of March 2016
Nuclear Power Plant	**Net Capacity (MW_e)**	**Operator**	**Type**	**Prefecture**	**Application for Re-licencing**	**Operational years**
Takahama NPP	3220	Kansai EP	PWR (4)	Fukui	07/13 (units 3, 4) 03/15 (units 1, 2)	41 40 31 30
Mihama NPP	780	Kansai EP	PWR (1)	Fukui	03/15	39
Ikata NPP	1922	Shikoku EP	PWR (3)	Ehime	07/13 (unit 3)	38 34 21
Tokai II NPP	1060	JAPCO	BWR (1)	Ibaraki	05/14	37
Ohi NPP	4494	Kansai EP	PWR (4)	Fukui	07/13 (units 3, 4)	37 36 24 23
Genkai NPP	2783	Kyushu EP	PWR (3)	Saga	07/13 (units 3, 4)	35 22 18
Fukushima II NPP	4268	TEPCO	BWR (4)	Fukushima		33 32 30 28
Onagawa NPP	2090	Tohoku EP	BWR (3)	Miyagi	12/13 (unit 2)	31 20 14
Sendai NPP	1692	Kyushu EP	PWR (2)	Kagoshima	07/13	31 30
Kashiwazaki-Kariwa NPP	7965	TEPCO	BWR (5), ABWR (2)	Niigata	09/13 (units 6, 7)	30 25 22 21 25 19 18
Tsuruga NPP	1110	JAPCO	PWR (1)	Fukui	11/15	29
Hamaoka NPP	3473	Chubu EP	BWR (2) ABWR (1)	Shizuoko	02/14 (unit 4) 06/15 (unit 3)	28 22 11
Shimane NPP	791	Chugoku EP	BWR (1)	Shimane	12/13 (unit 2)	27
Tomari NPP	1966	Hokkaido EP	PWR (3)	Hokkaido	07/13	26 24 6
Shika NPP	1809	Hokuriku EP	BWR (1) ABWR (1)	Ishikawa	08/14 (unit 2)	22 10
Higashidori NPP	1067	Tohoku EP	BWR (1)	Aomori	06/14	10
Monju NPP	280	JAEA	FNR (1)	Fukui		20

Legend:
Green = restarted reactors
Red = Reactors with 30 or more years of service
Blue = Reactors with less than 30 years of service
Orange = lifetime extension under consideration

Like the decommissioning strategies of many other countries, the basic decommissioning strategy in Japan consists of sequential stages: Site preparation (including site characterisation, defueling and decontamination), safe storage, and deconstruction & dismantling (D&D), as shown in Figure 15-2. Waste management and disposal is also a part of the decommissioning process. While this is acknowledged in the individual decommissioning plans for Japanese reactors, lingering problems with waste management have led to delays in some ongoing decommissioning projects [Schmittem, 2016].

In the first stage of the decommissioning project, the fuel in the reactor core and the spent fuel pool (SFP) is retrieved and transported to either a temporary storage site or a reprocessing plant. After a survey and characterisation of the radioactive inventory of the facility, systems and facilities are decontaminated to reduce the radioactive dose rates in the work spaces and to prepare the site for dismantling.

In the second stage, the reactor core is placed in safe storage, during which basic safety, monitoring and cooling systems are maintained. This stage is meant to reduce the radioactive inventory in the reactor through natural decay processes. The duration of this phase is usually around 10 years for physicochemical reasons. The dismantling of non-essential and redundant systems and peripheral facilities also begins at this point [Schmittem, 2016].

