10

Decommissioning nuclear power reactors

Kalman A. Robertson

Abstract

Global demand for decommissioning services is poised to rise rapidly over the next 20 years, creating major technical and administrative challenges for a large number of states and operators that have only limited experience in this field. This chapter explains the radiological risks associated with each step from shutting down a reactor to releasing the former reactor site for a new use. The selection of a strategy for decommissioning a reactor involves competing policy imperatives that may be assessed in light of two key principles related to funding decommissioning and assuring safety, inter-generational equity and the polluter/user pays principle. Based on an assessment of current trends in decommissioning, there are opportunities to improve cost estimates for decommissioning and strengthen international cooperation to meet rising demand. Risk communication and public participation also warrant special attention due to the highly technical nature of the risks associated with decommissioning and remediation of reactor sites.

Introduction

As commercial nuclear power generation enters its seventh decade, the world is set to undergo an unprecedented increase in the number of reactors requiring decommissioning. The combination of ageing reactor fleets and early shutdowns will see a doubling in the number of reactors undergoing decommissioning within the next 20 years, and it is projected to create a global market for decommissioning and waste storage worth over US$100 billion by 2030 (*Nucleonics Week* 2016).

In principle, many of the risks to nuclear safety associated with a reactor site progressively decrease as it is shut down and decommissioned. However, due to the long time periods typically involved in the life cycle of a power reactor, decommissioning poses unique choices and challenges. Worldwide, experience with complete decommissioning of full-scale power reactors is restricted to a handful of cases. Decommissioning costs and requirements vary significantly with the design of the reactor, its operational history, and the state in which it is located. Maintaining continuity of knowledge over the conditions at a site is also difficult—decisions that were made during design, construction, or operation of a reactor, as well as accidents during its operational life, can have important implications many decades later during decommissioning.

The projected upsurge in decommissioning is coming at a time when the issue of disposal of radioactive waste, particularly spent fuel (high-level waste), has not yet been completely resolved in any state. This has important implications for all other decommissioning activities and for the end-state of the former reactor site. Choices involved in scheduling decommissioning activities involve complex trade-offs between different generations' interests in radiation protection for workers and the public, environmental protection, and financial expenses.

This chapter outlines each of the basic steps that are typically involved in decommissioning with reference to examples of power reactors that have reached advanced stages of the process. It explains current challenges in the field of decommissioning, including managing the increasing number of reactor shutdowns, handling unexpected changes in the cost/timing of decommissioning, and achieving unrestricted release of decommissioned sites for safe use by the public. It makes recommendations for ensuring adequate finance for decommissioning, promoting transparency in decommissioning, and developing international cooperation to cope with the emerging demand for decommissioning services.

Defining 'decommissioning'

Power reactors are among the most complicated industrial facilities to decommission. During operation, a nuclear reactor maintains a controlled, self-sustained fission chain reaction (IAEA 2002: paragraph 5.5).[1] A power reactor uses this reaction to generate useful energy, typically electricity. By contrast, a research reactor is not used to produce electricity and therefore does not use turbines and generators. A research reactor tends to have smaller physical dimensions and lower levels of radioactivity because of its relatively low thermal power.

There are six major stages in the lifetime of a reactor: siting, design, construction, commissioning, operation, and decommissioning. In addition to radioactive spent fuel, an operating reactor generates two basic categories of radiation hazards: contamination and activation.[2] Contaminants are radioactive materials that have been deposited on a solid surface or in a liquid or gas. Since the reactor's primary coolant is in contact with radioactive material (chiefly the fuel itself) in the core, it tends to become highly contaminated during reactor operation. All surfaces that come in contact with this coolant (for example, pipes and pumps) also tend to be contaminated. Depending on the chemical form of those contaminants, it may be relatively easy for them to subsequently leave the surface and enter the surrounding environment. Activation primarily occurs when neutrons from the fission process in the reactor core are absorbed by a material that is not fissile (for example, traces of cobalt in the wall of a reactor), causing that material to become radioactive. Since neutrons may travel significant distances in some materials before being absorbed, activation products may be found deep inside the building materials of old reactors.

---

1 For present purposes, a critical assembly can be thought of as a small research reactor with fewer provisions for cooling and shielding. Note that radioisotope thermoelectric generators, which use the heat released by the decay of radioactive material to generate electricity (usually for long-term, low-power applications like spacecraft), are not nuclear reactors because they do not involve a fission chain reaction.

2 The radiation hazards associated with nuclear energy involve ionising radiation—radiation that, by virtue of its type and/or energy, is capable of ionising atoms or molecules in body tissue. For general information on radiation, see Knoll (2010). This chapter only covers nuclear safety and radiation protection aspects of decommissioning. It does not cover the challenges posed by other hazardous substances that may be present at nuclear sites, such as solvents, non-radioactive heavy metals, and asbestos.

Once a reactor ceases operations, it must eventually be decommissioned so that the site can be made safe for other uses.[3] The International Atomic Energy Agency (IAEA) defines decommissioning as: 'Administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility' (IAEA Department of Nuclear Safety and Security 2007: 48; IAEA 2016a: 34). Decommissioning usually involves dismantling a facility or decontaminating buildings to reduce radiation risks, ensure the long-term protection of the public and the environment, and free up the site for a new use.

In essence, decommissioning involves two key principles related to assuring safety: inter-generational equity and the polluter/user pays principle. Despite the long timescales involved in constructing, operating, and decommissioning a reactor, and the even longer timescales associated with the decay of radioactive waste, it is generally accepted that reactors should be decommissioned in such a way as to avoid unduly burdening future generations (Bråkenhielm 2005). Decisions on decommissioning should avoid compromising acceptable standards of public safety, environmental sustainability, nuclear security, and resource availability for future generations (see Taebi and Kadak 2010).

The polluter/user pays principle means that those who benefit from nuclear power (i.e. utility companies and end-users) should be responsible for ensuring that decommissioning is completed and should pay the entire cost, rather than passing the cost onto taxpayers as a whole. The IAEA recommends that each state place primary responsibility for decommissioning on facility licensees acting under the supervision of national regulators, including the national decommissioning authority, health and safety regulators, local authorities, and environmental regulators (Stoiber et al. 2010: 73). In this respect, nuclear regulation has improved significantly since the early days of nuclear power, although financing unforeseen costs in decommissioning remains a challenge (see below). Today, most states with nuclear power reactors (or contemplating their construction) require utilities to have a decommissioning plan drafted prior to commissioning of the reactor (see Laraia 2012). By contrast, many of the first-generation reactors were built without detailed

3 The term 'decommissioning' is also used to refer to other fuel cycle facilities but this chapter will only consider reactors.

consideration of how they would eventually be decommissioned (Samseth et al. 2013). It is telling that the IAEA's first major guidance document on decommissioning was not published until the mid-1970s (IAEA 1976).

Global status of decommissioning and current outlook

Demand for decommissioning services is likely to rise rapidly over the next 15 years. Worldwide, there were 443 power reactors either operational or in temporary shutdown at the end of 2015.[4] The average age of these reactors is approximately 30 years. Although some reactors are receiving life extensions, most have a projected operating life of 40 years. Germany will complete an early phase-out of its nuclear power plants by 2022 (Schneider et al. 2015; International Energy Agency 2016).

