IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

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Managing Spent Fuel from Nuclear Power Reactors

Experience and Lessons from Around the World

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About the IPFM

The International Panel on Fissile Materials (IPFM) was founded in January 2006. It is an independent group of arms-control and nonproliferation experts from seventeen countries, including both nuclear weapon and non-nuclear weapon states.

The mission of the IPFM is to analyze the technical basis for practical and achievable policy initiatives to secure, consolidate, and reduce stockpiles of highly enriched uranium and separated plutonium. These fissile materials are the key ingredients in nuclear weapons, and their control is critical to nuclear disarmament, halting the proliferation of nuclear weapons, and ensuring that terrorists do not acquire nuclear weapons.

Both military and civilian stocks of fissile materials have to be addressed. The nuclear weapon states still have enough fissile materials in their weapon and naval fuel stockpiles for tens of thousands of nuclear weapons. On the civilian side, enough plutonium has been separated to make a similarly large number of weapons. Highly enriched uranium is used in civilian reactor fuel in more than one hundred reactors. The total amount used for this purpose is sufficient to make hundreds of Hiroshima-type bombs, a design potentially within the capabilities of terrorist groups.

The Panel is co-chaired by Professor R. Rajaraman of Jawaharlal Nehru University in New Delhi and Professor Frank von Hippel of Princeton University. Its members include nuclear experts from Brazil, China, France, Germany, India, Ireland, Japan, South Korea, Mexico, the Netherlands, Norway, Pakistan, Russia, South Africa, Sweden, the United Kingdom, and the United States.

IPFM research and reports are shared with international organizations, national governments and nongovernmental groups. It typically has full panel meetings twice a year in capitals around the world in addition to focused workshops. These meetings and workshops are often in conjunction with international conferences at which IPFM panels and experts are invited to make presentations.

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1 Overview

This report analyzes the policy and technical challenges faced over the past five decades by international efforts at long-term storage and disposal of spent fuel from nuclear power reactors. These challenges have so far prevented the licensing of a geological repository for spent fuel or high-level reprocessing waste anywhere in the world.

The first section of the report, *Country Studies*, describes how ten countries are managing their spent fuel and searching for ways to dispose of the fuel. The cases presented are Canada, France, Germany, Japan, South Korea, Russia, Sweden and Finland, the United Kingdom and the United States. This list includes the largest and oldest nuclear-energy programs and covers more than 80 percent of the world's nuclear power capacity. It includes some countries that reprocess spent fuel as well as those that are most advanced in siting geological repositories. This section also includes a review of efforts to develop the option of a shared, multinational repository for spent nuclear fuel.

The second section of the report, *Technical Background*, describes our current understanding of technical issues relevant to the disposal of spent fuel: interim storage and transport, design considerations relating to geological repositories, International Atomic Energy Agency safeguards on spent nuclear fuel and plans for monitoring of geological repositories containing spent fuel for the indefinite future.

This overview describes first the technical challenges associated with spent fuel storage and disposal, outlines the key policy findings from the country studies and provides a short summary of the individual country studies.

Technical background

Nuclear power reactors today are fueled mostly with uranium, which undergoes a fission chain reaction releasing heat and creating radioactive fission products and plutonium and other transuranic elements. After a time, the concentration of chain-reacting isotopes drops to the point where the fuel is considered "spent" and has to be replaced with fresh fuel.

Spent nuclear fuel from power reactors is unloaded into a water-filled pool immediately adjacent to the reactor to allow its heat and radiation levels to decrease. It is held in these pools for periods ranging from a few years to decades. After cooling, the fuel may be transferred to massive air-cooled dry casks for storage on site or in a centralized facility.

In a few countries, the fuel is sent to a reprocessing plant, where the fuel is dissolved and the plutonium and uranium recovered for potential use in reactor fuel. These processes also produce high-level wastes that contain much of the radioactive content of the spent fuel as well as other streams of radioactive waste, including plutonium waste from the manufacture of plutonium-containing fuel.

It is widely accepted that spent nuclear fuel, high-level reprocessing waste and plutonium waste require well-designed storage for periods ranging from tens of thousands to up to a million years to minimize releases of the contained radioactivity into the environment. Safeguards are also required to ensure that any contained plutonium or highly enriched uranium is not diverted to weapon use.

Spent fuel inventories

There are three major types of nuclear power plants in use in the world today. The most common are light-water reactors (LWRs), which use ordinary "light" water as a moderator (i.e., to slow down the neutrons associated with the nuclear chain reaction in the reactor core) and as a coolant to carry away the produced heat. LWRs come in two main varieties, Pressurized Water Reactors (PWRs), where the water is maintained at high pressure so as to prevent its boiling into steam, and Boiling Water Reactors (BWRs), where the water is allowed to boil.

The second most common type of reactor in use today is the Pressurized Heavy Water Reactor (PHWR, also called CANDU for Canada Natural Uranium Deuterium), which uses heavy water in place of normal water. A third reactor type uses graphite as a moderator and light water or carbon dioxide as a coolant.

An average modern reactor has a capacity of about 1 GWe (1 gigawatt-electric or 1,000 megawatts-electric). According to the International Atomic Energy Agency, there exist today 331 GWe of LWRs, 23 GWe of PHWRs, and 19 GWe of graphite-moderated reactors. Almost all the reactors now under construction are LWRs, and indeed most are PWRs.[1]

The amount of spent fuel discharged from a nuclear power plant depends upon the fuel "burn-up," i.e., the thermal energy (heat) generated per unit mass of fuel.[2] Table 1.1 shows the approximate amount of spent fuel that would be discharged per year from a 1 GWe reactor of the three most common reactor types.

As of the end of 2009, there were about 240,000 metric tons* of heavy metal (tHM, mostly uranium) in spent fuel in storage worldwide, most of it at reactor sites. About 90% was in storage ponds, the balance was in dry-cask storage.[3] The annual spent fuel generated is approximately 10,500 tons of heavy metal per year, with roughly 8,500 tons of heavy metal going into long-term storage and about 2,000 tons of heavy metal being reprocessed.

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* Throughout this report, tons refer to metric tons. One metric ton corresponds to 1000 kg or about 2205 pounds.

Reactor type	Typical burn-up (GWd/tHM)	Annual discharge of spent fuel (tons)
LWR (light-water moderated)	50	20
CANDU (heavy-water moderated)	7	140
RBMK (graphite moderated)	15	65

Table 1.1: Annual discharge of spent fuel for three common reactor types. This assumes a reactor of 1 GWe operating at 90% capacity. GWd/tHM is the amount of thermal energy (heat) in gigawatt-days released per metric ton of heavy metal (HM) in the fuel.