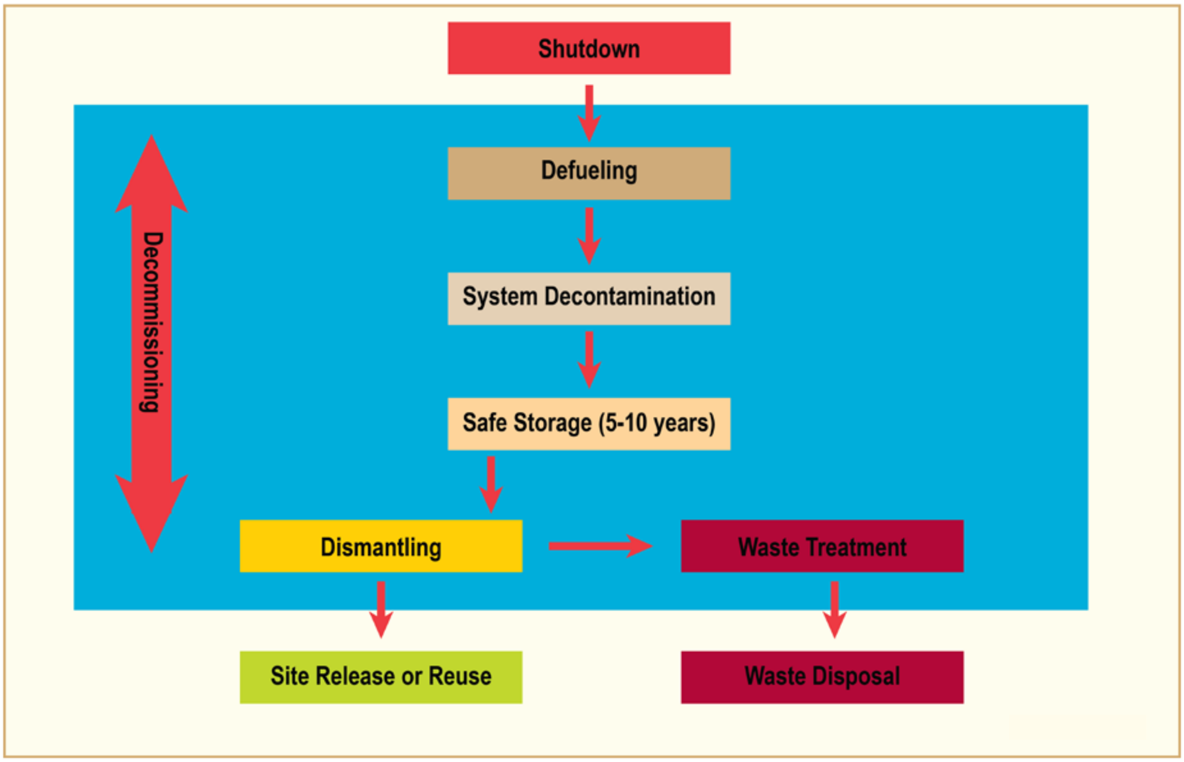

Figure 15-2: Basic decommissioning strategy in Japan [Schmittem, 2016].

During the third stage, various components of the reactor are dismantled. This stage also sees the highest demand for specialised equipment, particularly during the dismantling of the highly radioactive reactor pressure vessel (RPV) and its internals, where remote-controlled, submersible equipment is required. After the reactor has been dismantled, the reactor building and the remaining facilities are dismantled. Large quantities of waste, both radioactive and non-radioactive are generated during this stage.

At the end of the decommissioning process an application for verification of completion is submitted to the Nuclear Regulation Authority (NRA), which then assesses the final state of the site. If the radioactive dose rates are within the legal limits and all targets of the decommissioning plan have been reached, the NRA formally terminates the license of the operator and releases the site from regulatory control. The released reactor site can then be reused for new purposes [Schmittem, 2016].

Waste Management

Japan recognises two basic categories, low-level waste (LLW) and high-level waste (HLW). LLW is further divided into very low-level waste (L3 waste), relatively low-level waste (L2 waste) and relatively high-level waste (L1 waste). Table 15-2 gives an overview of the categorisation of the three types of LLW and the clearance definition in Japan.