A large proportion of states currently operating power reactors have little, if any, experience with decommissioning them (see Table 10.1). The United States has the most experience, with the Nuclear Regulatory Commission (NRC) releasing much of the land at several decommissioned power plant sites over the past 15 years, usually while continuing to regulate residual spent fuel storage installations. Some states may be able to fall back on their experience in decommissioning research reactors. Worldwide, 33 states (plus Taiwan) have together decommissioned a total of 352 research reactors (IAEA 2016b). Compared with power reactors, the cost and technical complexity of decommissioning research reactors tend to be limited because of their comparatively small physical dimensions and low levels of radioactive contamination/activation. Research reactor pressure vessels may often be removed and buried in one piece without undertaking the arduous process of cutting the vessel, which may expose workers to radioactive dust particulates. Consequently, experience with research reactor decommissioning is not necessarily equivalent to experience

4 This chapter does not cover decommissioning of naval propulsion reactors. Quoted values for the cost of decommissioning nuclear submarines generally cover the cost for the entire vessel, rather than the reactor unit, making comparisons with stationary reactors difficult. On the effects of disposal of Soviet naval propulsion reactors at sea, see Mount, Sheaffer, and Abbott (1994). This chapter also does not cover end-of-operating-life activities for the handful of nuclear-powered satellites launched by the Soviet Union and the United States during the 1960s, 1970s, and 1980s. For a description of measures to place shutdown satellite reactor cores in safe orbit and a description of the environmental damage caused when one of these satellites, Kosmos 954 Radar Ocean Reconnaissance Satellite, came crashing down to Earth, see Harland and Lorenz (2006: 235–6).

with power reactor decommissioning. States with limited experience in decommissioning power reactors may benefit from information exchanges with more experienced states.

Table 10.1 Status of all nuclear power reactors in the world, 31 December 2015

Status	Number	Number of states
Operational or in temporary shutdown	443	31 (plus Taiwan)[1]
Permanently shut down (includes reactors that have entered decommissioning process)	157	19 (Europe, North America, Kazakhstan, and Japan)[2]
In decommissioning process or decommissioned	124	18[3]

[1] Does not include the 5 megawatt electric (MWe) Yongbyon reactor (North Korea) or the Bataan nuclear power plant (the Philippines).

[2] Does not include a handful of experimental power reactors (fewer than 10).

[3] Does not include the Santa Susana Sodium Reactor Experiment.

Source: IAEA (2016c: 47–58).

The end point of decommissioning

There is no universal standard for determining when a facility is fully decommissioned—the definition depends on the type of regulatory controls in question and their underlying purpose. For example, the purpose of nuclear safeguards is primarily to verify that nuclear materials, equipment, and technology are used for exclusively peaceful purposes, rather than contributing to a nuclear weapons program. From a nuclear safeguards standpoint, a facility is decommissioned once it becomes effectively impossible to utilise the remaining structures or equipment at the site to process or use nuclear material (IAEA 2002: paragraph 5.31). By contrast, from a nuclear safety standpoint, it makes sense to say that a site is only fully decommissioned once radiological and other risks at the site have been reduced to a pre-defined acceptable level. The IAEA asserts that, as of October 2014, 17 power reactors have been 'fully decommissioned', although it does not expressly define the term and it appears to have left out some small experimental power reactors (IAEA 2015b: paragraph 74).

Most national regulators declare that decommissioning is complete once the licensee has completed the tasks in its decommissioning plan, no further dismantling or decontamination operations are foreseen, the reactor licence has been terminated, and the site is suitable for a new purpose, either with or without restrictions imposed by the regulator. This study identifies about 30 power reactors that could be referred to as 'fully decommissioned' in this sense (see Table 10.2 and Table 10.3). National legislation or regulations typically contain specific safety and environmental criteria for the end-state of decommissioning and the removal of regulatory controls from a site.

Table 10.2 Fully decommissioned nuclear power reactors in the US and current site uses, December 2015[1]

Reactor	Location	Type	Reference unit power (MWe)	Operating life[2]	Current site use
Big Rock Point NPP	Charlevoix, MI	BWR	67	1962–97	Unrestricted + dry cask spent fuel storage[4]
Boiling Nuclear Superheater	Rincón, Puerto Rico	BWR	17	1964–68	Unrestricted[3] with reactor entombed on site
Carolinas–Virginia Tube Reactor	Parr, SC	PHWR	17	1963–67	Adjacent to new nuclear power plant
Connecticut Yankee (Haddam Neck) NPP	Haddam Neck, CT	PWR	560	1967–96	Unrestricted + dry cask spent fuel storage[4]
Elk River Station	Elk River, MN	BWR	22	1963–68	Fossil fuel power station
Enrico Fermi APP, Unit 1	Monroe, MI	FBR	61	1966–72	Newer nuclear power plant (most of the components of Fermi 1 have been removed but the site currently hosts Fermi 2)
Fort St Vrain	Platteville, CO	HTGR	330	1974–89	Fossil fuel power station + dry cask spent fuel storage
Hallam	Hallam, NE	SCGR	75	1963–64	Fossil fuel power station + low-level radioactive waste storage and reactor vessel entombed onsite
Humboldt Bay 3	Eureka, CA	BWR	63	1963–76	Fossil fuel power station

Reactor	Location	Type	Reference unit power (MWe)	Operating life[2]	Current site use
Maine Yankee NPP	Wiscasset, ME	PWR	860	1972–97	Unrestricted + dry cask spent fuel storage[4]
Pathfinder APP	Sioux Falls, SD	BWR	59	1966–67	Fossil fuel power station
Piqua NPP	Piqua, OH	Other	12	1963–66	Unrestricted[3] + reactor vessel entombed onsite
Rancho Seco	Herald, CA	PWR	873	1974–89	Cooling towers remain; low-level radioactive waste storage and spent fuel storage; plan for solar power array on part of site
Santa Susana Sodium Reactor Experiment	Bell Canyon, CA	SCGR	~6[5]	1957–64	Industrial research
Saxton Nuclear Experiment Station	Saxton, PA	PWR	3	1967–72	Unrestricted[3]
Shippingport APP	Shippingport, PA	PWR	60	1957–82	New nuclear power plant
Shoreham NPP	East Shoreham, NY	BWR	820	1986–89	Fossil fuel power station
Trojan NPP	Rainier, OR	BWR	1095	1975–92	Unrestricted + dry cask spent fuel storage[4]
Yankee Rowe NPP	Franklin, MA	PWR	167	1960–91	Unrestricted + dry cask spent fuel storage[4]

[1] This table does not include cases where one reactor has been decommissioned, while other reactors of the same type continued to operate on the same site (i.e. Dresden, OH; and San Onofre, CA).

[2] 'Operating life' is the period between the first grid connection and the last year in which the reactor supplied electricity to the grid.

[3] 'Unrestricted' means the site is now 'greenfield'. In some cases, part of the site is now parkland (for example, Trojan NPP) or a wildlife refuge (for example, Connecticut Yankee).

[4] 'Unrestricted + dry cask spent fuel storage' means most of the original site is now 'greenfield'. A small lot is licensed by the regulator for dry cask storage of spent fuel (independent spent fuel storage installation).

[5] Reactor not listed in IAEA (2015a, 2016c). Power approximated using Wald (2011).

