

# Closing and Decommissioning Nuclear Power Reactors

## Another look following the Fukushima accident

Since the accident at Japan's Fukushima Daiichi nuclear power plant, nuclear power programmes in several countries have been under review. Germany has decided to end its programme entirely. Whatever other governments decide, the number of civilian nuclear power reactors being decommissioned is set to increase internationally as the first generations of these reactors reach the end of their original design lives.

There are plans to close up to 80 civilian nuclear power reactors in the next ten years. While many of these reactors are likely to have their operating licenses extended, they will eventually be decommissioned. The scale of the task ahead means that adequate national and international regulations, extensive funding, innovative technologies, and a large number of trained workers will be required.

Decommissioning has been carried out for a number of years without major radiological mishaps. Nevertheless, there is a need to ask: How safe is decommissioning? What are the implications of national nuclear shutdowns such as the one planned in Germany? Do countries have the necessary expertise and infrastructure to cope with the expected increase in the number of reactors to be decommissioned? And how will the very high and unpredictable costs of decommissioning be met?

### What is nuclear decommissioning?

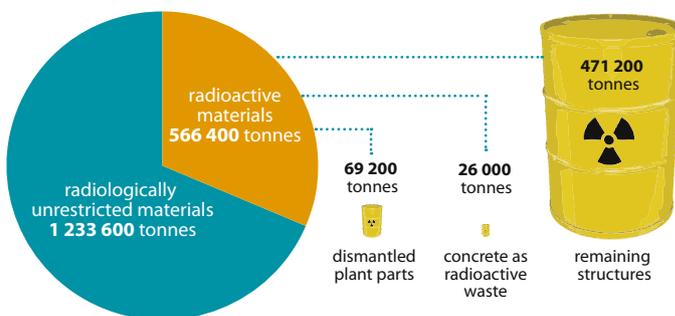
The term "decommissioning" refers to safe management – at the end of life – of many different types of nuclear facilities and sites. Decommissioning is carried out at power stations, fuel processing facilities, research reactors, enrichment plants, nuclear and radiological laboratories, uranium mines and uranium processing plants. Reactors that power submarines and ships (including ice breakers and aircraft

The number of civilian nuclear power reactors being decommissioned is set to increase significantly in the coming decade. *Credit: visdia*

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carriers) must also be decommissioned. The biggest growth area for decommissioning is civilian nuclear power reactors (Box 1).

Decommissioning is only part of the final shutdown of a nuclear reactor, which begins with the removal of highly radioactive spent fuel and may end with the clean-up of an entire facility or site, including in some cases contaminated soil and groundwater (IAEA 2004a). Decommissioning involves the demolition of buildings and other structures, including the parts near the reactor core that may have become radioactive, as well as on-site handling of construction materials (mostly steel and concrete) and the packaging and transport of these materials for safe storage and disposal. Each decommissioning is associated with particular technical challenges and risks to human



**Figure 1:** During the decommissioning of a nuclear power reactor large amounts of waste are generated, both radioactive (orange) and radiologically unrestricted (blue). The diagram is based on the mass flow for the decommissioned Greifswald nuclear power plant in Germany. *Source: Adapted from EWN – The Greifswald Nuclear Power Plant Site*



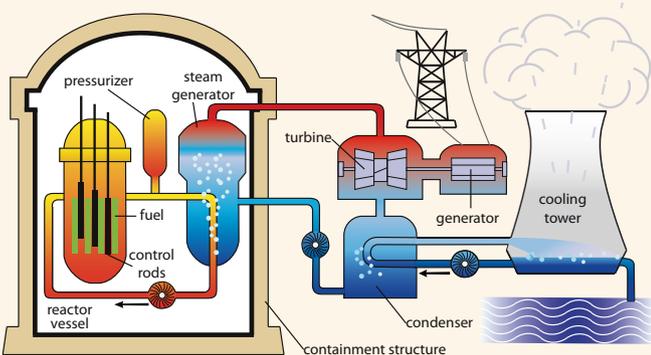
health and the environment. These have often been determined by choices made about reactor design and construction decades earlier (when decommissioning was little considered) as well as by operational practices over a period of years.

Most of the waste generated during decommissioning is not radiologically restricted (**Figure 1**). Radioactive decommissioning waste predominantly ranges from very low level to intermediate

### Box 1: Nuclear power reactor

The most common type of nuclear power reactor is the pressurized water reactor (**Figure 2**). In this type, heat generated by radioactive uranium fuel inside the reactor vessel is taken up by water and transported through a heat exchanger where steam is generated. Steam drives a turbine and generator, which produces electricity. Using a cooling source (water from a river, a lake or the sea, or from a cooling tower), the steam is condensed into water.

The reactor vessel, steam generator and, in some cases, the storage pool for spent fuel (not shown in the figure) are located within a containment structure made of thick steel and/or concrete, which protects against releases of radioactivity to the environment. The parts that have become radioactive in the reactor, and require special attention during decommissioning, are the reactor vessel itself and the materials inside the vessel, including the control rods. Piping, pumps and other equipment which has been in direct contact with water that has passed through the reactor vessel or storage pool are also contaminated. A comparatively small amount of concrete may be contaminated and therefore require further treatment (O'Sullivan et al. 2010).



**Figure 2:** A pressurized water reactor produces electricity using heat generated by radioactive uranium fuel to create large amounts of steam that drive a turbine and generator. *Source: Kazimi (2003)*

level radioactive (**Table 1**). High level radioactive waste (spent nuclear fuel) is generated during a reactor's operation. While the *radioactivity levels of decommissioning waste* are much lower than those of the waste generated during operations, the *volume of radioactive waste generated* during decommissioning is far greater than the volume generated during operations. Once the reactor has been closed down, radiation levels decrease over time.

## State and trends in nuclear decommissioning

As of January 2012, 138 civilian nuclear power reactors had been shut down in 19 countries, including 28 in the United States, 27 in the United Kingdom, 27 in Germany, 12 in France, 9 in Japan and 5 in the Russian Federation (IAEA 2012a). Decommissioning had only been completed for 17 of them at the time of writing. Decommissioning is a complex process that takes years. The United Kingdom, for instance, completed its first decommissioning of a power reactor in 2011. This reactor, located at Sellafield, was shut down in 1981 (WNN 2011a).