The most systematic reporting on spent fuel inventories by country is done by the national reports required under the *Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management*. The third and the most recent national reports were mostly done in 2008 and gave inventories of spent fuel as of the end of 2007. The spent fuel inventories for the countries covered in this study are shown in Table 1.2, with totals for France and Japan reported from other sources.[4]

The United States has by far the largest holding of spent fuel. As of the end of 2010, the total U.S. stockpile of spent power-reactor fuel was 64,500 tons, including 15,350 tons in dry casks.[5]

Country	Spent fuel inventory (tons of heavy metal) end of 2007	Spent fuel policy
Canada	38,400	Direct disposal
Finland	1,600	Direct disposal
France	13,500	Reprocessing
Germany	5,850	Direct disposal (now)
Japan	19,000	Reprocessing
Russia	13,000	Some reprocessing
South Korea	10,900	Storage, disposal undecided
Sweden	5,400	Direct disposal
United Kingdom	5,850	Reprocessing but future unclear
United States	61,000	Direct disposal

Table 1.2: Spent fuel inventories in cooling ponds and dry-cask storage as of the end of 2007 for the 10 countries in the present study—except for France and Japan. For the data for France and Japan, see the respective chapters.

Spent fuel assemblies

LWR fuel rods consist of stacks of cylindrical pellets of uranium dioxide (UO_2) in zirconium alloy (zircaloy) cladding. The rods are assembled into arrays containing 50 to 300 rods forming an assembly (see Figure 1.1).

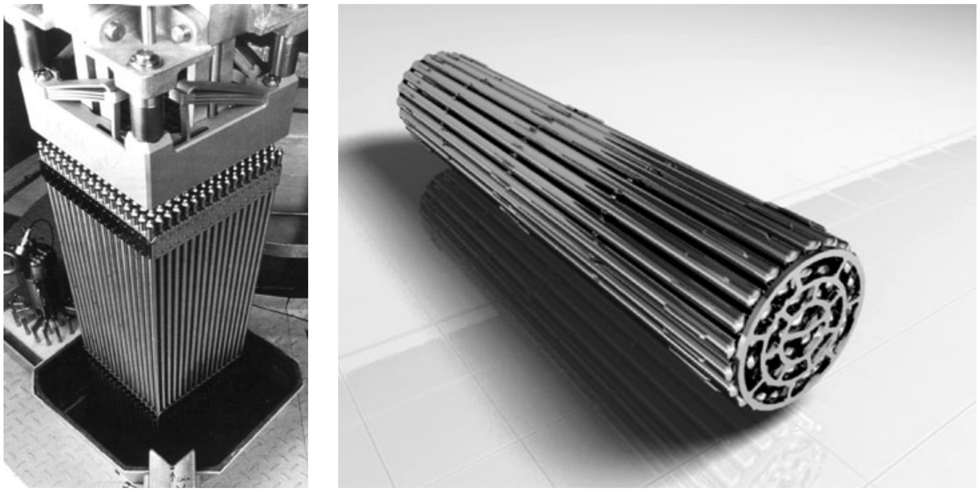

Figure 1.1: PWR fuel assembly (left) and CANDU fuel bundle (right). A typical PWR assembly is made up of 1 cm diameter fuel pellets inside zircaloy tubes. The assembly is approximately 4 m in length and 20 cm across and contains about 460 kg of uranium.[6] A CANDU fuel bundle is about 0.5 m in length and 10 cm in diameter and contains about 20 kg of uranium. *Source: International Atomic Energy Agency.*

The enrichment of fresh LWR fuel has risen since the 1970s from about 3 to 4.5 percent U-235, and the average burn-up from about 33 to 50 GWd/tHM.

PHWR fuel is also composed of UO_2 pellets in zircaloy cladding. The fuel rods are assembled into bundles of about 37 rods. The fuel is natural uranium, and has a typical average mass of about 19 kgHM with burn-up of 7–7.5 GWd/tHM.

Composition, heat generation, and radioactivity

The composition, heat output and radioactivity per ton of heavy metal of the spent fuel depend upon the burn-up. For LWR spent fuel with a burnup of 50 GWd/tHM, the spent fuel consists of about 93.4% uranium (~0.8% U-235), 5.2% fission products, 1.2% plutonium (12 kg or 1.5 weapon equivalents per ton of fuel), and 0.2% minor transuranic elements (neptunium, americium, and curium).

As the radioactive elements in the spent fuel decay, they produce heat. As the abundance of these elements decreases with time, so does the heat production. Figure 1.2 shows the reduction in decay heat for the first 100 years after the fuel has left the reactor for a range of past, current, and likely future burn-ups for low-enriched uranium LWR fuel.[7] The decay heat beyond 100 years is shown in Figure 1.3.

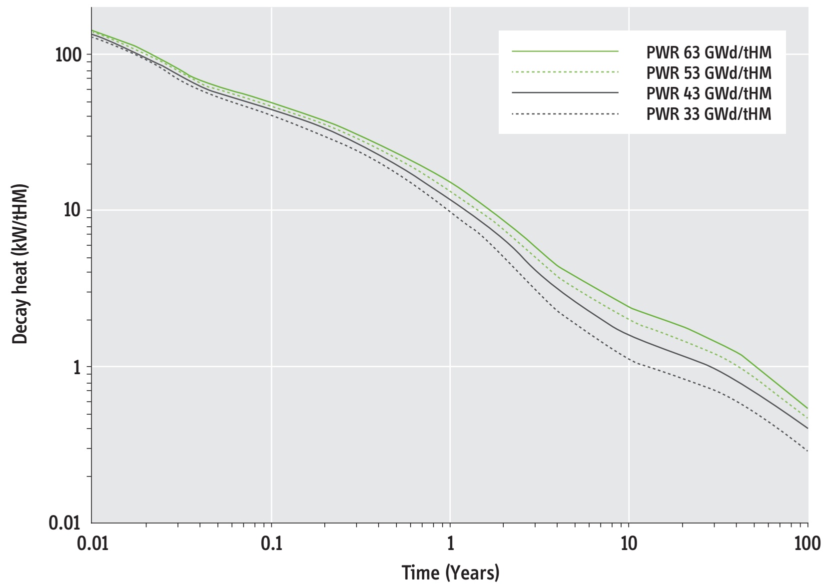

Figure 1.2: Decay heat as a function of time from 0.01 years (about 4 days) to 100 years for low-enriched uranium spent-fuel with burnups of 33, 43, 53 and 63 GWd/tHM. The lowest burnup was typical for the 1970s. Current burnups are around 50 GWd/tHM.

As Figure 1.2 shows, between four days and one year after discharge, the heat output decreases by roughly a factor of ten. Ten years after discharge, it is down by roughly a further factor of ten. By 100 years after discharge, it is down by another factor of five.

In countries recycling plutonium the quantities of spent mixed uranium-plutonium-oxide (MOX) fuel amount to about one seventh the mass of the low-enriched uranium spent fuel that was reprocessed to recover the plutonium used to produce the MOX fuel. At present, spent MOX fuel is not being reprocessed and is being stored. The heat output comparison between uranium and MOX fuel assemblies depends upon burn-up and the initial plutonium loading. Figure 1.3 compares the heat output for PWR uranium and MOX fuel assemblies, and also that of CANDU spent fuel. As may be seen, the heat output of the MOX fuel at 100 years is several times higher than the output of spent low-enriched uranium fuel. This greater heat output per ton approximately offsets the effect on repository area resulting from a reduction in the amount of tonnage of spent fuel.