Table 15-2: Categorisation of low-level waste in Japan [Schmittem, 2016]

Category	Dose rate	Disposal
Relatively high-level β · γ waste	Upper limit Np-237: 1.3×10^{10} Bq/t, C-14: 5.2×10^{14} Bq/t etc.	Upper limit (L1 repository) Cl-36: 1.0×10^{13} Bq/t, C-14: 1.0×10^{16} Bq/t etc.
Relatively low-level waste	Upper limit Total α: 1.11×10^{9} Bq/t, Co-60: 1.1×10^{13} Bq/t etc.	Upper limit (L2 repository) Co-60: 1.0×10^{15} Bq/t, Cs-137: 1.0×10^{14} Bq/t etc.
Very low-level waste	Upper limit Total α: 1.7×10^{7} Bq/t, Co-60: 8.1×10^{9} Bq/t etc.	Upper limit (L3 repository) Co-60: 1.0×10^{10} Bq/t, Cs-137: 1.0×10^{8} Bq/t etc.
Cleared materials	$\Sigma D/C<1$ C (Co-60: 0.1 Bq/g, H-3: 100 Bq/g, C-14: 1 Bq/g, Pu-238: 0.1 Bq/g etc.)	
Legend: D: Nuclide density, C: Nuclide clearance level		
		© ANT International, 2017

Almost all radioactive waste from decommissioning except for the fuel is classified as LLW in Japan. Very low-level waste (L3 waste in Japan) consists of slightly radioactive waste. Most of the radioactive waste generated during decommissioning falls into this category, up to 60%, depending on the reactor type and other factors such as service life and operational history. L3 waste consists mainly of material from the biological shield of the reactor and some components of the cooling and heat-exchange cycle. A trench-like repository without engineered barriers just below ground is considered to be sufficient for this type of radioactive waste. After being backfilled with soil, periodic inspections of the facility are conducted to monitor its structural integrity and the dose rates in the surrounding area.

Relatively low-level waste (L2 waste) makes up about 36% of the radioactive waste from a decommissioning project. It consists of components such as parts of the steam generator (PWR) and the central part of the RPV. The envisioned strategy for L2 waste disposal is similar to L3 waste, but the repository is constructed with concrete shielding and at slightly greater depth. After being filled with the waste, the storage areas are further stabilised by grouting for additional safety.

Around 4% of the radioactive waste is classified as relatively high-level waste (L1 waste), mainly the reactor internals in the direct vicinity of the fuel. According to the waste disposal concept for this type of waste, repositories will be engineered facilities similar to the L2 waste facilities, but built at a much greater depth (50 to 100 m below ground) and with reinforced shielding.

HLW is more problematic than L1 waste. This material has very high radioactive dose rates and high concentrations of long-living radionuclides, requiring storage for hundreds of years. In Japan, this category is basically reserved for spent fuel waste and waste from reprocessing, in particular transuranic nuclides. Japan plans to build a deep geological repository for this type of radioactive waste and has begun several R&D programs in this direction, mostly under the supervision of the Japan Atomic Energy Agency (JAEA). In the meantime, spent fuel is temporarily stored in the SFPs of remaining NPPs or at a storage facility near Rokkasho, where a new reprocessing plant is slated to commence operations in 2018.

Material with contaminated surfaces can be decontaminated to allow its subsequent unrestricted release. Depending on the purpose and the component, different technologies may be employed (see Table 15-3 below). In general, the inner surfaces of tubes and pipes are decontaminated by using chemical solutions (system decontamination), whereas the surfaces of equipment, components and structures are decontaminated with mechanical, chemical or thermal methods (component decontamination). The decontamination and clearance system in Japan currently focuses on metallic materials, whereas a treatment system for concrete waste is not yet established. The clearance system was introduced during the decommissioning of Tokai I and follows IAEA standards. The central clearance criterion for unrestricted release in Japan is a radionuclide concentration of less than 10 µSv/year. Waste cleared for unrestricted release can be disposed of in conventional waste streams [Schmittem, 2016].