The backlog of civilian nuclear power reactors that have been shut down but not yet decommissioned is expected to grow. There is also a large legacy of military and research reactors (**Box 2**). The typical design life of a civilian nuclear power reactor is 30 to 40 years. There are currently 435 such reactors in operation worldwide, with a total installed electrical capacity of 368.279 billion watts (GWe) (**Figure 3**). Of these 435 civilian nuclear power reactors, 138 are more than 30 years old and 24 are more than 40 years old (IAEA 2012a). The average age of the civilian nuclear power reactors currently in operation is 27 years (IAEA 2012a, WNA 2011a).

Many civilian nuclear power reactors will continue to operate safely beyond their original design life. Some will have their operating licences renewed for up to 60 or even 80 years (Energetics Inc. 2008). In addition, there are 63 civilian nuclear power reactors under construction with a net electrical capacity of 61 GWe (IAEA 2012a, WNA 2011b) (**Figure 4**). All nuclear reactors will have to be decommissioned some day, and the resulting radioactive waste will then need to be safely managed and disposed of (Bylkin et al. 2011).

In March 2011, a devastating 8.9 magnitude earthquake followed by a 15-metre tsunami, affected the people of Japan. Thousands of lives were lost, many people were injured and the damage to housing and infrastructure was unprecedented. The tragic earthquake and subsequent tsunami also caused the accident at the Fukushima nuclear power plant whereby radioactive material was released to the air and sea. Contamination of the reactor site

## Box 2: The nuclear legacy

The early years of nuclear energy left a considerable legacy of contaminated facilities, including nuclear reactors. Some are civilian in nature, but the majority are military, scientific and demonstration facilities. Until old, contaminated facilities are successfully decommissioned, they pose continuing risks and will cast a shadow over today's nuclear industry in the minds of much of the public. The challenges those involved in decommissioning must often address include incomplete facility histories and inadequate information about the state of sites and equipment. The United Kingdom's Nuclear Decommissioning Authority has reported that some facilities "do not have detailed inventories of waste, some lack reliable design drawings [and] many were one-off projects" (UK NDA 2011).

The United States Department of Energy (DOE) has undertaken to decontaminate more than 100 former research and nuclear weapons sites, covering thousands of hectares, by 2025. This will entail the management of millions of cubic metres of debris and contaminated soil, including large areas where groundwater is contaminated (Szilagyi 2012). For instance, the Oak Ridge National Laboratory in Tennessee covers 15 000 hectares with more than 100 known contaminated sites (US DOE 2011). At the larger Hanford nuclear facility in the State of Washington there are significant amounts of radioactive liquid waste (US EPA 2011a).

The DOE has successfully cleaned up complex sites such as Rocky Flats in Colorado (Tetra Tech 2012). Nevertheless, some sites may never be cleaned up for unrestricted use. In the United Kingdom, the Scottish Environment Protection Agency (SEPA) concluded in 2011 that it would do "more harm than good" to try and remove all traces of radioactive contamination from the coastline and sea bed around the Dounreay nuclear reactor site (SEPA 2011). In many countries it will be possible to reuse decommissioned sites that are not fully cleaned up for new nuclear applications (IAEA 2011a).

Reactors built to power submarines or ships are one type of legacy concern. Decommissioning a typical nuclear submarine produces more than 800 tonnes of hazardous waste (Kværner Moss Technology 1996). At the end of the Cold War there were over 400 nuclear submarines, either operational or being built, mainly in the former Soviet Union and in the United States (WNA 2011d). Many nuclear submarines have been withdrawn from service and most await decommissioning. The United States has decommissioned a number of them, with their reactors removed, properly packaged and staged for disposal at Hanford. Before 1988, some 16 reactors from dismantled nuclear submarines in the former Soviet Union were disposed of by dumping at sea (Mount et al. 1994, IAEA 1999).

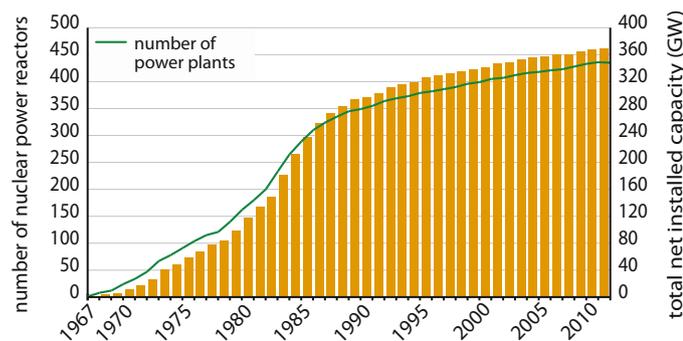
and its surroundings made an area with a radius of about 30 km uninhabitable or unsuitable for food production – in some cases for months or years to come. Japan's power-generating capacity has been seriously affected, and the political impact in other countries has led some governments to question their reliance on nuclear energy. So far, only Germany has decided to end

nuclear power generation (BMU 2011, WNA 2011c). However, the debate continues in a number of other countries (Okyar 2011). The company which built many of Germany's nuclear reactors has announced that it does not plan to build any more reactors anywhere in the world (Der Spiegel 2011). As some civilian nuclear power reactors that had previously been expected to operate for many more years join those nearing the end of their design life, the total number awaiting decommissioning is likely to increase significantly.

### Three approaches to decommissioning

There are three generally accepted approaches to decommissioning: immediate dismantling, deferred dismantling and entombment. Each approach requires early and clear decisions about the timing of the closure of facilities and intended future use of the site (Figure 5). Each also requires adequate funding, trained personnel, regulatory oversight and waste storage and disposal facilities (IAEA 2006).