Key

APP = atomic power plant
BWR = boiling water reactor
FBR = fast breeder reactor
HTGR = high-temperature gas-cooled reactor
MWe = megawatt electric
NPP = nuclear power plant
PHWR = pressurised heavy-water reactor
PWR = pressurised water reactor
SCGR = sodium-cooled, graphite-moderated reactor

Sources: IAEA (2015a, 2016c); US NRC (2015b).

Table 10.3 Fully decommissioned nuclear power reactors (and selected reactors at advanced stages of decommissioning) outside the US and current site uses, December 2015[1]

Reactor	Location	Type	Reference unit power (MWe)	Operating life[2]	Current site use
Chinon Units A-1, A-2, and A-3	Avoine, France	GCRs	70, 180, 360	1963–90	Newer nuclear power reactors; part of Chinon A-1 is now a museum; final dismantling to take place after shutdown of newer reactors
Saint Laurent Units A-1 and A-2	Saint-Laurent-Nouan, France	GCRs	390, 465	1969–92	Newer nuclear power reactors
HDR Großweltzheim (Kahl)	Karlstein a.Main, Germany	BWR	25	1969–71	Unrestricted;[3] current use is light manufacturing
Kahl VAK NPP	Seligenstadt, Germany	BWR	15	1961–85	Unrestricted[3] (commercial/manufacturing)
Niederaichbach NPP	Landshut, Germany	HWGCR	100	1973–74	Adjacent to new nuclear power plant
Stade	Bassenfleth, Germany	PWR	640	1972–2003	Awaiting final demolition of remaining (non-active) structures + storage of low-level radioactive waste

Reactor	Location	Type	Reference unit power (MWe)	Operating life[2]	Current site use
Wuergassen NPP	Beverungen, Germany	BWR	640	1971–94	Temporary storage of low- and intermediate-level radioactive waste from decommissioning
Japan Power Demonstration Reactor	Tokai-mura, Japan	BWR	12	1963–76	Nuclear research institute + very low-level radioactive concrete waste buried onsite
Tokai NPP, Unit 1	Tokai-mura, Japan	GCR	137	1965–98	Newer nuclear power reactor
Lucens reactor	Lucens, Switzerland	HWGCR	6	1968–69	Reactor was in underground cavern; appears to be sealed off with greenfield above
Windscale Advanced Gas Cooled Reactor	Sellafield, United Kingdom	GCR	24	1963–81	Newer nuclear facilities

[1] This table does not include cases where one reactor has been decommissioned, while other reactors of the same type continued to operate on the same site (i.e. Gundremmingen, Germany).

[2] 'Operating life' is the period between the first grid connection and the last year in which the reactor supplied electricity to the grid.

[3] 'Unrestricted' means the site is now 'greenfield'.

Key

BWR = boiling water reactor
GCR = gas-cooled, graphite-moderated reactor
HWGCR = heavy water–moderated, gas-cooled reactor
MWe = megawatt electric
NPP = nuclear power plant
PWR = pressurised water reactor

Sources: IAEA (2015a, 2016c); Schmittem (2016); Weigl (2008); *World Nuclear News* (2015).

The end-states of former power reactor sites tend to fall into three categories. First, decommissioned sites may host newer nuclear facilities, such as new reactors or new low-level waste disposal. Former power plant sites (and their residual electricity infrastructure) may also be released for re-use by fossil fuel power plants. Since the proposed new use for the site tends to determine remediation goals, including acceptable residual radiation levels, these examples are of limited value in studying site restoration (Laraia 2012).

Second, the majority of a site may be released from regulation, while the remaining part continues to host long-term dry cask spent fuel storage (an 'independent spent fuel storage installation'). This is an artefact of the current deficit of permanent disposal options for high-level radioactive waste and the persistent difficulties with using reprocessing as a source of fresh reactor fuel (Hiruo 2016). In some of these cases, despite being 'unrestricted use' from the standpoint of nuclear regulations, access to the site is limited by the owners (the utilities that completed the decommissioning) to activities in connection with spent fuel storage or groundwater monitoring. This is the case for Connecticut Yankee and Yankee Rowe in the United States, where there are currently no timetables for making a decision on disposition of former site property (Connecticut Yankee 2015). Compared with wet (pool) storage, dry casks require minimal maintenance for safe storage of spent fuel. However, protecting casks against sabotage is a necessary, ongoing expense (see US NRC 2016). In the United States, most independent spent fuel storage installations are far from major population centres and unlikely to be high-value targets for sabotage. However, terrorists who lack the strength, weaponry, or training to attack an operating reactor might choose to try to damage storage casks with the aim of dispersing radioactive material, causing economic damage, and producing panic among local residents.

Third, the entire site may be released without restrictions for general use in agriculture, park land, or commerce. To date, the only power reactors that fall into this category were either low-power or short-lived (see Tables 10.2 and 10.3). A key requirement for suitability for a new purpose without restrictions is verification by the regulator of reduction of the degree of radioactivity at all parts of the site to a limit set by legislation or regulations. In order to meet the limits on annual doses required for reactor licence termination and site release, the radioactive structures from the plant must usually be removed from the site. It may also be necessary to remove topsoil from beneath the former reactor.

It is often asserted that dose limits are set with a view to ensuring that radiological risks to humans and the environment are 'no longer present' (see, for example, Nuclear Energy Agency 2016: 51). However, there is no generally accepted definition of an effective dose (measured in sieverts, Sv) that constitutes a 'radiological risk', or a limit below which radiological risk is absent. There are no straightforward means of precisely measuring all stochastic health effects of radiation exposure at very low levels. Effects from doses of less than about 0.1 Sv per year are difficult to assess, particularly if exposure is spread over the course of the year rather than associated with an acute event.

The most obvious anticipated effect from low-dose exposure is an increased risk of cancer, but the effect on cancer rates is difficult to measure due to the time delay and the high naturally occurring background rate of cancer. Instead, effects at low doses are extrapolated from measurements of effects at higher doses. This is typically accomplished by assuming a linear relationship between dose and response with no threshold below which risk vanishes, known as linear no-threshold (LNT) theory (see Calabrese 2013; Morgan 2013). LNT is widely accepted as a prudent and conservative model for estimating radiological risk.

Applying LNT strictly, it is impossible to say that any location is, or ever was, completely devoid of radiological risk due to the presence of naturally occurring sources of radiation in all environments. The average annual radiation dose from natural sources for a human varies considerably with geographical location but is typically 1 to 5 milliSieverts (mSv) (UNSCEAR 2008).

For this reason, dose limits from artificial sources are usually set at arbitrary levels, based on an assessment that a particular level of risk is both acceptable and realistically achievable. For the return of a decommissioned or otherwise contaminated site to unrestricted use, national regulations and international standards tend to set annual dose limits attributable to the artificial source at levels that are lower-than-average annual effective doses for humans from either natural sources or medical procedures.[5] The dose attributable to a decommissioned reactor may be inferred by comparing activity levels after decommissioning with activity levels prior to the reactor's construction.[6] Applying LNT, any additional risk

5 For example, the NRC imposes a limit of 0.25 mSv annual dose equivalent from residual radioactivity associated with decommissioned nuclear sites as a requirement for release of the site for unrestricted use (US NRC Regulations 2015: Section 20.1402). Doses are typically calculated using measurements of external radiation and then adding on calculated values of internal radiation exposure for various organs based on assumptions about normal rates of inhalation and ingestion.