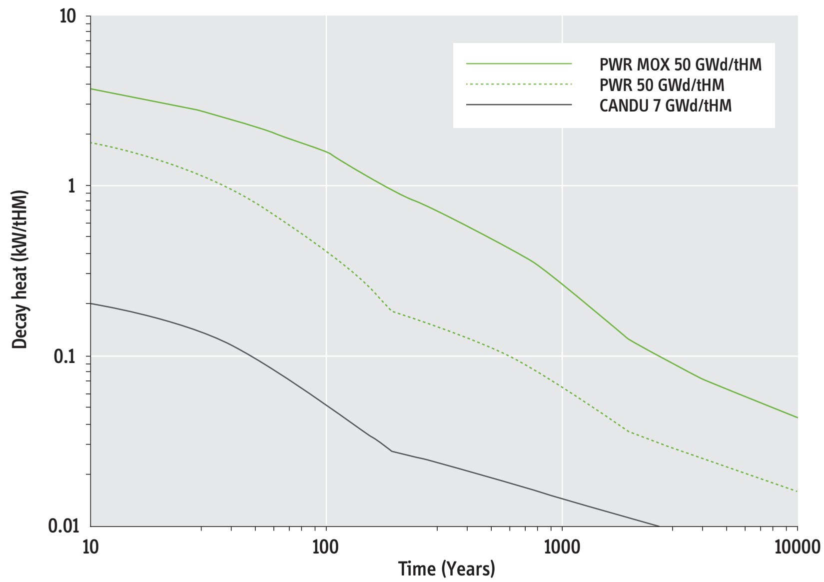

Figure 1.3: Decay heat over time for LEU, CANDU, and MOX spent fuel from ten to ten thousand years after discharge.[8]

For about the first 100 years, LWR spent fuel emits gamma radiation at a dose rate greater than 1 sievert per hour, which would be lethal to about 50% of adults (LD50) in three to four hours. At such exposure, the IAEA considers irradiated spent fuel sufficiently radioactive that it could only be moved and processed with specialized equipment and facilities, beyond the practical capabilities of sub-national groups, therefore "self protecting." Figure 1.4 shows the radiation levels from PWR and CANDU spent fuel for the first hundred years after discharge. It will be seen that CANDU spent fuel is self protecting for only a few years.[9]

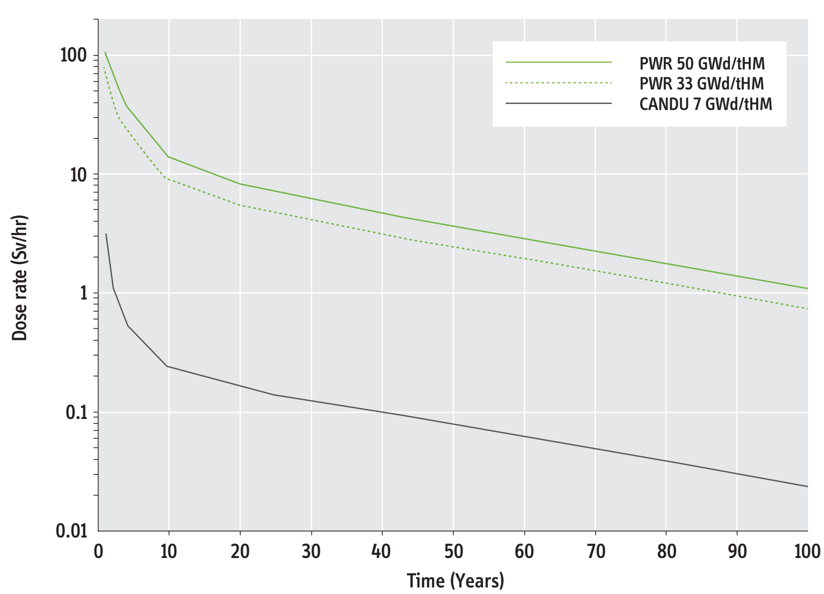

Figure 1.4: Dose rate at 1 meter perpendicular to the center of a PWR or CANDU fuel assembly.[10]

For much of the first 100 years, the radioactivity of spent fuel is dominated by the fission products—by two 30-year half-life fission products, strontium-90 and cesium-137, after the first ten years. After a few hundred years, the total radioactivity is dominated by the transuranics: plutonium, americium, neptunium, and curium.

For spent fuel in long-term storage, the primary threat to public health would be water contamination and ingestion of the long-lived radioisotopes. It takes several hundred thousand years for the ingestion radiotoxicity of spent fuel to become less than that of the natural uranium (including its associated decay products) from which it was derived. This is shown in Figure 1.5.

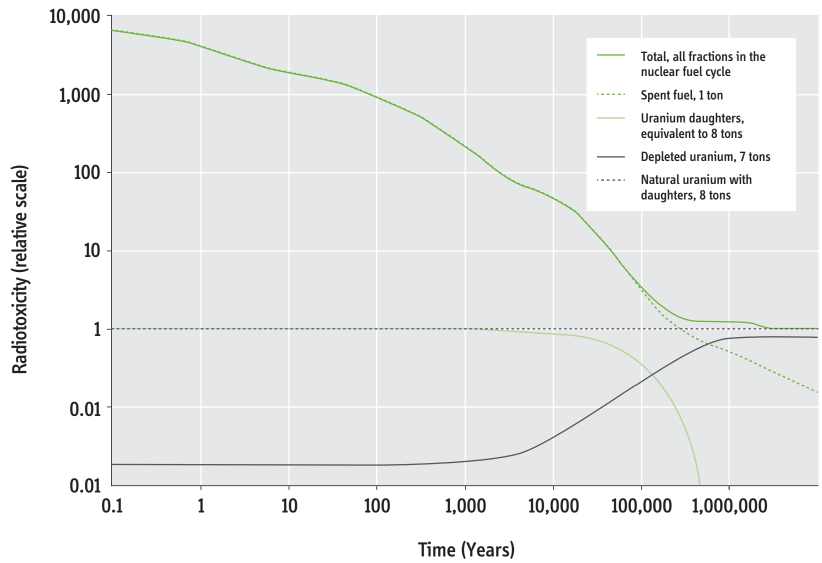

Figure 1.5: Relative ingestion radiotoxicity of uranium ore, of the spent LWR fuel that could be derived from it, the toxicity of the uranium decay products that are separated in the uranium mill, and of the depleted uranium that is stored at the enrichment plant. Approximately eight tons of natural uranium are used to produce one ton of enriched uranium fuel (and seven tons of depleted uranium). *Source: A. Hedin.*[11]

The long-term hazards from the radiotoxicity of the spent fuel require that it be sequestered from the surface environment for at least hundreds of thousands of years. Given the plutonium content in the spent fuel, the fuel also will have to be safeguarded.