**Immediate dismantling:** All equipment, structures and other parts of a facility that contain radioactive contaminants are removed (or fully decontaminated) so that the site can be treated as uncontaminated



**Figure 3:** By early 2012 the number of nuclear power reactors in the world had increased to 435. Total installed electrical capacity has increased relatively more rapidly than the number of reactors. Source: IAEA (2012)





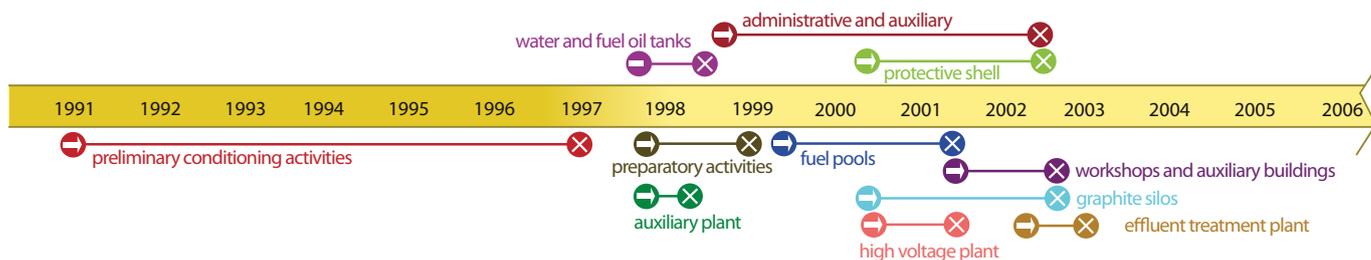
Figure 4: Sixty-three nuclear power reactors are under construction. The majority are in China, India and the Russian Federation. Source: Adapted from IAEA (2012)

for either unrestricted or more restricted use (sometimes referred to as a “greenfield” site). This internationally agreed approach has the advantage that experienced operational staff from the facility are still available who know the history of the site, including any incidents in the past that could complicate the decommissioning process. Immediate dismantling also avoids the unpredictable effects of corrosion or other degradation of the reactor parts over an extended period, eliminates the risk of future exposure to radiation, and removes a potential blight on the landscape. A disadvantage of this approach is that levels of radioactivity in the reactor parts are higher than in the case of deferred dismantling. This means that greater precautions must be taken during dismantling, and that larger volumes of decommissioning waste will be classified as radioactive.

**Deferred dismantling:** After all the spent fuel is removed, the plumbing is drained, and the facility is made safe while dismantling is left for later. This approach is often called “safe enclosure”. The deferral periods considered have ranged from 10 to 80 years (Deloitte 2006). For instance, the Dodewaard reactor in the Netherlands was shut down in 1997 but will not be

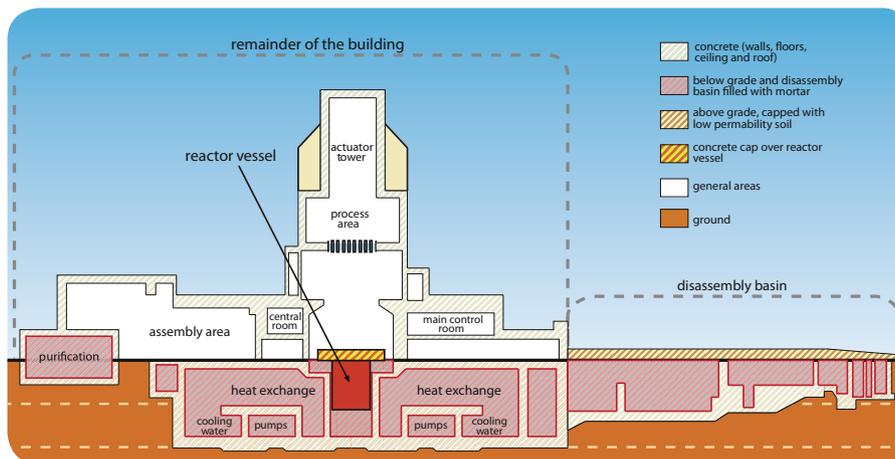
decommissioned until at least 2047 (IAEA 2004b). Deferred decommissioning has the advantage of allowing radioactive materials to decay to lower levels of radioactivity than in the case of immediate dismantling (Box 3). This reduces both disposal problems and risks of harm to workers. In the meantime, robotic and other types of techniques that make dismantling safer and cheaper may undergo further development. A disadvantage is that some materials, including concrete and steel, may deteriorate, making the eventual decommissioning more difficult. Moreover, personal knowledge of a site’s history will be lost as time passes.

**Entombment:** Once the spent fuel has been removed, reactors can be entombed. This involves encasing the structure in highly durable material such as concrete while its radioactivity decays. Entombment is a relatively new approach that is mainly considered in special cases (examples are small research reactors or reactors in remote locations). It can reduce worker exposure to radioactivity since there is less handling of contaminated materials. However, long-term maintenance and monitoring are





Nuclear power plant prior to decommissioning



Cross-section of the entombment structure

**Figure 6:** Entombment at the Savannah River site, United States. All the spent fuel and other high level waste was removed from the reactor, as well as that portion of waste/contamination indicated as unacceptable based on rigorous risk and performance assessments. Entombment entailed subsequent filling with specialized mortar of all subsurface spaces where contamination existed. Above-ground uncontaminated areas were generally left as they were. To provide additional protection against water intrusion and infiltration, the building was left standing and will be monitored over the long term. *Source: Adapted from US DOE (2012)*

required. Five reactors have been entombed in the United States, with the entombment of two reactors at the Savannah River site completed in 2011 (**Figure 6**).

## The challenges of decommissioning

Decommissioning has been accomplished so far without creating significant additional health and safety or environmental risks, although it has occasionally revealed unsuspected past contamination from nuclear operations (WNA 2011a). An adequate legal framework nevertheless needs to be in place, with clear responsibilities assigned to different actors including regulatory authorities. Otherwise, risks could increase as the number of decommissionings increases; as pressures grow in some countries to speed up the closing and decommissioning of nuclear power plants, shorten overall schedules and cut costs; and as decommissioning begins in countries with little or no previous experience and insufficient waste management capacity. More experience should eventually contribute to improved techniques and reduced costs. However, unless the accelerated phase-out of nuclear reactors is carefully managed, with adequate regulatory oversight, it could lead to overly hasty decisions to decommission or to reactors standing idle for many years before decommissioning finally takes place. The latter situation, if not

properly monitored and managed, could lead to increased risks of releases of radioactive contaminants to the environment and exposure of nearby populations (IAEA 2007).