6 The IAEA's model provisions for national legislation on decommissioning recommend that the regulatory body require a baseline survey of the radiological conditions at the site prior to facility construction for comparison with the end-state after decommissioning (Stoiber et al. 2010: 72).

from such artificial sources of radiation tends to be comparable with or smaller than the risk from natural sources of radiation. The most notable contemporary exception to this trend is the reported use of a dose reference level of 20 mSv per year above natural background for evacuees from the region surrounding the Fukushima Daiichi nuclear power plant (Office of the Deputy Chief Cabinet Secretary 2011).

Financing decommissioning

Financing can be among the most contentious of issues in decommissioning. Consistent with the user/polluter pays principle, financing is the responsibility of the licensee in most states. However, states parties to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (1997: article 26) are obligated to ensure that 'qualified staff and adequate resources are available' to ensure the safety of decommissioning. Although a small amount of revenue may be generated during decommissioning by salvaging resaleable reactor components,[7] decommissioning is essentially a cost that is only realised once commercial activity has ceased. Financing decommissioning therefore involves the challenge of coping with a future financial liability. Ensuring sufficiency of funds is difficult because a variety of events during the reactor's lifetime may generate sudden, unexpected costs or losses of revenue. If a reactor needs to be shut down and decommissioned earlier than expected due to an accident or a change in national regulations, then ensuring the availability of funds at the right time may also be a challenge.

Funding strategies

There are two basic strategies for funding decommissioning: prepaid funding and accumulation. The former involves setting aside a set amount of money, proportional to the presumed cost of decommissioning, prior to construction as part of the upfront cost. The latter involves establishing a sinking fund and then gradually paying a small percentage of electricity

7 In order for scrap materials to be 'cleared' for unrestricted re-use or disposal, their radioactivity must fall below certain thresholds. These limits are often set very conservatively so that only materials exhibiting roughly natural background levels of radioactivity are cleared. Conservative activity limits and careful quality assurance are important because radioactive material may not be homogeneously distributed over the volume of scrap material.

revenue into the fund throughout the operating life of the reactor. Both strategies typically involve investing funds set aside with the aim of ensuring that some target value, presumed to be adequate capital to finance decommissioning, is available by the end of the projected operational life of the reactor.

Prepaid funding provides a degree of protection in the event that the reactor fails to generate projected revenue as a result of early shutdown, but it is difficult to finance. Accumulation has the advantage of allowing financing by electricity consumers as part of the cost of electricity but it is difficult to make arrangements for the possibility of loss of revenue following earlier than expected reactor shutdown. Neither prepaid funding nor accumulation can guarantee available and sufficient funds in every possible contingency. In principle, funds can include contingency estimates for incidents that increase decommissioning costs; however, due to the indeterminate nature of the timing and cost of decommissioning, there is not much guidance available for calculating contingency estimates (Nuclear Energy Agency 2016: 82). If adequate funds are not available when it comes time to decommission a reactor then it may be necessary to abrogate the polluter/user pays principle by passing the cost on to taxpayers or by charging a levy against future electricity consumers even though they are drawing electricity from other sources (Drozdiak and Busche 2015; Pagnamenta 2016). In April 2016, Germany's Commission on the Review of the Financing of the Nuclear Phaseout recommended that utility companies pay €23 billion of the cost associated with decommissioning their power reactors (*World Nuclear News* 2016a). There is an unresolved debate about whether or not the liability of these utility companies for decommissioning costs should be limited given that their projected revenue may have already been cut by the government's decision to phase out nuclear power early.

Calculating costs

The cost of decommissioning is heavily dependent on the specific conditions at the reactor site, the state's regulations, and the precise decommissioning strategy employed. However, a few general observations can be made about the influence of reactor size, age, and type on the cost of decommissioning. First, the extent of radioactive contamination/activation at a reactor tends to increase gradually with the power of the reactor and the length of time over which it has operated. So far, several of the reactors that have reached an advanced stage of decommissioning (see especially Tables 10.2 and 10.3) are comparatively low-power reactors with short operating lives. By comparison, decommissioning modern 1 gigawatt electric reactors that have operated for over 40 years involves dealing with larger volumes of radioactive waste.

The US NRC Regulations (2015) require a licensee to have a set amount of funds for decommissioning that depends on the type of reactor, as well as the cost of labour, energy, and waste disposition (US Government Accountability Office 2012). The applicable values for the year 2016 range from a few hundred million to about US$1 billion (see US NRC 2013). These values provide some insights into the differences between the basic types of reactors.

The NRC has estimated pressurised water reactors (PWRs, a type of light-water reactor) to be among the least expensive. PWRs make up 64 per cent of operational reactors. PWRs use heat exchange between two cooling loops, one runs through the core and is highly radioactive, while the other runs through the turbine and is effectively non-radioactive. The turbine room tends to be, at most, mildly contaminated so it can be dismantled in a straightforward way, with components being recycled or disposed of by near-surface burial. Pressurised heavy-water reactors (i.e. Canada Deuterium Uranium CANDU reactors), tend to be similar except that there is an additional cost associated with storage or treatment of the heavy-water moderator, which tends to contain relatively high levels of radioactive tritium resulting from neutron absorption during reactor operation.

By contrast, boiling water reactors (BWRs), which make up the majority of reactors in Japan and Sweden, use a single cooling loop. This means that the 'radiation control area' of the facility is much larger, incorporating the turbine and condenser. Since more parts of the facility are contaminated, decommissioning tends to be more complicated and disposal of components tends to be more costly.

The NRC Regulations indicate that decommissioning gas-cooled, graphite-moderated reactors (GCRs, like the British MAGNOX reactors) will be several times more expensive than decommissioning PWRs or BWRs. The graphite moderator in GCRs accumulates radioactive carbon while the reactor is operating. This makes it difficult to safely access the reactor for the purposes of decommissioning and it creates an additional highly radioactive waste stream. Former Soviet graphite-moderated, light-water cooled reactors, like those at Chernobyl, are similar (*NucNet* 2015).

The main distinguishing feature of decommissioning liquid metal–cooled fast reactors is the cost of draining the coolant while preventing its oxidation and dealing with subsequent radioactive coolant residues (Goodman 2009). This represents an additional complexity compared with draining water from PWRs or BWRs, particularly if the coolant becomes highly contaminated with fission products as a result of breached fuel cladding. However, experience at six fast reactors (Santa Susanna Sodium Reactor Experiment, Hallam, Fermi-1, Phenix, EBR-1, and EBR-2) indicates that the overall cost of decommissioning is similar for fast breeder reactors (FBRs) and BWRs (see Michelbacher et al. 2009).

Overall, there is a lack of reliable and comparable data on decommissioning costs across states. Even for reactors of comparable type, power, and operating history, cost and time estimates for decommissioning vary considerably. Costs depend heavily on the desired final state of the reactor site—it will be more expensive to achieve release of the site for unrestricted use than it will be to make the site suitable for a new nuclear facility. There are large and complex differences in defining the scope of the 'decommissioning costs' of a reactor, as opposed to its 'operating costs' (Nuclear Energy Agency 2012). For most types of power reactors, nuclear fuel is repeatedly loaded and unloaded during the operational life of the reactor. The disposition (storage, disposal, or reprocessing) of spent fuel may therefore be considered an operational cost, rather than a decommissioning cost.[8] Some estimates include the cost of dry cask storage, either at the reactor site or off-site, while others do not.