Interim storage and transport

For several years after discharge, while the spent fuel is kept in water-filled pools, the principal risk is that a loss of cooling water could result in the fuel heating to a temperature high enough to ignite the zirconium alloy cladding of the fuel, resulting in a release of volatile radioactive fission products. This risk has been aggravated by reactor operators packing the spent fuel more closely together in the pools as a way to store greater quantities of spent fuel in each pool. One way to lower this risk is to move spent fuel to dry-cask storage once the heat output from the spent fuel has decreased adequately. This could be done easily five years after discharge.[12]

In dry-cask storage, spent fuel assemblies are typically placed in steel canisters that are surrounded by a heavy shielding shell of reinforced concrete, with the shell containing vents allowing cooling air to flow through to the wall of the canister. A typical dry cask for PWR fuel contains about 10 tons of spent fuel, roughly one-half of an annual discharge from a 1 GWe reactor. In the United States, casks are typically stored at or close to the reactor site. Figure 1.6 shows about a quarter of all the casks that store the spent fuel generated over the lifetime of the now-decommissioned Connecticut Yankee nuclear reactor.

Figure 1.6: Dry cask storage at the Connecticut Yankee spent fuel storage facility. There are 43 dry storage casks on the site, of which 40 hold spent fuel and three store high-level radioactive waste. *Source: Connecticut Yankee Atomic Power Company*.

Interim storage in dry casks is increasingly being employed even in countries like Japan and Russia that reprocess some of their spent fuel. There are a variety of cask types in use. Some countries store casks in buildings for additional protection against weather damage, accidents and attack.[13]

In December 2010, the U.S. Nuclear Regulatory Commission (NRC) expressed confidence that spent fuel could be stored in pools or dry casks for up to 60 years beyond the operating lifetimes of the reactors that produced it. Given that U.S. reactors are now being licensed to operate up to 60 years, this corresponds to interim storage for a period of up to 120 years.

No country is contemplating the possibility of indefinitely keeping spent fuel above ground at its reactor sites. Therefore, eventually, whether a country is planning on interim centralized storage, direct disposal or reprocessing, spent fuel will have to be transported off most sites. The countries that reprocess their spent fuel have the most experience with spent-fuel transport. Sea transport is used between Japan and Europe and between continental Europe and the UK. Sweden also transports its spent fuel by coastal ship to a central underground storage pool. Most of the transport within continental Europe is by rail. A rail cask might hold 10–18 tons of spent fuel and weigh 150 tons or more when loaded. Smaller casks, containing up to 2 tons of spent fuel, are transported by truck.

A U.S. National Academy of Sciences committee reviewed the safety of spent fuel transport and concluded in 2006 that the risk of large releases of radioactivity from accidents was small.[14] It did, however, note that the vulnerability of transport casks to terrorist attack should be examined. It appears that this has not yet happened.

Centralized storage pending decisions on final disposal would create unnecessary cost and additional exposure of spent fuel to transportation hazards for spent fuel stored at sites with operating power reactors.

Geological disposal

Most countries with nuclear power programs assume that the eventual disposal of spent fuel and high level radioactive waste will require underground repositories, hundreds of meters deep, where the surrounding media (rock, clay, or salt) offers a natural barrier to the escape of radioactivity. Most experts believe that emplacement of containers of spent fuel, high-level waste or plutonium waste into well-designed geological repositories could reliably prevent the escape of radioactive materials to the biosphere for at least several thousand years. There remain important uncertainties, however, about the longer-term containment of the long-lived radioisotopes in a geological repository. There also are differences of opinion over the length of time spent fuel should be easily retrievable.

As Figure 1.7 shows, transuranics (also known as "actinides" because of their chemical properties) are the most significant contributors to the heat of the spent fuel after the first 100 years. They are also the major contributors to its radiotoxicity—although a few very long-lived fission products, notably cesium-135 and technicium-99, are also of concern because of their solubility. For the viability of a geological repository, however, the solubility of the transuranics is a critical long-term issue.

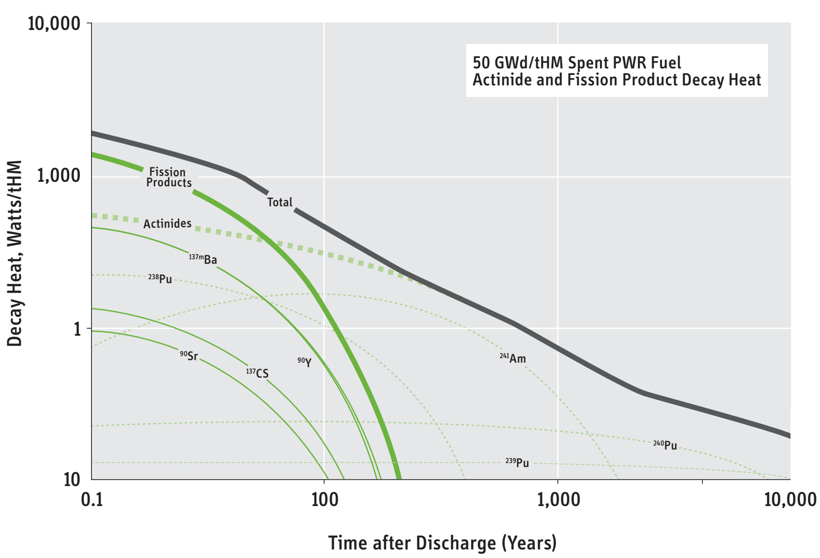

Figure 1.7: Contributions to the decay heat generated by spent PWR fuel irradiated to 50 GWd/tHM. *Source: Roald Wigeland.*[15]

In general, it appears that reducing (i.e., oxygen-free) conditions in the repository will reduce the solubility and mobility of transuranics in the disposal environment. Such conditions are expected in deep granite and clay. From this perspective, the proposed U.S. repository in Yucca Mountain, which was to be sited above the water table where the water flowing down through the repository would be oxygen rich, was a poor choice.

During the past decade, the disposal of spent fuel (or other radioactive wastes) in boreholes 3 to 5 kilometers deep has been made thinkable by technological advances in deep drilling techniques. The attractions of the deep borehole alternative are the possibility of a wide range of locations where the boreholes could be drilled, and the greater difficulty in recovering material from such depths.

Borehole disposal could be of interest for the disposal of excess separated plutonium. There are technical challenges, however, requiring much more study to determine the feasibility of borehole disposal of spent fuel. These include the dangers to workers of the gamma radiation that would be released from the relatively thin containers around the spent fuel assemblies and the problems that would be encountered if such a package became stuck part way down the borehole.

International monitoring

The International Atomic Energy Agency (IAEA) currently monitors non-nuclear-weapon-state spent fuel in storage and reprocessing. It is also considering how to monitor spent fuel at repositories. This is necessary because the huge quantities of plutonium contained in the spent fuel could become a long-term proliferation risk—although much less in the near-term than the proliferation risk from reprocessing.

At the reactor site, the IAEA installs remote surveillance systems viewing the fuel transfer gates between the reactor and the spent-fuel storage pool, the storage pool, and the dry cask loading area. For all reactors, inspectors witness the loading of dry storage casks, and seal the casks.