## Smarter dismantling

A critical aspect of decommissioning is that dismantling needs to be carried out in such a way that radioactive and non-radioactive materials are separated. This minimizes the amount of waste that will require special treatment because of its radioactivity. Separation also maximizes the amount of materials such as steel and aluminium that can be recycled, as well as the amount of concrete rubble that can be reused on site (Dounreay 2012). Some materials may need to be dismantled and decontaminated on-site. The complex task of dismantling requires good information at the beginning of the process about the radiological characteristics and state of the reactor, including its operational history, such as incidents and accidents, and the presence of any spent fuel debris.

The need to dismantle structures whose purpose has been to protect workers during the reactor's operation can make decommissioning more difficult. For instance, steel pipes



**Figure 5:** The dismantling and decommissioning of the Vandellós I civilian nuclear power reactor in Spain is taking place in three main phases: reactor shutdown and preliminary activities (1991-1997); removal of non-reactor structures (1998-2003); and dismantling of the reactor vessel (around 2028). The third phase is scheduled to begin after a 25-year dormancy period, during which the reactor is to remain under close surveillance. *Source: Adapted from ENRESA (2009)*

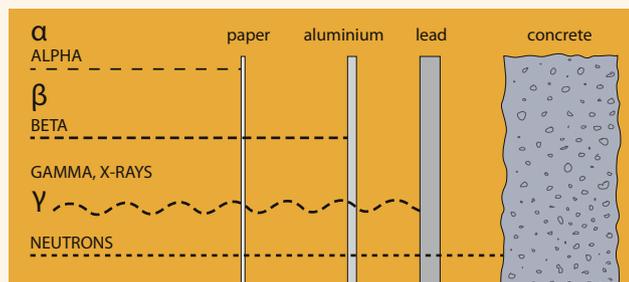
### Box 3: Radiation associated with decommissioning

The bulk of the radioactive waste from decommissioning consists of very low level and low level waste, mostly steel and concrete. Higher level radioactive waste from decommissioning consists mainly of reactor components. This waste contains isotopes that emit radiation as they decay. The initial release of radiation decreases rapidly due to the relatively short half-life of a number of isotopes. After 50 years, the radiation level in most decommissioning waste decays to a small percentage of the initial level.

Isotope	Half-life (years)
C-14	5 730
Ni-59	75 000
Ni-63	96
Fe-55	2.7

At very high doses radiation can cause radiation sickness, cancers and even near-term or immediate death, as in the case of on-site workers at the time of the Chernobyl accident. At lower doses it may induce cancers and genetic damage. At doses normally received during operations or decommissioning, however, risks to workers should be negligible.

The radiation encountered during decommissioning and the disposal of the waste generated is almost exclusively beta and gamma radiation (Figure 7). Decommissioning risks are mostly associated with exposure to these types of radiation. Since the waste from decommissioning is most commonly in solid form, only unintended releases of radioactive dust generated during demolition has the potential to result in exposure of the general public (US EPA 2011b).



**Figure 7:** Alpha, beta, gamma and neutron radiation differ in their ability to penetrate materials. Alpha particles do not penetrate far. They can be stopped by a sheet of paper, while beta particles can be stopped by a thin piece of aluminium, gamma rays by heavy metals, such as lead, and neutrons by concrete or water. *Source: WNA (2011e)*

carrying highly radioactive liquids are often encased in concrete. This makes decommissioning more complex, in that the pipes may be radioactive while the large volumes of concrete in which they are embedded are not. The contaminated material will either have to be removed separately or segregated later (O'Sullivan et al. 2010).

A key to reducing the volume of contaminated waste is to improve the separation of materials during decommissioning. But reconciling this practice with the minimization of worker exposure may be difficult. Evaluations are therefore carried out prior to decommissioning in order to choose appropriate approaches that make use of manual or remote control techniques. In many cases remotely operated vehicles, manipulator arms and robots can be used to cut waste materials into smaller pieces. Further development of such technologies will be invaluable, as they can reduce volumes of radioactive waste through more selective cutting, thus reducing both costs and radiological risks.

Experience with decommissioning the first generations of nuclear reactors suggests that decommissioning would have been easier and less expensive if they had been designed with this stage in mind (OECD/NEA 2010a). Few old reactors incorporate design features that help or simplify decommissioning. Nuclear power plants currently in operation commonly have a decommissioning plan, as preliminary plans are often a requirement for the application for a licence to operate a nuclear facility (OECD/NEA 2010a). Decommissioning plans should be updated regularly, with a detailed scheme drawn up at least two years before the scheduled shutdown (IAEA 2008, 2011b). However, some



Compactable low level waste may include radioactive clothing, glass and building materials. *Credit: Sellafield Ltd.*



Cut through a barrel containing intermediate level liquid waste solidified in concrete. Intermediate level waste consists of heavily contaminated materials, such as fuel rod casings or decommissioned parts of the reactor vessel. This waste requires radiation shielding. Storage time will depend upon which radioactive isotopes are present in the waste. Radioactive liquids are solidified before disposal. *Credit: Dounreay*

reactors are inevitably shut down early because of a change of policy, an accident or a natural disaster (**Box 4**).

### Resources and capacity

Several countries have developed expertise in decommissioning. In the United States, for instance, 1 450 government nuclear facilities of various kinds have been fully decommissioned, including a number of reactors (US DOE 2012). While such expertise in some countries is ground for optimism, a number of other countries have yet to develop expertise and infrastructure on the scale that will be necessary in the future. Universities and technical centres in a number of countries are setting up training programmes or undertaking research and development specifically related to decommissioning. Much of this activity is focused on automatic equipment and innovative methods of working in a radioactive environment.

Future decommissioning of civilian nuclear power reactors will compete for expertise, resources and waste disposal facilities with the decommissioning of many military and research reactors and other facilities. More than 300 such reactors, both small and large, have been taken out of operation (WNA 2011a), but the majority have not yet been decommissioned.