Even where costs are broken down by dismantling activities, project management activities, and waste management activities, costs estimates for individual items are heavily dependent on the cost of labour and other services in the specific state (see Nuclear Energy Agency 2016: 67). Costs may also depend on the amount of prior experience that the regulators, licensees, and contractors have with decommissioning.

8 For a summary of the approaches taken by seven countries with nuclear facilities, see Nuclear Energy Agency (2016: 61).

Depending on the state, much of the cost of decommissioning may be disposal of components of the reactor that are either low-level or intermediate-level radioactive waste.[9] Some states, including France and the United States, have tended to possess sufficiently capacious storage or disposal sites for low-level waste to allow dismantling of facilities with large components intact. These states tend to have more flexibility in removing radioactive components from sites relatively soon after shutdown without the need for complex cutting procedures, significantly decreasing the cost of maintaining and ultimately dismantling the remainder of the components on the site.

The steps involved in decommissioning

This section explains some of the risks involved in each of the steps from shutting down the reactor to releasing the site, as well as choices and trade-offs in specific approaches to decommissioning.

Pre-decommissioning 1: Shutting down the reactor

The decision to cease operations and permanently shut down a power reactor is usually based on a mix of technical, financial, and political considerations. Six reactors have been permanently shut down as a direct result of 'major accidents', 'serious accidents', or 'accidents with wider consequences' during operation, as defined by the International Nuclear and Radiological Event Scale (INES): St Lucens, Three Mile Island Unit 2, Chernobyl Unit 4, and Fukushima Units 1 to 3.[10] By definition, these events involve release of radioactive material either producing severe damage to a reactor core, causing deaths from radiation, or requiring implementation of counter-measures (IAEA n.d.).[11]

9 For a conceptual overview of waste classification, including disposal of various levels of radioactive waste, see IAEA (2009).

10 The other units at Fukushima Daiichi were not in operation at the time of the Tohoku earthquake. Some nuclear reactors were restarted after experiencing accidents, including the Santa Susana Sodium Reactor Experiment and Saint Laurent Units A-1 and A-2. The Santa Susana accident pre-dates the scale and does not appear to have been given a definitive rating.

11 Note that events, such as generator failures at PWRs, are sometimes referred to in the media as 'accidents' even though they may not have direct radiological consequences for workers, the public, or the environment.

Most reactors are shut down around the time that they reach the end of their expected operating lives. Typically, the shutdown date is based on an assessment that it is no longer economical to run the reactor due to the increasing cost of maintenance or upgrades as components age or regulatory requirements change. Decreasing demand for electricity and decreasing cost of fossil fuels are also factors in some recent reactor shutdowns.

Once a decision is made to permanently shut down a reactor, it is common practice to leave the final irradiated fuel load inside the reactor core to cool. Once the temperature and pressure in a water-cooled reactor fall below a certain level, it is no longer essential to circulate cooling water to prevent it from boiling off ('cold shutdown'), significantly reducing the potential for accidents to cause a catastrophic loss of cooling. At the time that the Tohoku earthquake and tsunami hit, Units 5 and 6 at Fukushima Daiichi were in cold shutdown, so these reactors did not experience hydrogen explosions. Units 1 to 3 achieved cold shutdown in December 2011, but they continued to require injections of water due to leaking through cracks in the reactors (Brumfiel 2011).

The period following shutdown also corresponds to a significant cultural and organisational change for the reactor licensee. Worker morale is often adversely impacted by the end of electricity production (Laraia 2012). Some of the employees at the power plant will need to undertake additional training for new short-term tasks involved in the post-shutdown period (such as removing or deactivating equipment), only to then face the prospect of unemployment. For specialised decommissioning tasks, it may be necessary to hire new contractors, who must then be informed of the precise layout, history, and conditions of the plant.

Pre-decommissioning 2: Closing down the reactor

Once the radiation (and resulting heat) from the spent fuel drops to a certain level, the licensee may remove the spent fuel rods from the core and the wet (pool) storage, and then drain the coolant. On average, about 99 per cent of radioactivity at shutdown is associated with the spent fuel itself (Nuclear Energy Agency 2016: 50).

If the reactor has undergone a core melt, then, in addition to the fuel rods, it is also necessary to remove melted core debris. Removal of melted debris from Fukushima Daiichi Units 1 to 3 is not scheduled to be completed until at least the early 2020s, and a disposal method for retrieved debris has not been finalised (Schneider et al. 2015; International Energy Agency 2016: 78). Removal from these units will require the use of new remotely controlled, radiation-resistant equipment (Inter-Ministerial Council for Contaminated Water and Decommissioning Issues 2015: 18).

Once all spent fuel is removed from the reactor and on-site storage pools, the reactor is said to be 'closed-down' (IAEA 2002: paragraph 5.30) and the risk of a large-scale release of radioactivity at the reactor is greatly reduced. At this point, the regulator may grant the licensee an exemption from maintaining full emergency response mechanisms at the site (Cama 2014). According to US Senator David Vitter, there have not been any incidents in the United States during decommissioning (i.e. post-fuel removal) that resulted in harm to public safety (Cama 2014). The spent fuel itself tends to be safer in dry casks as well (US Senate 2014). Unlike the fuel in Units 1 to 4, spent fuel that had already been loaded into dry casks at the Fukushima Daiichi site withstood the earthquake and tsunami without suffering significant damage (Suzuki 2015: 597).

Around the time that spent fuel and coolant are being removed, the licensee is usually responsible for submitting an updated decommissioning plan, ensuring that radioactive contamination and activation throughout the site have been carefully measured and mapped out ('site characterisation').[12] Depending on the country, it may be a regulatory requirement to complete this process before shifting from closing down the reactor to actually dismantling and removing reactor components (IAEA 2014: 15).[13]

Strategies for decontamination, dismantlement, and disposal

Once the reactor has been closed down, the licensee has developed a decommissioning plan, and the regulator has provided the necessary approvals, decommissioning can begin. With the spent fuel gone, the main radiological risks are exposure of workers in residual radioactive structures during the hands-on processes involved in dismantling the

12 For examples of dose rate maps at Fukushima Daiichi reactors, see Kotoku (2016).

13 For example, in the United States, the First Circuit Court of Appeals has ruled that removal of reactor components is a form of decommissioning for the purposes of the National Environmental Policy Act. The NRC could not allow Yankee Atomic Energy Company to conduct an 'early component removal' prior to submitting a complete decommissioning plan. See *Citizens Awareness Network Inc. v United States Nuclear Regulatory Commission* (1995).

various systems that were designed to move, store, shield, and cool fuel assemblies. Unlike the routine operation of a reactor, the process of decommissioning is likely to involve personnel accessing moderately or highly contaminated parts of the facility for extended periods of time. However, licensees and regulators must also be mindful of the long-term, low-dose effects of residual radioactivity on the surrounding environment.

There are three basic options for decommissioning a nuclear reactor: immediate dismantling, safe storage, and entombment. Each approach has its own implications for activity-dependent costs (i.e. the 'hands-on' activities involved in decommissioning, including equipment and labour), period-dependent costs (i.e. management, licensing, security, electricity, insurance, property tax, and other site maintenance), and contingency costs (i.e. costs allocated for unforeseeable disruptions, adverse weather, changes to regulations, or loss of an essential service provider) (Atomic Industrial Forum 1986).