Table 15-3: Available decontamination technologies [Schmittem, 2016]

Decontamination method	Examples	
Chemical	Chemical solutions (CAN-DECON, CITROX, CORD, LOMI etc.) Chemical gels, etc.	
Mechanical	Flushing with water Steam cleaning Abrasive cleaning Drilling and spalling	Vacuuming/wiping/scrubbing CO_2-blasting Scarifying/scabbling/planning etc.
Other	Electro-polishing Ultrasonic cleaning Melting	
Emerging techniques	Supercritical fluid extraction Microwave scabbling etc.	
		© ANT International, 2017

Decontamination technology is also used on a large-scale basis for the treatment of irradiated water at Fukushima Daiichi site, with mixed results. While caesium, strontium and other unwanted nuclides and substances can be removed followed by desalination (Figure 15-3), there are currently no means to remove tritium from the water, making it impossible to release the treated water into the environment. This has led to the construction of large tank farms as shown in Figure 15-4 to store the water on-site until a clearance system or disposal method becomes available (the total volume of stored water exceeds 700,000 t). The application of decontamination technology generates secondary waste therefore, it is important to find a balance between the waste reduction achieved through decontamination and the generation of new waste.

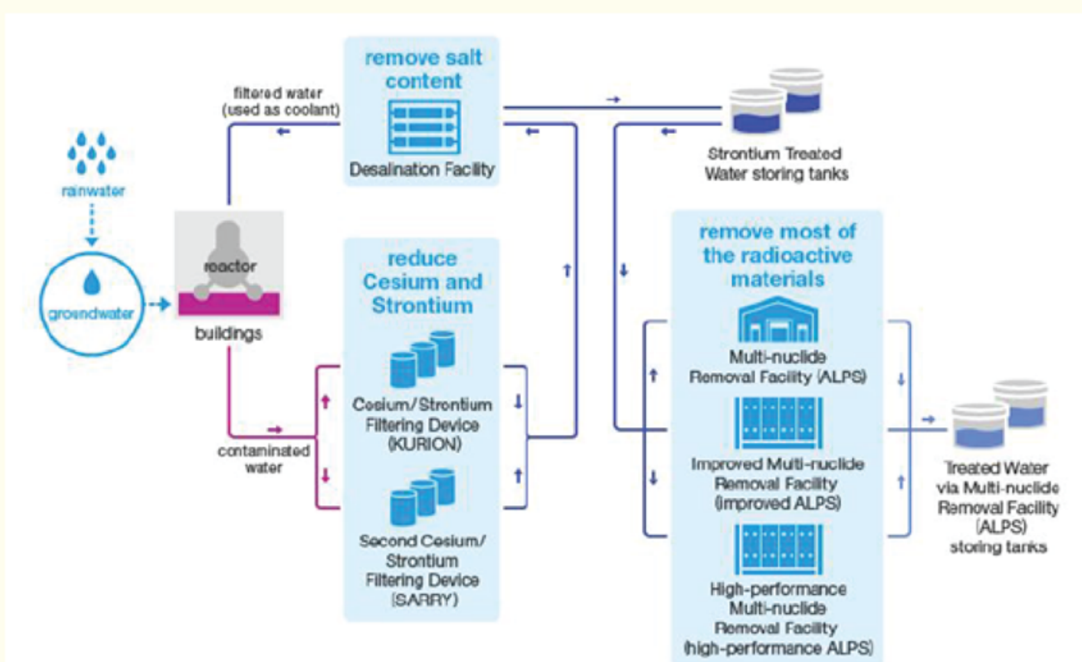

Figure 15-3: Water treatment flow diagram for units 1 – 4 of Fukushima Daiichi NPP [Schmittem, 2016].

Figure 15-4: Radioactive water containing tank farm at Fukushima Daiichi Site [Reuters, 2015].

A significant amount of non-radioactive waste is generated during decommissioning. This is in fact the vast majority of all waste, making up over 95% of the total waste volume. Non-radioactive waste is designated by reviewing documents such as the initial characterisation of the radioactive inventory of the facility. Measurements are taken on a periodic basis for confirmation, with the NRA auditing the process. This waste, mainly concrete and steel, but also electrical equipment, wiring and similar material, may be recycled or disposed of with conventional means [Schmittem, 2016].