### Public acceptability

Public acceptability is critical to the future of nuclear power (OECD/NEA 2010b). Whether nuclear power plants are decommissioned immediately or after some delay, what happens to radioactive waste, and whether the end result is a greenfield site, entombment or something in between can depend on acceptance by the public as

## Box 4: Managing damaged reactors

Decommissioning requires a safety assessment to be approved by regulatory authorities, and both an environmental impact assessment (EIA) and an environmental impact statement (EIS) to be completed. Decommissioning in the aftermath of a major accident such as Three Mile Island (the United States), Chernobyl (Ukraine) or Fukushima (Japan) is quite different from planned decommissioning at the end of a facility's lifetime. Different types of planning, equipment and funding are needed. A damaged reactor may contain exposed nuclear fuel and its containment may be compromised. The reactor and associated facilities must be stabilized and made safe before dismantling or entombment take place.

In 1979 the Three Mile Island No. 2 reactor experienced a partial meltdown during which the core overheated. The operators carried out a clean-up, removing fuel, decontaminating radioactive water and shipping radioactive waste to a disposal site. Fuel and debris from the molten core were moved to a government facility, where they are now in dry storage awaiting a decision on the final disposal location. The reactor itself is in "monitored storage" until the No. 1 reactor is shut down. Both reactors will then be decommissioned (US NRC 2009).

In 1986 the Chernobyl No. 4 reactor exploded and burned, releasing large amounts of radioactive material to the air. The fire caused by the explosion was extinguished after several hours, but the graphite in the reactor burned for several days. It took half a year to encase the reactor in a concrete sarcophagus. This will not be the final entombment, however. The sarcophagus has deteriorated to such an extent that water is leaking in and it may be collapsing. There are plans to put a new containment around the sarcophagus by the end of 2015, so that the decaying structure and the fuel and other contaminated material inside can be removed safely to a new waste store (Wood 2007, Yanukovych 2011).

In December 2011 the Tokyo Electric Power Company (Tepco), the Ministry of Economy, Trade and Industry's Agency for Natural Resources and Energy, and the Nuclear and Industrial Safety Agency of Japan announced the first roadmap for decommissioning of the Fukushima reactors. It calls for the removal of fuel remaining in the storage pools within ten years. Starting in ten years, the fuel that constituted the cores of the reactors will be removed. This will be a very complex task, as the extent of damage to the cores is unknown. One of the reactor cores is thought to have melted through the reactor vessel and into the concrete floor below the reactor. To remove the cores will take another 10-15 years. Final demolition of the reactor structures will to be completed in 30-40 years (WNN 2011b).





Interim packaging and storage of radioactive waste. *Source: Nuclear Decommissioning Authority, United Kingdom*

much as on technical considerations. Intense decommissioning activity may be disliked by neighbours, but it can remove a blight on the landscape and allow new land use. Entombment, on the other hand, is not only visually unattractive, but maintaining a reactor in “safe mode” requires permanent security arrangements (OECD/NEA 2010b).

Some operators fear public debate, while others embrace it. The Nuclear Decommissioning Authority in the United Kingdom, for instance, is taking a more open approach than in the past (UK DTI 2002). Increased openness can have demonstrable success. In the United States, the National Aeronautics and Space Administration (NASA), which operates the Plum Brook research reactor in the State of Ohio, responded to public concern about decommissioning with a programme of community workshops, websites, videos, reactor media tours and open days. This potentially controversial decommissioning eventually gained local support (IAEA 2009a). The Forum of Stakeholder Confidence, created in 2000 by the intergovernmental Nuclear Energy Agency (NEA), facilitates sharing of experience in addressing the societal dimension of radioactive waste management. This body explores ways to maintain a constructive dialogue with the public in order to strengthen confidence in decision-making processes, which may involve players at the national, regional and local levels (OECD/NEA 2011).

### Unpredictability of decommissioning requirements

Decisions resulting from countries’ reappraisal of their nuclear power programmes following the Fukushima accident will have important implications for their national decommissioning programmes. They will also raise questions about whether the necessary skills, expertise, funding and infrastructure are in place to meet new and unanticipated decommissioning demands.

Of Japan’s 50 remaining nuclear power reactors, only 5 are operating at the time of writing (IAEA 2012a, WNN 2012a). Any of these reactors could eventually be restarted once stress tests are performed, improved protection against tsunamis is in place, and approval from both the government and local authorities has been obtained. The government closed the Hamaoka nuclear power plant temporarily in 2011 because of fears concerning a future large earthquake in its area. This plant will be reopened when better protection against tsunamis has been provided (WNN 2011d).