The strategies differ primarily in their approach to the relatively highly contaminated or neutron-activated parts of the facility, including the reactor pressure vessel, the reactor internal components, the coolant piping, radiation-shielding concrete, and spent fuel storage racks. Regardless of the strategy employed, building materials and auxiliary systems that are far enough from the reactor core and the coolant to avoid being contaminated or activated should exhibit only natural background radiation—these parts may be treated as normal demolition waste and disposed of whenever it is convenient.

Immediate dismantling involves commencing decommissioning as soon as possible after permanent shutdown, although past experience suggests that it still takes at least 10 years to move from permanent shutdown to site release (see Tables 10.2 and 10.3). Despite ongoing efforts at Fukushima Daiichi, decommissioning of its reactors is projected to take 30 to 40 years (Inter-Ministerial Council for Contaminated Water and Decommissioning Issues 2015: 8). That said, immediate dismantling tends to minimise period-dependent costs, making it an attractive option from a financial standpoint, provided that the funds are readily available. It also ensures that employees who are familiar with the reactor's operation and who have been responsible for maintaining records can be involved in its decommissioning.

Immediate dismantling appears to have political and practical appeal for several states in Europe, as well as Taiwan, that are either reducing their reliance on nuclear power or phasing it out (Adelman 2016). France, Germany, Italy, Lithuania, Slovakia, Spain, Sweden, and the United States are increasingly opting for immediate dismantling of shutdown reactors or requiring accelerated decommissioning of reactors previously in safe storage (Adelman 2016; Autorité de sûreté nucléaire 2009: 4; *Nuclear Energy Insider* 2016; Thomas 2016). Immediate dismantling permits earlier re-use of the site and reduces the burden on future generations. By decontaminating and dismantling containment structures in a timely manner, immediately decommissioning also reduces the risk of radiological release over time as a result of weathering, deterioration, or corrosion of the reactor building.

Safe storage is deferred dismantling of the radioactive parts of a facility. Currently, just over half of all reactors undergoing decommissioning are in safe storage. Depending on national regulations, reactor licences may be extended for up to about a century to accommodate projected storage times. Since many of the radioactive contaminants and activation products at a reactor have a half-life of years or less, radiation levels at the reactor decrease significantly during the storage period. In principle, this allows decommissioning workers to dismantle the reactor at a time when they will receive comparatively low radiation exposure. The volumes of higher level radioactive wastes requiring disposal are also reduced by deferring dismantlement.

If the stored reactor is co-located with another nuclear facility, such as an operational reactor, then keeping it in safe storage involves minimal additional site maintenance costs. Safe storage is also attractive where a licensee needs extra time to shore up decommissioning funds or to build up a decommissioning workforce. Finally, licensees and regulators that choose safe storage may stand to benefit from future technological developments, including improvements to long-term waste disposal options and robotics for remote decommissioning operations (Nagata 2016).

Entombment involves encasing a facility's radioactive structures (including the reactor pressure vessel) in a long-lived material like concrete. Since entombment does not require complete dismantlement of the plant, it minimises workers' contact with radioactive components and decreases volumes of waste that must be disposed of elsewhere. However, entombment may require very long-term surveillance and maintenance to ensure that the structure remains intact while radioactivity gradually declines. Currently, the IAEA cautions against the use of entombment for most types of power reactors (IAEA 2016a: 35). The Soviet Union chose entombment for Chernobyl Unit 4 since neither immediate dismantling nor safe storage could be achieved without posing considerable risks to workers or the surrounding environment. An additional 'New Safe Confinement' steel structure is being placed over the entombed reactor in 2016/2017 at a cost of over US$1 billion (*World Nuclear News* 2016b). Entombment has also been used for a few small, short-lived reactors with relatively low levels of contamination (see Table 10.2).

The choice of decommissioning strategy involves trade-offs between minimising the exposure of workers, the long-term impact on the local environment, the financial costs, and the volumes of radioactive waste requiring disposal. Similar trade-offs are inherent in dismantlement and decontamination of individual radioactive structures. Often, only a small volume is highly contaminated, while the majority of the structure is only slightly contaminated. For example, the inside of a metal coolant pipe may be highly radioactive, while the concrete around the pipe is effectively non-radioactive. From the standpoint of minimising the volume of material that must be sent for long-term storage or burial as intermediate-level waste, it is desirable to carefully cut the metal pipe out of the concrete, but during this process workers could be exposed to relatively high levels of radiation. Similarly, the surface of a wall could be highly contaminated, while the bulk concrete in the wall is only very slightly radioactive. Workers could use a technique like dry abrasive blasting to decontaminate the wall, but this would tend to increase their exposure to radiation. The International Commission on Radiological Protection (2005) recommends balancing these considerations by placing one set of limits on exposure to the public (for example, 1 mSv per year from artificial sources) and another set of limits on exposure to workers at nuclear facilities (for example, 20 mSv per year), in part because workers knowingly accept some degree of risk (see Clarke 2011: 31).

Current and future challenges for decommissioning

Regardless of the future direction of nuclear power, decommissioning is a high-priority area for human resources and technology development. Worldwide, experience with power reactor decommissioning and long-term site restoration is limited. Due to current trends in reactor shutdowns, demand for decommissioning services will increase in coming years. Attracting, motivating, and training the necessary experts, personnel, and contractors will be a particular challenge for states where nuclear energy is in decline.

It is important to start planning for decommissioning early in the life cycle of a reactor. For reactors that are currently operating, improvements made over the last 50 years to detailed record-keeping and site characterisation activities will help to ensure that events that could affect levels of radioactive contamination (and therefore decommissioning plans) at various parts of the site are well documented. For future reactors, the state should require a decommissioning plan to be drawn up during the design phase with an explanation of the proposed end-state for the site after decommissioning. Where decommissioning cost estimates are used as a basis for collecting funds, the estimates should make it clear when funds will be available, what contingencies are foreseen, and what assumptions are being made about end-use of the site. Furthermore, cost projections should take into consideration possible future scenarios for spent fuel management, particularly the possibility that a lack of high-level waste disposal options will make it necessary to continue to use interim independent spent fuel storage installations.

From the standpoint of transparency to regulatory and public scrutiny, it would be desirable to standardise cost estimate methodologies for decommissioning across states. At present, this appears to be almost impossible due to the large variation in the cost of decommissioning services among states. However, a competitive market for international decommissioning service contracts is emerging (see Schmittem 2016; Fell 1999). As this occurs, the question of standardisation should be revisited with a view to ensuring that cost projections are consistent across all states and accurately reflect the true cost of all activities associated with decommissioning.

More broadly, information exchange and promotion of best practice among practitioners will become increasingly important during the projected upsurge in decommissioning activities. Forums like the IAEA's International Decommissioning Network should focus on how lessons learned from decommissioning the first generation of reactors in North America and Europe can be used to assist countries in Asia that are currently planning, constructing, or operating reactors.