The IAEA has examined the safeguards challenge raised by geological disposal of spent fuel and determined that "with appropriate advanced planning, the operational and safety impacts of applying routine traditional IAEA safeguards in a geological repository is no greater or more technically challenging than those affecting other types of nuclear facilities."[16]

The IAEA would need to become involved during the repository design and construction phase to verify the declared design of the repository and the absence of undeclared chambers or tunnels or hot cells for opening spent fuel packages and to detect undeclared excavation. At closure of a repository, the IAEA would monitor the backfilling of tunnels and shafts. Thereafter, the IAEA would use various means including satellite observation to ensure that there are no unmonitored intrusions at the repository. The safeguarding of a geological spent fuel repository would have to be of indefinite duration. The means to ensure continuity of the responsible institutions and knowledge on time scales exceeding thousands of years is unknown.

Status of spent-fuel management in key countries

This section summarizes the current status of spent-fuel management in the ten countries considered in this report. Four of these countries reprocess their spent fuel (France, Japan, Russia, and the United Kingdom) and five are planning on direct disposal (Canada, Germany, the United States, Finland and Sweden). South Korea's disposal plans are currently a subject of discussions with the United States in connection with the renewal of their bilateral agreement on nuclear cooperation.

Canada. Canada's first attempts, in the 1970s and 1980s, at finding a location to dispose of nuclear waste were abandoned due to public opposition. This led to a recognition that the strategy for nuclear waste disposal had both to be technically sound and socially accepted. In 2002, several Canadian utilities and Atomic Energy of Canada Limited (AECL) created the Nuclear Waste Management Organization (NWMO) to recommend a path forward and oversee the selection of a suitable repository site. NWMO set out various criteria for site selection after extensive public consultation and, in 2010, began a multi-year process of finding a community willing to host a geological repository. Meanwhile, all spent fuel is stored at the reactor sites in pools and dry storage.

France. France is reprocessing its spent uranium fuel and using the recovered plutonium in LWR MOX fuel. The spent MOX fuel is being stored pending commercialization of fast breeder reactors. France has accumulated a large volume of high-level and intermediate-level, long-lived (i.e., plutonium) waste from its reprocessing and plutonium-recycle activities. Planning for a common geological repository for these wastes 500 meter deep in a clay formation at Bure in eastern France is being implemented by the National Radioactive Waste Management Agency (ANDRA). It is aiming for a start up of repository operations by 2025.

Germany. Until mid-2005, Germany sent most of its spent fuel to France and the UK for reprocessing. High-level reprocessing waste is being returned to a centralized interim storage facility at Gorleben. In the 2002 nuclear-power phase-out agreement, it was decided that shipments to the reprocessing plants would end in mid-2005 and the spent-fuel would be stored on the reactor sites pending ultimate disposal. A Committee on a Site Selection Procedure for Repository Sites (AkEnd) was established which recommended a consultative approach that would include a consideration of several possible repository sites. The AkEnd process collapsed in 2003, however, and no site selection process has been launched. After the Fukushima nuclear-power plant accidents of March 2011, the government decided to shut down eight reactors immediately and all power reactors by 2022.

Japan. Japan's fuel cycle policy has been premised on the assumption that spent fuel will be reprocessed. Initially, spent fuel was sent to France and the UK for reprocessing. Then Japan built a domestic reprocessing plant at Rokkasho with a design capacity of 800 tons of spent fuel per year. However, full operation of the plant has been delayed repeatedly and is currently scheduled for 2012. Almost all of Japan's spent fuel is stored in the reactor pools. Construction of an interim dry cask storage facility was launched in Mutsu near the Rokkasho Reprocessing Plant but has been put on hold following the March 2011 accidents at the Fukushima Dai-ichi Nuclear Power Plant. Solicitation of volunteer communities to host a national geological repository has not yet produced any candidates. The earthquake and tsunami of March 2011 have had a devastating impact on the operation of Japan's nuclear power plants and have put the future direction of its nuclear energy program into question.

South Korea. At present, South Korea stores its spent fuel on-site at its four nuclear reactor sites. At one of these, the Wolsong nuclear power plant, which has four CANDU heavy-water reactors, dry storage facilities have been built to accommodate the older spent fuel to make space in the pools for newly discharged spent fuel. South Korea's nuclear utility, Korea Hydro and Nuclear Power (KHNP), states, however, that at the LWR sites, such dry storage is not politically possible even though the storage pools at these sites too will all fill up in the next decade or two. Attempts to establish off-site central spent fuel interim storage have failed due to local opposition. The Korea Atomic Energy Research Institute (KAERI) has used this situation to argue for the need to reprocess (pyro-process) South Korea's light-water reactor spent fuel—although such a plan could not be realized for decades. After several failed attempts to site a repository for low and intermediate waste, the government succeeded by adopting a consultative approach and providing substantial financial incentives to local governments. A public consensus-building process on spent fuel management, including issues of interim storage and final disposal, was planned but then put on hold by the government.

Russia. Russia currently reprocesses at the small RT-1 plant at Ozersk the spent fuel from its six first generation 400 MWe light-water reactors, two similar Ukrainian reactors, and Russia's BN-600 HEU-fueled prototype fast-neutron reactor. Almost 50 tons of recovered power-reactor plutonium and 34 tons of excess weapons plutonium are being stored for future use in Russia's planned breeder reactors. The spent fuel from Russia's 1 GWe light water reactors, along with the spent fuel of similar reactors in Ukraine and Bulgaria, is sent for storage to Zheleznogorsk, near Krasnoyarsk, in Siberia, where a large storage pool was built in the 1980s for the never-completed RT-2 reprocessing plant. A second smaller pool has been built and a very large dry cask storage facility is planned at the same location. At present, the spent fuel from the Russian graphite-moderated, water-cooled RBMK reactors is stored at the reactor sites but the older spent fuel is to be shipped to a planned dry-cask storage facility at Zheleznogorsk. Drafts of two laws, "Management of Radioactive Wastes," and "On Spent Fuel Management," to establish a repository site-selection process have been under consideration in the Duma.

Sweden and Finland. Sweden initially signed reprocessing contracts with France and the UK, but decided in the 1980s to follow the lead of the U.S. and forego reprocessing. In Finland, spent nuclear fuel from two Soviet-designed reactors was initially exported to the Soviet Union for reprocessing with no waste or plutonium coming back but this was discontinued after the collapse of the Soviet Union. Both Sweden and Finland decided that they would manage their spent fuel domestically by disposing of it in national repositories. They have gone through extended site-selection processes for national geological repositories and both have selected sites adjacent to existing nuclear power plants. Both countries plan to use copper casks embedded in bentonite clay. In 2001, Finland's parliament took a decision in principle to store all its spent fuel in a repository next to the Olkiluoto nuclear power plant. In Sweden, the license application for a geological repository next to the Forsmark nuclear power plant was submitted in early 2011. Questions have been raised about the longevity of the copper casks and about the potential effects on the repository of the weight of an ice sheet such as that which covered most of Scandinavia during the Ice Age.