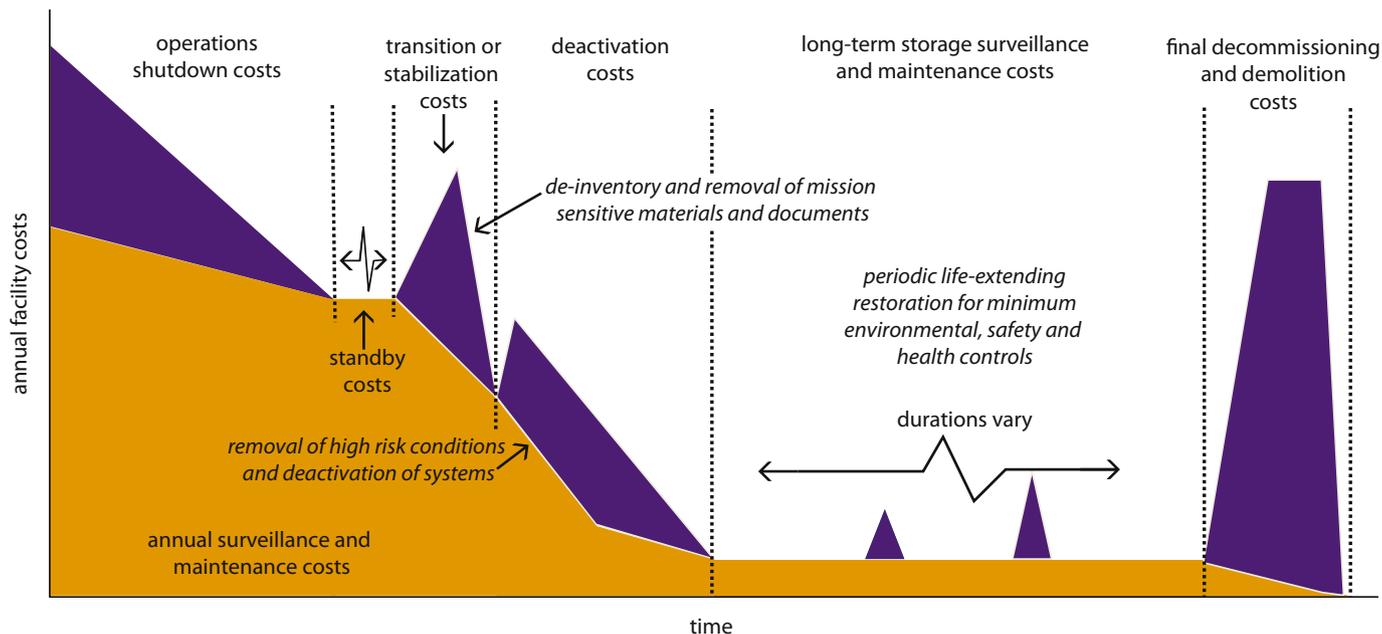
Germany’s decision to phase out all of its nuclear power plants by 2022 means bringing forward the closure of 13 currently operating plants (WNA 2011d). These plants’ early phase-out will be costly. It will also require safe handling of very large volumes of decommissioning waste or, if decommissioning is deferred, the safe maintenance of a number of mothballed facilities. Considerable demands will be made on Germany’s decommissioning expertise and infrastructure.

Those involved in decommissioning in any country need to be prepared for the unexpected. For instance, legislators, regulators or lawyers could intervene to initiate or halt decommissioning. In 2010 the Vermont State Senate in the United States revoked the license of the Vermont Yankee nuclear power plant because of concerns about leaks of radioactive tritium gas, as well as allegations that misleading statements on this issue had been made by the operators. The plant was scheduled to close in March 2012, but the operators were successful in their legal challenge to the state’s right to shut it down (WNN 2011d, 2012b).

### Costs and financing of decommissioning

The costs of decommissioning nuclear power reactors vary greatly, depending on the reactor type and size, its location, the proximity and availability of waste disposal facilities, the intended future use of the site, and the condition of both the reactor and the site at the time of decommissioning. Methods for carrying out cost estimates have been developed (OECD/NEA 2010c). However, published data on the costs of the small number of decommissionings completed so far are sparse (OECD/NEA 2010c, US GAO 2010). Estimates of future costs vary hugely.

Decommissioning costs represent a substantial share of the costs of a nuclear power reactor’s operation (**Figure 8**). On the other hand, they may represent only a small percentage of the income generated by a civilian nuclear power reactor over a 40-year period. In the United States, the average costs of decommissioning a nuclear power reactor have been around US\$500 million or approximately 10-15 per cent of the initial capital cost. In France, it is estimated that decommissioning the small Brennilis reactor (in operation from 1967 to 1985) will equal 59 per cent of the reactor’s



**Figure 8:** Decommissioning a nuclear power plant takes many years and costs vary widely. The highest costs will be incurred during the initial shutdown and final decommissioning and demolition. Any intervening period of standing by will be less expensive. These factors may influence decisions on how rapidly decommissioning will take place. *Source: United States Department of Energy (2010)*

initial cost. This estimate rose by 26 per cent between 2001 and 2008, to almost €500 million – as much as 20 times the original estimate (Cour des comptes 2005, 2012). In the United Kingdom, the government’s financial provision for decommissioning rose from £2 million in 1970 to £9.5 billion in 1990 and £53.7 billion in 2011 (Huhne 2011). It is clear that decommissioning can sometimes be much more expensive than originally budgeted (OECD/NEA 2010d). As more experience is gained, this type of uncertainty should diminish and the costs come down.

In many countries the responsibility for funding decommissioning activities rests with the owner, in compliance with the polluter pays principle (Deloitte 2006, Wuppertal 2007). Nevertheless, governments are responsible for ensuring that adequate funds are generated during the operation of nuclear power plants on their territory to pay these high and sometimes unpredictable costs. The extent to which funds are protected against financial crises is not always clear. Investment funds will not necessarily deliver the anticipated returns. In any event, governments are likely to be the funders of last resort (SwissInfo 2011).

In 2006 the European Commission issued a recommendation and a guide on the management of financial resources for the decommissioning of nuclear installations and the handling of

spent fuel and radioactive waste (EU 2006a, b). Furthermore, under a recent EU Directive establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste, all Member States are to ensure that funding resources are available for decommissioning (EU 2011). Many

#### Box 5: Regulating decommissioning at the global level

The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management is the first legal instrument to directly address, among other issues, the management of radioactive waste from decommissioning on a global scale (IAEA 2011c). The Joint Convention, which entered into force on 18 June 2001, has been ratified by 62 countries. Its Article 26 specifies that “Each Contracting Party shall take the appropriate steps to ensure the safety of decommissioning of a nuclear facility. Such steps shall ensure that: (i) qualified staff and adequate financial resources are available; (ii) the provisions of Article 24 with respect to operational radiation protection, discharges and unplanned and uncontrolled releases are applied; (iii) the provisions of Article 25 with respect to emergency preparedness are applied; and (iv) records of information important to decommissioning are kept.”



Table 1: Radioactive waste classification. Source: Adapted from IAEA (2009b)

	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 metres	shallow disposal at depth from a few tens to a few hundred metres	deep geological formations
need shielding	no	no	yes	yes
need cooling	no	no	no	yes

European governments – but not all – have ensured that such funding is available. The funding systems vary. In Spain, for instance, a public company is in charge of funding, while in Slovakia this is the responsibility of the Ministry of Economy. At the global level, the need to have adequate resources available for decommissioning is being addressed by the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (Box 5).