Fukushima Specific Decommissioning

International Research Institute for Nuclear Decommissioning (IRID) remains in charge of the implementation of R&D projects for Fukushima I and has developed a number of robots for the exploration and decontamination of the damaged reactor units 1 – 4. The TEPCO Fukushima Daiichi Deconstruction and Dismantling Engineering Company (TEPCO D&D Co.) is responsible for conducting the actual decommissioning work on-site. It is one of the few dedicated organisations for nuclear decommissioning in Japan.

The decommissioning of the damaged reactors at the Fukushima Daiichi NPP, particularly reactor units 1 – 4, are much more complex and technically demanding than conventional decommissioning projects. Furthermore, as each of the damaged reactors is in a different condition, the technology and method for dismantling needs to be customised accordingly. The management of the radioactive waste from each plant also creates additional challenges. The equipment and services have to be specifically tailored to the unique requirements and conditions of each individual reactor. Much of this equipment is not yet developed. This is not necessarily due to technological limitations or limited manufacturing capabilities of the Japanese industry. Instead, the biggest obstacle at the moment is the still incomplete knowledge of the interior of the reactors and uncertainty about the feasibility of the currently adopted fuel retrieval strategy. The safety regulations for the handling, processing and disposal of the molten fuel debris are also not yet established [Schmittem, 2016].

Due to the difficulties of entering the highly radioactive reactor interior, technology development has also focused on developing technologies for the investigation of the reactor interior from the outside. The principal technology developed for this purpose is the muon tomography technology. This technology is used for two purposes: the analysis of the reactor interior and the search for the fuel debris. So far, the technology has confirmed that no large bodies of fuel remain in the reactor cores of

16 Worldwide BWR Decommissioning Status

A list of the worldwide BWRs under decommissioning is shown in Table 16-1.

Table 16-1: Worldwide BWRs in Decommissioning, Adapted from [WNA, 2017].

Country	Reactor	Type	MWe net	Start Date	Years' operating	Shut-down
Germany	Lingen	Prot BWR	183	1968	10	1979
	Groswelzheim	Prot BWR	25	1969	2	1971
	Wuergassen	BWR	640	1972	22	1994
	Gundremmingen A	BWR	237	1967	10	1977
	Brünsbüttel *	BWR	771	1977	30	2007
	Isar 1 *	BWR	878	1979	32	2011
	Krümmel	BWR	1260	1984	25	2009
	Phillipsburg 1 *	BWR	890	1980	31	2011
Italy	Garliano	BWR	150	1964	18	1982
	Caorso	BWR	860	1974	12	1986
Japan	Hamaoka 1	BWR	515	1974	26	2001
	Hamaoka 2	BWR	806	1978	25	2004
	Fukushima Daiichi 1	BWR	439	1971	40	2011
	Fukushima Daiichi 2	BWR	760	1974	37	2011
	Fukushima Daiichi 3	BWR	760	1976	35	2011
	Fukushima Daiichi 4	BWR	760	1979	32	2011
	Fukushima Daiichi 5	BWR	760	1978	33	2011
	Fukushima Daiichi 6	BWR	1067	1979	32	2011
	JPDR	Prot BWR	12	1963	12	1976
	Shimane 1	BWR	439	1974	41	2015
	Tsuruga 1	BWR	341	1970	45	2015
Spain	Garona	BWR	446	1971	42	2012
Sweden	Barseback 1	BWR	600	1975	24	1999
	Barseback 2	BWR	600	1977	28	2005
	Oskarshamn 2	BWR	638	1974	39	2013
USA	Big Rock Point *	BWR	67	1962	35	1997
	Dresden 1	BWR	197	1960	18	1978
	Elk River	BWR	22	1963	5	1968
	Humboldt Bay	BWR	63	1963	13	1976
	Lacrosse	BWR	48	1968	19	1987
	Pathfinder	BWR	59	1966	1	1967
	Millstone 1	BWR	641	1970	28	1998
	Vallecitos	Prot BWR	24	1957	6	1963
	Shoreham	BWR	820	1986	3	1989
	Oyster Creek	BWR	620	1969	28	1997
	Vermont Yankee	BWR	620	1972	43	2015
Prot: prototype						
* Operated for approximately full term						
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List of Abbreviations