United Kingdom. The UK has been reprocessing all the uranium-metal spent fuel from its first-generation gas-cooled graphite-moderated MAGNOX reactors, the last of which are to be shut down by 2012. It is also reprocessing a significant quantity of the uranium-oxide fuel discharged by its second-generation Advanced Gas-cooled Reactors. There are no final plans on how to manage the UK's approximately 100 tons of separated plutonium although the preference of the current government appears to be to use it as MOX in a proposed new generation of LWRs. In 2003, after two decades of little success in siting waste facilities, the government established a Committee on Radioactive Waste Management (CoRWM) to consider long-term strategy both for intermediate and high-level reprocessing waste. Its final report in 2006 recommended a voluntary partnership approach to site selection backed up by robust interim storage, possibly for 100 years or longer. The UK has not yet developed a site-selection process, however, and the degree of consensus that was been achieved could be threatened if the UK goes ahead with the construction of new reactors.

United States. The United States has been attempting since 1970 without success to site a geological repository for spent fuel and high-level waste. The 1982 Nuclear Waste Policy Act mandated that the Department of Energy select three candidate repository sites. In 1987, Congress intervened and selected Yucca Mountain, Nevada. The Department of Energy spent approximately $15 billion preparing the technical basis for a license application but, in 2010, in response to strong opposition from the Nevada state government and its Congressional delegation, the Obama Administration halted the project. Currently, almost all spent fuel remains at the reactor sites, with dry cask storage for older spent fuel being deployed as the pools fill up. In 1998, the U.S. Department of Energy successfully put into operation the Waste Isolation Pilot Plant (WIPP) in a salt formation in New Mexico for defense-related plutonium wastes. In January 2010, as a first step toward establishing a new U.S. spent-fuel policy, the Obama Administration established the Blue Ribbon Commission on America's Nuclear Future "to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle and to provide recommendations for developing a safe, long-term solution to managing the Nation's used nuclear fuel and nuclear waste." The Commission produced an interim report in July 2011 and is expected to produce a final report by January 2012.

Policy lessons

An analysis of the country studies in the following chapters yields as key policy findings:

- Reprocessing has not led to a simplification or expedition of radioactive waste disposal;
- Voluntary and consultative processes for siting of geological repositories have been more successful than top-down decision making;
- Safe long-term underground disposal likely will require well-designed waste packaging and backfill as well as appropriate geology;
- Most countries have adopted dry cask spent-fuel storage as an interim strategy since no repository has yet been licensed and reprocessing plants have been delayed;
- No country has accepted foreign spent power-reactor fuel for ultimate disposal, although Russia takes back for interim storage and reprocessing some of the nuclear fuel it has sold to other countries for use in Soviet/Russian-designed reactors;
- No country appears ready to host a multinational spent fuel facility, which will face the same siting and licensing issues that confront national repository efforts and possibly more public opposition; and
- In some countries, the politics of waste repository siting have become entangled with the larger issue of the future of nuclear power.

Reprocessing and radioactive waste policies

Reprocessing spent fuel began as a way to obtain plutonium for nuclear weapons. In the 1960s, however, almost all countries with nuclear power programs were planning to reprocess their spent fuel in order to use the recovered plutonium in startup fuel for breeder reactors. By the early 1980s, much more low-cost uranium had been discovered than initially projected, reprocessing was found to cost much more than originally expected, and breeder reactors were generally found to be much more expensive and less reliable than light water reactors. These developments, in combination with proliferation concerns relating to the commercial separation of plutonium, led the United States and many other countries to abandon reprocessing. Some countries, including Argentina, Brazil, South Korea, Sweden and Taiwan ended their reprocessing programs when they abandoned their pursuit of nuclear weapons.

The nuclear establishments in France, the UK, Russia, Japan and India, however, persisted with reprocessing. In the absence of breeder reactors, France and Japan launched programs to recycle their separated plutonium in light water reactors in the form of "mixed oxide" fuel (MOX, a mixture of uranium and plutonium oxides). The UK has simply stored its separated plutonium and only now is beginning to consider disposal options. Russia and India are building prototype breeder reactors—although on a much-delayed schedule.

Advocates of reprocessing today argue that it can ease the technical and political problems of radioactive waste disposal by allowing most of the plutonium and other long-lived transuranic elements to be recycled. According to a comprehensive study by the U.S. National Research Council published in 1996, however, even with repeated recycle and fissioning of the transuranics in fast-neutron reactors, it "would take about two centuries… to reduce the inventory of the [transuranics] to about 1% of the inventory of the reference LWR once-through fuel cycle."[17] The study also concluded that this would be extraordinarily costly.

Plutonium is recycled in MOX fuel in light water reactors in a few countries today. This results in a net reduction of the mass of plutonium in the spent fuel by about half. France, which has the most extensive reprocessing and recycling program, does not attempt to recover the plutonium from the spent MOX fuel. In effect, it has exchanged the problem of managing spent fuel for the problem of managing spent MOX fuel, high level waste from reprocessing, plutonium waste from plutonium recycle, and eventually the waste from decommissioning its reprocessing and plutonium fuel fabrication facilities.

When all long-lived waste streams are taken into account, it appears that reprocessing may not reduce the size of a radioactive waste repository dramatically. ANDRA, France's radioactive waste management agency, has estimated the repository tunnels for the radioactive waste generated by its reprocessing and plutonium recycle activities will underlie about 15 square kilometers of surface area.[18] This is about the same area that would have been required had France not reprocessed at all.[19] Thus, reprocessing does not reduce the political challenges to repository siting. This is illustrated by the impasses over repository siting in Japan and the United Kingdom. In contrast, Sweden and Finland, the countries that are most advanced in the repository siting process, do not reprocess their spent fuel.

Voluntary, consultative processes for geological repository siting

There is general agreement in the technical communities of most countries that underground geological repositories are safer than indefinite storage on the surface and the repositories are needed regardless of whether countries choose to reprocess their spent fuel or directly dispose it. Finding sites for repositories has proven politically very difficult, however. Almost all countries that have tried to site repositories have had one or more failures.

The first approach pursued by nuclear establishments has been "top-down," with the central government deciding which sites should be considered for repositories. This has almost always resulted in strong local opposition, leading to the abandonment of the sites. This sequence has been described with the acronym DADA: Decide, Announce, Defend and Abandon.

The Obama Administration's decision to abandon the Yucca Mountain repository project provides only the most recent example. In the UK, in 1981, in the face of intense local opposition, the government abandoned efforts to investigate possible sites that it had identified for a high-level repository and decided not to resume the effort for 50 years.

In Germany, in 1977, the state government of Lower-Saxony, the federal government and the nuclear industry chose the salt dome under Gorleben on the East German border as a place to dispose of spent fuel and high-level reprocessing waste. The site became the focus of huge demonstrations and, in 2000, the government halted further development of Gorleben as a final repository. In 2009, a successor government gave a go-ahead to further exploratory work at Gorleben, which again became a focus of demonstrations.