## Risks associated with decommissioning

The risks of large-scale releases of radioactivity during decommissioning are much lower than during a reactor's operations. Once the nuclear fuel has been removed, most of the radioactivity is gone. When the tanks and plumbing are drained, the majority of the radioactive materials that remain are in solid form, which is easier to handle and less likely to enter the environment. However, the non-routine and hands-on nature of the work means risks related to worker exposure are higher during decommissioning than during operations.

## Types and quantity of radioactive waste

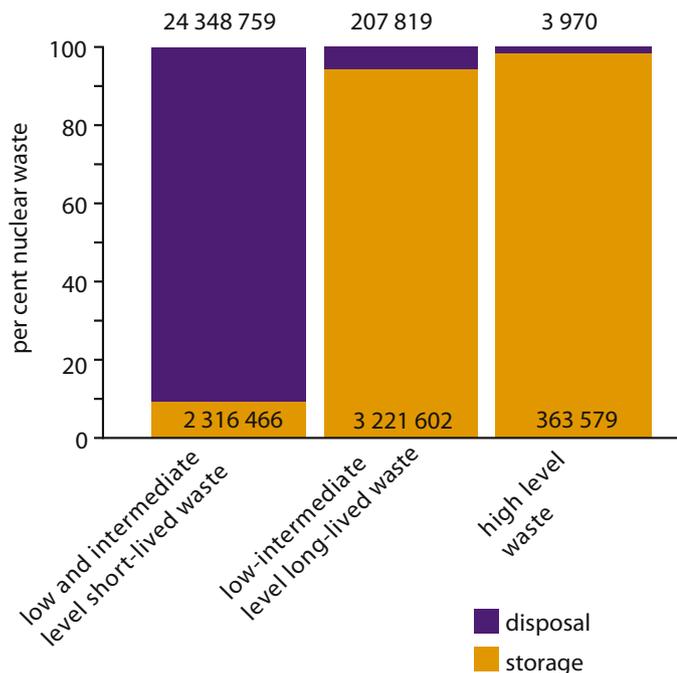
During operations, a nuclear reactor produces isotopes that give out potentially harmful radiation as they decay. Their half-life (the time it takes to halve the radioactivity of the isotope) varies from seconds to millions of years. Those with a half-life of more than ten days may contribute to radioactive 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, low level,

intermediate level and high level radioactive waste) according to risks and decay time (Table 1).

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-MW reactor produces about 27 tonnes of this waste per year (WNA 2011e). 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.



A typical disposal method for low level radioactive waste is burial underground. Care needs to be taken that water does not transport radioactive isotopes beyond the burial site. Credit: US NRC



**Figure 9:** Decommissioning generates waste that can be categorized as low, intermediate and high level nuclear waste. The total waste inventory shows the percentage of nuclear waste by type in storage, compared with that sent to disposal. Volumes are expressed in cubic metres and based on data reported by countries using the older 1994 IAEA waste classification, according to which low level waste and intermediate level waste were combined into two subgroups: short-lived and long-lived. Very low level waste was not distinguished as a separate category. *Source: Adapted from IAEA (2011d)*

According to current waste management practices, high level waste will ultimately require disposal in deep geological formations. While some countries, including Finland, France and Sweden, have selected sites, no country yet has an operational high level radioactive waste disposal facility. This is partly related to costs, partly to public opposition to proposed sites (WNA 2011f), and partly to the fact that insufficient time has elapsed for the spent fuel and other high level radioactive waste to become cool enough to be placed in a permanent repository. In the first 20 to 30 years after final shutdown, part of the inner components to be handled by decommissioning belongs to the high level waste class.

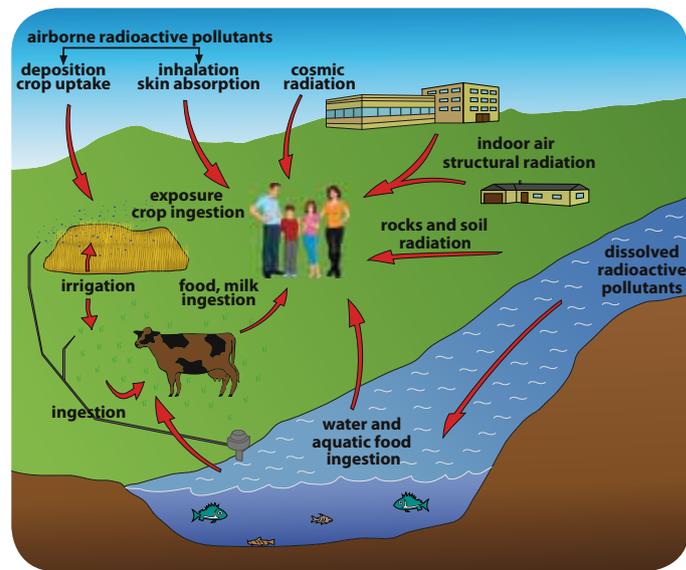
After the spent fuel is removed, decommissioning produces only small amounts of high level waste (HLW), most of which is nuclear fuel debris left behind after the last fuel was removed from the reactor. However, decommissioning typically generates two-thirds of all the very low, low and intermediate level waste (VLLW, LLW and ILW) produced during a reactor's lifetime.

Dismantling a 1000-MW reactor generates around 10 000 m<sup>3</sup> of VLLW, LLW and ILW, but that amount may be greatly reduced with proper management and use of robots to more selectively 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.

Of the low and intermediate level long-lived radioactive waste produced during decommissioning, only 7 per cent has been disposed of so far (Figure 9). The remaining 93 per cent remains in storage and is awaiting safe disposal. Many countries have established radioactive waste management agencies, but there is a long way to go before these agencies are equipped to handle the volumes of waste likely to emerge from future decommissioning (CoRWM 2006). Disposal facilities for very low level waste already exist in countries producing nuclear power.