For nuclear experts, decommissioning involves the familiar challenge of communicating information about risks associated with stochastic and unobservable processes. Education, communication, and engagement with the public should be the shared responsibility of operators and governments. Licensees in the United States currently have the option to create citizen advisory panels to improve public participation in aspects of decommissioning, including final site-use and environmental remediation (US NRC 2015a). The use of these panels, and publication of their discussions, should be more widely encouraged. As the number of reactors undergoing decommissioning rises, transparency about the steps involved in the process and the projected end-state of former reactor sites will be increasingly important for maintaining public trust in nuclear technologies.

Acknowledgements

The author wrote this chapter while he was working as a Stanton Nuclear Security Postdoctoral Fellow for the Belfer Center for Science and International Affairs at the John F. Kennedy School of Government, 2015–16. This chapter represents the views of the author. It does not represent the views of any institution.

References

Adelman, Oliver, 2016. 'Prompt' decommissioning a potential trend, some in industry say. *Nucleonics Week* 57(10): 5.

Atomic Industrial Forum, 1986. Guidelines for producing nuclear power plant decommissioning cost estimates. National Environmental Studies Project AIF/NESP–036, Washington, DC.

Autorité de sûreté nucléaire, 2009. La politique de l'ASN en matière de démantèlement et de déclassement des installations nucléaires de base en France. Revision 0.v3, Paris, April. www.asn.fr/Media/Files/La-politique-de-l-ASN-en-matiere-de-demantelement-et-de-declassement-des-installations-nucleaires-de-base-en-France (accessed 24 January 2017).

Bråkenhielm, Carl Reinhold, 2005. Ethical guidance in connection with decommissioning of nuclear power plants. Nuclear Energy Agency Report No. NEA/RWM/WPDD(2005)4. Paper presented to Topical Session on Funding Issues in Connection with Decommissioning of Nuclear Power Plants, Paris, 9 November 2004. www.iaea.org/inis/collection/NCLCollectionStore/_Public/45/026/45026338.pdf (accessed 24 January 2017).

Brumfiel, Geoff, 2011. Fukushima reaches cold shutdown. *Nature*, 16 December. doi.org/10.1038/nature.2011.9674

Calabrese, Edward J., 2013. Origin of the linearity no threshold (LNT) dose-response concept. *Archives of Toxicology* 87(9): 1621–33. doi.org/10.1007/s00204-013-1104-7

Cama, Timothy, 2014. Senators: Nuclear decommissioning process is flawed. *The Hill*, 14 May. thehill.com/policy/energy-environment/206110-senators-nuclear-decommissioning-process-is-flawed (accessed 24 January 2017).

Citizens Awareness Network Inc. v United States Nuclear Regulatory Commission, 1995. *Federal Reporter*, third series, 59: 284.

Clarke, Roger H., 2011. Changes in underlying science and protection policy. In *Evolution of ICRP Recommendations 1977, 1990 and 2011-42.07: Changes in Underlying Science and Protection Policy and Their Impact on European and UK Domestic Legislation*, edited by Nuclear Energy Agency, 11–42. NEA No. 6920. Boulogne-Billancourt: Nuclear Energy Agency.

Connecticut Yankee, 2015. CY property. www.connyankee.com/html/future_use.asp (accessed 24 January 2017).

Drozdiak, Natalia, and Jenny Busche, 2015. Germany's nuclear costs trigger fears. *Wall Street Journal*, 22 March.

Fell, Nolan, 1999. Decommissioning: A rapidly maturing market. *Nuclear Engineering International*, 29 October.

Goodman, L., 2009. Fermi 1 sodium residue cleanup. In *Decommissioning of Fast Reactors after Sodium Draining*, 39–43. IAEA TecDoc 1633. Vienna: IAEA.

Harland, David M., and Ralph D. Lorenz, 2006. *Space Systems Failures: Disasters and Rescues of Satellites, Rocket and Space Probes*. Chichester: Praxis Publishing.

Hiruo, Elaine, 2016. DOE should take fuel from reactors in order they shut, former executive says. *Nuclear Fuel* 41(11): 8.

IAEA (International Atomic Energy Agency), 1976. Decommissioning of nuclear facilities. Report of a technical committee meeting held in Vienna, 20–24 October 1975. IAEA TecDoc 179.Vienna: IAEA.

IAEA (International Atomic Energy Agency), 2002. *IAEA Safeguards Glossary: 2001 Edition*. 3rd edn. Vienna: IAEA.

IAEA (International Atomic Energy Agency), 2009. Classification of radioactive waste: General safety guide. Safety Standards Series No. GSG-1, STI/PUB/1419. Vienna: IAEA.

IAEA (International Atomic Energy Agency), 2014. Decommissioning of facilities: General safety requirements part 6. IAEA Safety Standards for Protecting People and the Environment. No. GSR Part 6. Vienna: IAEA.

IAEA (International Atomic Energy Agency), 2015a. *Nuclear Power Reactors in the World*. Reference Data Series No. 2. 35th edn. Vienna: IAEA.

IAEA (International Atomic Energy Agency), 2015b. Nuclear technology review 2015: Report by the director general. General Conference Document GC/59/INF/2, 2 July.

IAEA (International Atomic Energy Agency), 2016a. *IAEA Safety Glossary: Terminology used in Nuclear Safety and Radiation Procedures, Draft*. Vienna: IAEA.

IAEA (International Atomic Energy Agency), 2016b. Research reactor database. nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx?rf=1 (accessed 24 January 2017).

IAEA (International Atomic Energy Agency), 2016c. *Nuclear Power Reactors in the World*. Reference Data Series No. 2. 36th edn. Vienna: IAEA.

IAEA (International Atomic Energy Agency), n.d. INES: The international nuclear and radiological event scale. www.iaea.org/sites/default/files/ines.pdf (accessed 24 January 2017).

IAEA (International Atomic Energy Agency) Department of Nuclear Safety and Security, 2007. *IAEA Safety Glossary: Terminology Used in Nuclear, Radiation, Radioactive Waste and Transport Safety*. Vienna: IAEA.

Inter-Ministerial Council for Contaminated Water and Decommissioning Issues, 2015. Mid-and-long-term roadmap towards the decommissioning of TEPCO's Fukushima Daiichi nuclear power station. 12 June. www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20150725_01b.pdf (accessed 24 January 2017).

International Commission on Radiological Protection, 2005. Low-dose extrapolation of radiation-related cancer risk. *Annals of the ICRP* 35(4): publication 99.

International Energy Agency, 2016. *Energy Policies of IEA Countries: Belgium: 2016 Review*. Paris: International Energy Agency.

Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, 1997. Opened for signature 29 September, 2153 UNTS 37605 (entered into force 18 June 2001).

Knoll, Glenn F., 2010. *Radiation Detection and Measurement*. 4th edn. Brisbane: John Wiley & Sons.

Kotoku, Tetsuo, 2016. Robot challenges for nuclear decommissioning of Fukushima Daiichi nuclear power station. Presentation to the IAEA International Conference on Advancing the Global Implementations of Decommissioning and Environmental Remediation Programmes, Madrid, 25 June. irid.or.jp/_pdf/20160523.pdf (accessed 24 January 2017).

Laraia, Michele, ed., 2012. *Nuclear Decommissioning: Planning, Execution and International Experience*. Philadelphia, PA: Woodhead Publishing. doi.org/10.1533/9780857095336

Michelbacher, J. A., S. P. Henslee, C. J. Knight, and S. R. Sherman, 2009. Decommissioning of experimental breeder reactor-II complex, post sodium draining. In *Decommissioning of Fast Reactors after Sodium Draining,* 59–65. IAEA TecDoc 1633. Vienna: IAEA.