As a result of initial failures, several countries have sought to develop a more consultative site selection process in which local communities determine whether they wish to be included in site assessments. There is often also a greater role in the assessment process of stakeholders independent of the nuclear utilities and the government. As the official in charge of the Olkiluoto site investigation in Finland put it, "Instead of simply 'informing' we began to listen to stakeholders and the public at large and to acknowledge diverse perspectives."[20]

The United States has appeared to learn this lesson from its earlier mistakes in trying to site a repository. In its July 2011 draft report, the U.S. Blue Ribbon Commission recommended adopting an approach to siting future nuclear waste management facilities that was "consent-based", with a "heavy emphasis on consultation and cooperation" and based on "encouraging communities to volunteer to be considered to host a new nuclear waste management facility."[21]

Finland and Sweden provide the most advanced examples of the more participatory approach. Starting in the early 1990s, Sweden began a voluntary process for siting its spent-fuel repository. Initial attempts to site the repository in the north of the country were rejected by local referenda. Sweden then moved on to other sites that already had nuclear facilities. Even among these, some rejected the idea of hosting a geological repository. Finally, the Forsmark site, which already hosts a nuclear power plant, was selected.

In Finland, the 1987 Nuclear Energy Act and its amendment in 1994 gave municipalities the right to veto the siting of any nuclear facilities, including waste repositories in their areas. During the site selection process the organization in charge of waste management investigated three sites, but only one, next to the Olkiluoto nuclear plant, supported a repository.

These two cases suggest that communities that already host nuclear power plants are more willing than most others to host deep underground repositories.

Multiple barriers and reversibility

In many countries, the initial focus for siting an underground geological repository for waste disposal was that the rock would prevent the exposure of the public to the radiological hazard. The United States and Germany focused initially on salt beds because they were self-sealing, and France and Switzerland have focused on clay for the same reason. Sweden is underlain by granite and its radioactive-waste disposal organization, SKB, discovered that it could not find any large block that was crack-free. Cracks offer pathways for water and leachates from the spent fuel or waste. SKB therefore designed a cask covered with a 5-cm thick layer of copper that it believed would not corrode through for a million years and proposed to surround it with a thick layer of bentonite clay.

Both approaches have encountered problems. Salt has been found to have been penetrated often by human-made water channels and experiments have found that copper corrosion rates in anoxic water may be much higher than originally thought. It appears that both favorable geology and engineered barriers will be required.

Given the uncertainties in repository performance and the possibility that reprocessing may appear more attractive in the future, there has been interest in keeping underground disposal of spent fuel reversible. Allowing the spent fuel and waste to be retrievable from the repository for long periods of time may, however, make the challenge of safeguards more difficult.

Maintaining reversibility may be difficult in some cases. In salt, flow of the medium may result in tunnels closing themselves. In the case of deep borehole disposal, in which spent fuel would be lowered down a 3 to 5 kilometer deep drill-hole, recovery might be practically infeasible. In hard rock such as granite, however, the timing of repository closure is a policy decision.

In Canada, the Nuclear Waste Management Organization, which expects Canada's repository to be sited in hard rock, recommended a retrievable period of approximately 240 years. France's 2006 Act on Sustainable Management of Radioactive Materials and Waste specified that no license for a repository for long-lived ILW and HLW shall be granted "if the reversibility of such a facility is not guaranteed."

Dry cask spent-fuel storage as an interim strategy

With most spent-fuel pools full or nearly full and reprocessing and repositories delayed, the use of dry-cask storage is becoming common, including in the Canada, Germany, South Korea, Russia, and the United States. As of the end of 2010, about 70 percent of all U.S. sites with operating nuclear reactors had associated dry storage facilities.[22] U.S. citizens groups have indicated that they prefer hardened on-site storage, including the use of dry casks, to reprocessing or, in most cases, to central storage.

The IAEA notes that "long term [dry-cask] storage [is] becoming a progressive reality … storage durations up to 100 years and even beyond [are] possible."[23] The cost of dry cask spent fuel storage is low — only about $100–200 per kilogram of contained heavy metal versus more than $1000/kg for reprocessing.

Importing foreign spent power-reactor fuel for disposal

Spent fuel has been imported into France, the UK and Russia for reprocessing. In the cases of France and the UK, however, the contracts stipulate that the resulting high level wastes — and in most cases, the recovered plutonium and uranium would be sent back to the country of origin.[24] According to France's 2006 Act, "no radioactive waste whether originating from a foreign country or from the processing of foreign spent fuel and foreign radioactive waste shall be disposed in France," and "no spent fuel or radioactive material shall be introduced in France except for processing, research or transfer between foreign countries." The UK has a similar requirement.

In Russia, however, the present understanding is that, if the foreign spent fuel is from "Russian-origin" fuel, i.e., fuel provided by Russia and used in Soviet or Russia-provided power reactor the reprocessing waste and plutonium can be left in Russia. Although Russia's nuclear law gives the government considerable discretion with regard to the import of other spent foreign fuel, opinion polls show 90 percent of all Russians opposed.

Most of the imported Russian-origin fuel has not been reprocessed, however. It is stored in a large storage pool in Zheleznogorsk, where the Soviet Union started and then abandoned the construction of a large reprocessing plant. Russia expects eventually to build a reprocessing plant there. The fuel stored there will not necessarily be reprocessed, however. Russia's agreement with Ukraine, for example, is a 50-year storage contract that requires, at the end of that period, a decision on fuel return to the owner or an extension of the storage period or reprocessing.

Shared and multinational repositories

The idea of countries sharing a geological repository has been around since the 1970s. Three efforts to consider an international repository in the 1990s, focused on the Marshall Islands, Palmyra Island (also in the Pacific) and a site in Western Australia. All met determined public opposition. The idea resurfaced in the 2000s but, at present, no country appears ready to host a multinational spent fuel repository.

The lack of progress in the development of national repositories, combined with the widespread belief that each country has an ethical responsibility to manage its own nuclear waste have established enduring obstacles to hopes for a multinational spent fuel repository. An effort to build a multinational repository would face similar siting and licensing issues to those that confront national repository siting efforts, and likely a greater ethical challenge. Progress with siting a national repository has in some cases, for example in Finland, included a commitment that only national waste will be disposed at that site.

Nuclear-waste storage and disposal and the future of nuclear power

Practically all stakeholders, whatever their views of nuclear power, realize that spent fuel and any high level waste generated by existing nuclear programs must be disposed of eventually. The possibility of constructing new nuclear reactors, however, destroys this near consensus. Those opposed to an expansion of nuclear power feel that allowing for the disposal of existing waste removes one of the major obstacles to constructing new nuclear reactors. They have therefore supported geological disposal only when it is part of a commitment not to construct any new reactors.

In the UK, the Committee on Radioactive Waste Management sought to draw a clear distinction between "legacy" and "new-build" waste in drawing up a proposed national disposal policy. A similar distinction was made by Canada's Nuclear Waste Management Organization (NWMO), a body established by the Canadian utilities and the Atomic Energy of Canada Limited to oversee the repository selection process. In accepting the NWMO recommended approach, however, the Minister of Natural Resources described it as a step "toward a safe, long-term plan for nuclear power in Canada for future generations," thus implying that an agreement on waste management cleared the way for new nuclear power plants.