### Potential pathways for exposure to radioactivity

Decommissioning activities such as the cutting up of equipment have the potential to disperse radioactive dust or gas (Shimada et al. 2010) (Figure 10). Such air emissions present risks primarily to workers. These emissions need to be contained or ventilated



**Figure 10:** Radiation exposure pathways. During decommissioning, airborne radioactive dust particles may be released unintentionally if a mishap occurs. *Source: Adapted from Arizona State University (2011)*



safely, using filters to catch the dust. Highly contaminated reactor components can sometimes be cut up under water. This provides shielding for workers and prevents radioactive releases to the air. Waste stored on-site poses potential risks if the storage equipment suffers corrosion or dissolution, or in case of fire. There are also risks related to fires or floods at decommissioning sites that release radioactive materials to the air, soil or groundwater (for instance, from areas where waste is processed or stored). If water penetrates the disposal site, it can dissolve radioactive isotopes and transport them to the water system. However, most isotopes encountered during decommissioning are relatively insoluble or have a short half-life.

The potential for large-scale releases of radioactivity beyond a nuclear power plant during decommissioning is much less than that during its operation. However, low level releases can occur over short distances via the air or surface and groundwater. Careful planning, and the use of barriers and local and perimeter monitoring, can help protect against such releases.

Unanticipated conditions may be discovered during the decommissioning of a facility that has been in operation for several decades. There may be unexpected spent fuel debris within the reactor, although this occurs more often in research reactors and other reactors not used for power generation. Radioactive contamination beneath the reactor site that has not yet migrated to the underlying groundwater may not be detected until the facility has been demolished. Although this case represents the exception rather than the rule, when the Yankee nuclear power plant in the State of Connecticut (United States) was dismantled (**Figure 11**), decommissioners discovered 33 000 m<sup>3</sup> of radioactively contaminated soil that had to be removed and disposed of, greatly adding to the cost of making the site safe (EPRI 2008). Decommissioning itself may, through excavations or other activities, increase the risk of radioactive contamination migrating from soils to surface or groundwater.

During operations, parts of a nuclear power plant near the reactor core become radioactive. To keep the doses of radiation received by workers during decommissioning as low as reasonably achievable – and below regulatory limits – there is a need for extensive work planning, administrative and physical controls, use of protective clothing, and a comprehensive monitoring programme. Doses can be further reduced through the use of robots and other remote techniques that enable removal of workers from locations near radioactive hazards. To date, the level of exposure during decommissioning has been below regulatory limits.



**Figure 11:** The Connecticut Yankee nuclear power plant was successfully decommissioned and the site restored to a greenfield. The pictures show progress over time at the start (June 2003), during operations (January 2006) and after decommissioning was completed (September 2007).  
*Credit: Connecticut Yankee Atomic Power Company*

Nuclear power plants damaged as a result of accidents, such as those at Chernobyl and Fukushima, must be handled very differently from plants at the end of their expected design life. Contaminated material may have been released over long distances, in which case emergency responses will be required to prevent further releases. Once radioactive releases have been halted and the damaged plant has been stabilized, the nuclear fuel has to be removed from the reactor, which could be damaged. Only then can work begin to decommission the facility and clean up the site and surrounding areas.

Historically, discussions of the environmental impacts of nuclear activities (including decommissioning) have focused almost exclusively on human health risks. In 1991, the International Commission on Radiological Protection (ICRP) gave its opinion that “the standard of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk.” The Commission currently indicates that this view was too narrow. Instead, it states that risks to biodiversity and ecosystems from decommissioning and other activities cannot be assumed from those calculated for humans (Higley et al. 2004).

Since 2007 the ICRP has been developing radiation dose reference levels for 12 animals and plants, from duck to deer and from seaweed to earthworms (ICRP 2007). The reference levels are not regarded as limits, but as thresholds for further consideration (Andersson et al. 2009). Rather than eliminating all risks to individual organisms, the aim has been to “prevent or reduce the frequency of deleterious radiation effects to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats” (ICRP 2007).

## Lessons learned

Decommissioning is not simply demolition. It is the systematic deconstruction of a contaminated, complex nuclear facility made up of a reactor with many large components such as the reactor vessel, steam generators, pumps and tanks, and supporting systems including thousands of metres of pipes – along with even greater volumes of construction materials. This type of deconstruction requires considerable time and funding, detailed planning and precise execution, on a level similar to that required in order to build a nuclear facility. It also requires a similar degree of expertise and regulatory control.

While decommissioning is still a maturing industry in different parts of the world, it is fast-growing. There are considerable

geographical differences in degrees of expertise. A few countries have decades of experience. For others, such experience is all in the future. Important knowledge has been gained, but the lessons learned are not yet reflected in standard practice internationally. The International Atomic Energy Agency (IAEA) has established an international decommissioning network to facilitate exchanges of experience among countries (IAEA 2012b).

Ensuring that these important lessons are applied globally in time for the anticipated boom in decommissioning is of critical importance. International agencies and the owners and operators of nuclear facilities, in particular, need access to all the information available from contractors. There is a case for international and national laws that would require the sharing of such information. This would include expertise obtained when things have gone wrong, as it is often then that the most important lessons can be learned. There is a strong need to keep considerations of commercial confidentiality from getting in the way.

The nuclear industry will need to continue to innovate and develop new approaches and technologies that facilitate a “smarter” decommissioning process, meaning one that is safer, faster and cheaper. Additionally, meeting the decommissioning challenge will require policies and measures that support the continuing evolution of these decommissioning improvements. Research could further contribute to building the knowledge foundation and provide a strong scientific underpinning for decommissioning.

The coming decade will probably witness the rapid expansion of decommissioning activity, costing tens of billions of dollars. The decommissioning industry’s performance will be critical to the future of nuclear power generation. The challenges are technical, but also political, financial, social and environmental.

Experience shows that decommissioning can be carried out in a safe, timely and cost-effective manner. One lesson emerging is that nuclear power plants should be designed, from the beginning, for safe and efficient decommissioning as well as for their safe operation, accident prevention, and safety with respect to the potentially affected public and the environment. The first generations of nuclear power plants were designed with little thought for decommissioning, resulting in costs that might otherwise have been avoided. Today many operators and regulatory agencies incorporate features that will help or simplify decommissioning in the design of new nuclear power plants.



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