Morgan, William F., 2013. Issues in low dose radiation biology: The controversy continues: A perspective. *Radiation Research* 179: 501–10. doi.org/10.1667/RR3306.1

Mount, Mark E., Michael K. Sheaffer, and David T. Abbott, 1994. Kara Sea radionuclide inventory from naval reactor disposal. *Journal of Environmental Radioactivity* 25(1–2): 11–19. doi.org/10.1016/0265-931X(94)90004-3

Nagata, Kazuaki, 2016. Toshiba unveils remote-controlled device to remove reactor 3 fuel assemblies at Fukushima No. 1. *Japan Times*, 18 January.

Nuclear Energy Agency, 2012. *International Structure for Decommissioning Costing (ISDC) of Nuclear Installations*. Radioactive Waste Management Series, NEA No. 7088. Paris: NEA, www.oecd.org/publications/international-structure-for-decommissioning-costing-isdc-of-nuclear-installations-9789264991736-en.htm Accessed 13 February 2017).

Nuclear Energy Agency, 2016. *Costs of Decommissioning Nuclear Power Plants.* Nuclear Development Series, NEA No. 7201. Paris: NEA. www.oecd-nea.org/ndd/pubs/2016/7201-costs-decom-npp.pdf (accessed 24 January 2017).

Nuclear Energy Insider, 2016. European nuclear decommissioning activity to rise 8% per year. 2 June. analysis.nuclearenergyinsider.com/content/european-decommissioning-activity-rise-8-year (accessed 24 January 2017).

Nucleonics Week, 2016. China's nuclear waste market to get a boost. 57(13) (31 March): 5.

NucNet, 2015. Russia announces successful decommissioning of El-2 LWGR. 191(28 September). www.nucnet.org/all-the-news/2015/09/28/russia-announces-successful-decommissioning-of-el-2-lwgr (accessed 24 January 2017).

Office of the Deputy Chief Cabinet Secretary (Japan), 2011. Report: Working group on risk management of low-dose radiation exposure. 22 December. www.cas.go.jp/jp/genpatsujiko/info/twg/Working_Group_Report.pdf (accessed 24 January 2017).

Pagnamenta, Robin, 2016. Early closure of nuclear power station could cost £22bn. *The Times* (London), 19 March.

Samseth, Jon, Anthony Banford, Borislava Batandjieva-Metcalf, Marie Claire Cantone, Peter Lietava, Hooman Peimani, and Andrew Szilagyi, 2013. Closing and decommissioning nuclear power reactors. In *United Nations Environment Programme Year Book 2012*, 35–49. Nairobi: United Nations Environment Programme.

Schmittem, Marc, 2016. Nuclear decommissioning in Japan: Opportunities for European companies. Tokyo: EU–Japan Centre for Industrial Cooperation, March. www.eu-japan.eu/sites/default/files/publications/docs/2016-03-nuclear-decommissioning-japan-schmittem-min_0.pdf (accessed 24 January 2017).

Schneider, Mycle, and Antony Froggatt, with Julie Hazemann, Tadahiro Katsuta, M. V. Ramana, and Steve Thomas, 2015. *The World Nuclear Industry Status Report 2015*. Paris: Mycle Schneider Consulting Project.

Stoiber, Carlton, Abdelmadjid Cherf, Wolfram Tonhauser, and Maria de Lourdes Vez Carmona, 2010. *Handbook on Nuclear Law: Implementing Legislation*. Vienna: IAEA.

Suzuki, Tatsujiro, 2015. Nuclear energy policy issues in Japan after the Fukushima nuclear accident. *Asian Perspective* 39(4): 591–606.

Taebi, Benham, and Andrew C. Kadak, 2010. Intergenerational considerations affecting the future of nuclear power: Equity as a framework for assessing fuel cycles. *Risk Analysis* 30(9): 1341–62. doi.org/10.1111/j.1539-6924.2010.01434.x

Thomas, Karen, 2016. Sweden's plant closures to hike skills demand from 2017. *Nuclear Energy Insider*, 21 March. analysis. nuclearenergyinsider.com/swedens-plant-closures-hike-skills-demand-2017 (accessed 24 January 2017).

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 2008. *Sources and Effects of Ionizing Radiation*. Vol. 1. Annex B. New York: United Nations.

US Government Accountability Office, 2012. NRC's oversight of nuclear power reactors decommissioning funds could be further strengthened. GAO-12-258, April.

US NRC (Nuclear Regulatory Commission), 2013. Report on waste burial charges: Changes in decommissioning waste disposal costs at low-level waste burial facilities: Final report. NUREG-1307, Rev. 15. Washington, DC: Nuclear Regulatory Commission, January. www.nrc.gov/docs/ML1302/ML13023A030.pdf (accessed 24 January 2017).

US NRC (Nuclear Regulatory Commission), 2015a. Communication strategy for the enhancement of public awareness regarding power reactors transitioning to decommissioning. February. www.nrc.gov/docs/ML1501/ML15013A068.pdf (accessed 24 January 2017).

US NRC (Nuclear Regulatory Commission), 2015b. Backgrounder on decommissioning nuclear power plants. May. www.nrc.gov/reading-rm/doc-collections/fact-sheets/decommissioning.html (accessed 24 January 2017).

US NRC (Nuclear Regulatory Commission), 2016. Background on the proposed security rulemaking for independent spent fuel storage installations. www.nrc.gov/about-nrc/radiation/related-info/isfsi-security/background.htm (accessed 4 September 2017).

US NRC (Nuclear Regulatory Commission) Regulations, 2015. § 50.75: Reporting and recordkeeping for decommissioning planning. www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0075.html (accessed 24 January 2017).

US Senate, 2014. Nuclear reactor decommissioning: Stakeholder views. Hearing Before the Committee on Environment and Public Works, 130th Congress, 2nd Session, 14 May.

Wald, Matthew L., 2011. Keeping score on nuclear accidents. *New York Times*, 12 April.

Weigl, M., 2008. Decommissioning of German nuclear research facilities under the governance of the Federal Ministry of Education and Research. Paper presented to the Hazardous Wastes & Environmental Management Symposium, Phoenix, 25 February.

World Nuclear News, 2015. Vattenfall, EOn team up on German decommissioning. 29 May. www.world-nuclear-news.org/WR-Vattenfall-EOn-team-up-on-German-decommissioning-2905154.html (accessed 24 January 2017).

World Nuclear News, 2016a. Proposal for financing German nuclear phase-out. 28 April. www.world-nuclear-news.org/WR-Proposal-for-financing-German-nuclear-phase-out-2804164.html (accessed 24 January 2017).

World Nuclear News, 2016b. EU increases Chernobyl funding on eve of anniversary. 25 April. www.world-nuclear-news.org/WR-EU-increases-Chernobyl-funding-on-eve-of-anniversary-25041602.html (accessed 24 January 2017).

This text is taken from *Learning from Fukushima: Nuclear power in East Asia*, edited by Peter Van Ness and Mel Gurtov, published 2017 by ANU Press, The Australian National University, Canberra, Australia.

dx.doi.org/10.22459/LF.09.2017.10