ABWR	Advanced Boiling Water Reactor
AIF	Atomic Industrial Forum
ALARA	As Low As Reasonably Achievable
ALPS	Advanced Liquid Processing System
BRP	Big Rock Point
BWR	Boiling Water Reactor
CAAS	Critical Accident Alarm System
CANDU	Canadian Deuterium Oxide Reactor
CFR	Code of Federal Regulation
CLAB	Interim Storage Facility for Spent Fuel (Sweden)
D&D	Deconstruction and Dismantling
DP	Decommissioning Plan
DCON	Decontamination, Immediate Dismantling
DOC	Decommissioning Operations Contractor
DOT	Department of Transportation
DOE/NRC	Department of Energy/Nuclear Regulatory Commission
ENTOMB	Entombment
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FSAR	Final Safety Analysis Report
GEIS	Generic Environmental Impact Statement
HBPP	Humboldt Bay Power Plant
HEPA	High Efficiency Particulate Air
HLW	High Level
IAEA	International Atomic Energy Agency
ILW	Intermediate Level
IRID	International Research Institute for Nuclear Decommissioning
ISFSI	Independent Spent Fuel Storage Installation
JAEA	Japan Atomic Energy Agency
JAPCO	Japan Atomic Power Company
LLW	Low Level
LTP	License Termination Plan
MWe	Megawatt electric
NEI	Nuclear Energy Institute
NPP	Nuclear Power Plant
NRA	Nuclear Regulation Authority
NSSS	Nuclear Steam Supply System
NUREG	US Nuclear Regulatory Commission Regulation
OECD/NEA	Organisation for Economic Co-operation and Development/Nuclear Energy Agency
PCB	Polychlorinated Biphenyl
PCV	Primary Containment Vessel
PDMS	Post-Defueling Monitored Storage
PSDAR	Post Shutdown Activities Report
PWR	Pressurized Water Reactor
QA	Quality Assurance
R&D	Research and Development
RCA	Radiation Controlled Area
RPV	Reactor Pressure Vessel
SAFSTOR	Safe Storage (Safe Enclosure)
SFP	Spent Fuel Pool
SFR	Final Repository for Operational Waste (Sweden)
SKB	Swedish Nuclear Fuel and Waste Management Company
SNM	Spent Nuclear Material
SSC	Systems, Structures and Components
TEDE	Total Effective Dose Equivalent
TEPCO	Tokyo Electric Power Company

Unit conversion

TEMPERATURE		
°C + 273.15 = K		°C × 1.8 + 32 = °F
T(K)	**T(°C)**	**T(°F)**
273	**0**	32
289	16	61
298	25	77
373	**100**	212
473	**200**	392
573	**300**	572
633	360	680
673	**400**	752
773	**500**	932
783	510	950
793	520	968
823	550	1022
833	560	1040
873	**600**	1112
878	605	1121
893	620	1148
923	650	1202
973	**700**	1292
1023	750	1382
1053	780	1436
1073	**800**	1472
1136	863	1585
1143	870	1598
1173	**900**	1652
1273	**1000**	1832
1343	1070	1958
1478	1204	**2200**

Radioactivity	
1 Sv	= 100 Rem
1 Ci	= 3.7×10^{10} Bq = 37 GBq
1 Bq	= 1 s^{-1}

MASS	
kg	**lbs**
0.454	**1**
1	2.20

DISTANCE	
x (μm)	**x (mils)**
0.6	0.02
1	0.04
5	0.20
10	0.39
20	0.79
25	0.98
25.4	**1.00**
100	3.94

PRESSURE		
bar	**MPa**	**psi**
1	0.1	14
10	**1**	142
70	7	995
70.4	7.04	**1000**
100	10	1421
130	13	1847
155	15.5	2203
704	70.4	**10000**
1000	100	14211

STRESS INTENSITY FACTOR	
MPa√m	**ksi√inch**
0.91	**1**
1	1.10