In Germany, a coalition government of the Social Democrats and the Green Party decided in 2000 to phase out nuclear energy, partly in response to the contentious problem of nuclear waste management.[25] A subsequent coalition government of Christian Democrats and Liberals in 2009 delayed the scheduled phase-out, but reversed this position in the wake of the March 2011 Fukushima reactor accidents in Japan.

Country Studies

2 Canada

Canada began thinking about nuclear waste disposal seriously in the 1960s, two decades after it embarked on nuclear power. By that time, there was enough concern among local communities about the risks of nuclear waste that they opposed even attempts to characterize locations for experimental facilities. This led to a process of first developing deep geological disposal in a conceptual fashion, without reference to any individual site, and then showing that suitable sites are likely to exist. This disposal concept was examined by an independent environmental assessment panel that endorsed the technical concept but argued that it lacked social acceptability.

In 2002, several Canadian utilities and Atomic Energy of Canada Limited (AECL), Canada's government-owned nuclear R&D and reactor-construction organization, created the Nuclear Waste Management Organization (NWMO) to recommend a path forward and to oversee the selection of a suitable site. In 2005, NWMO recommended what it described as "Adaptive Phased Management" which involved disposing of waste in a deep geological repository, but with the possibility of monitoring and retrieving the fuel for approximately 240 years after emplacement. It also set out various criteria for site selection and, in 2010, began a multi-year process of finding an informed community willing to host a repository.

There have been some preliminary expressions of interest from relatively small communities in northern Canada. Meanwhile, all spent fuel is stored at the reactor sites in pools and dry storage. NWMO does not anticipate commencement of a repository until 2035.

Nuclear power and waste

Canada was part of the U.S. Manhattan Project to build the first nuclear weapons. In 1945, it set up its first reactor, the Zero Energy Experimental Pile at Chalk River, Ontario, followed by the National Research Experimental (NRX) reactor that started operating with a power of 20 MWt in 1947. Canada also set up facilities that recovered about 17 kilograms of separated plutonium and up to 0.5 kg of uranium-233 from uranium and thorium irradiated by the NRX before they were shut down by 1956.[26] Canada first produced electrical power from nuclear energy in the 20 MWe Nuclear Power Demonstration reactor, completed in 1962.

As of June 2011, Canada had 18 power reactors operating with a total generating capacity of 12.5 GWe (net) located in the provinces of Ontario, Quebec, and New Brunswick.[27] All these reactors are moderated and cooled by heavy-water, and fueled with natural uranium. All are operated by utilities owned by the provinces.

As of June 30, 2010, Canada had about 2.2 million spent fuel bundles in storage, 1.54 million in wet storage and 0.66 million in dry storage.[28] Since each bundle contains about 20 kilograms of uranium, the total inventory would contain about 44,000 tons of heavy metal.[29] According to 2010 projections from Canada's Nuclear Waste Management Organization, for the existing reactor fleet, the total spent fuel produced will be 2.8 to 5.1 million fuel bundles, i.e., approximately 56,000 to 102,000 tons of heavy metal.[30]

Current status of storage

All spent fuel is currently held in interim wet or dry storage at the generating stations where it is produced. Spent fuel discharged from CANDU reactors is placed into special storage pools for several years, with time periods varying from site to site, and is eventually transferred to an interim dry storage facility at the same site.

Three designs of dry storage containers are used in Canada: AECL silos, AECL MACSTOR, and OPG dry storage containers. The AECL Concrete Canister Fuel Storage Program was developed at the Whiteshell Laboratories in the early 1970s to demonstrate that dry storage for irradiated reactor fuel was a feasible alternative to continued water pool storage.[31] The AECL concrete canister design has been used at Chalk River Laboratories, the Point Lepreau Generating Station, and the partially decommissioned Douglas Point and Gentilly-1 Nuclear Generating Stations. These canisters come in different sizes and can hold between 324 and 600 bundles. The AECL MACSTOR (Modular Air Cooled STORage) is a variant of the canister storage technique. Currently, it is only being used at the Gentilly-2 Used Fuel Dry Storage Facility in Quebec (see Figure 2.1). Seven modules have been constructed since 1995. Each module holds 12,000 fuel bundles containing about 230 tons of uranium in spent fuel. Both the AECL storage concepts are intended to be used outdoors.

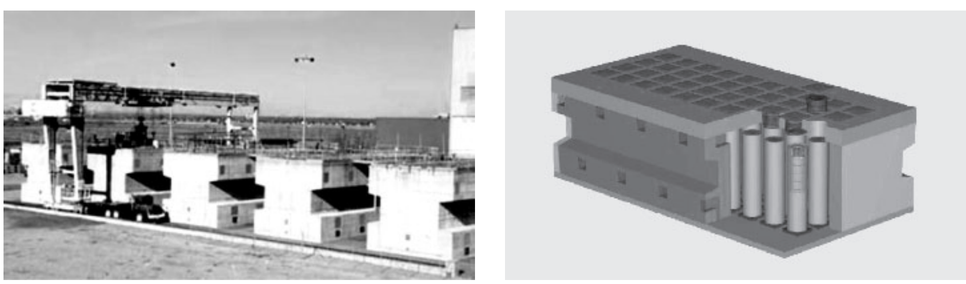

Figure 2.1: Spent fuel storage modules (MACSTOR) at Gentilly-2 reactor in Quebec (left) and schematic of the interior of a module. *Source: Atomic Energy Canada Limited.*

In contrast, Ontario Power Generation (OPG) dry storage facilities store spent fuel indoors and employ containers that are transportable. Each container is designed to hold 384 fuel bundles, and weighs approximately 60 tons when empty and 70 tons when loaded. The containers are rectangular in design, with walls of reinforced concrete sandwiched between interior and exterior shells made of carbon steel. The container cavity is filled with helium to protect the fuel bundles from potential oxidation.

Table 2.1 lists the inventories of spent fuel in wet storage and dry storage respectively. It also shows the authorized capacity for dry storage. There should be no shortage of storage capacity for spent fuel from power reactors in the foreseeable future.[32] There appears to be adequate storage at research reactors as well.

Site	Current net power capacity (GWe)	Number of fuel bundles in wet storage	Number of fuel bundles in dry storage	Authorized dry storage capacity
Bruce A and B Nuclear Generating Stations (ON)	4.69	739,947	192,376	750,000
Darlington Nuclear Generating Station (ON)	3.512	329,198	48,363	575,000
Douglas Point Waste Management Facility	-		22,256	
Gentilly-1 Waste Management Facility[33]			3,213	
Gentilly-2 Nuclear Generating Station (QC)	0.635	29,833	86,340	240,000
Pickering A and B Nuclear Generating Station (ON)	3.094	401,737	214,436	633,600
Point Lepreau Nuclear Generating Station (NB)	0.635	40,758	81,000	180,000
McMaster Nuclear Research Reactor (ON)	-	40		
Chalk River Laboratories (ON)	-	367	9,576	
Whiteshell Laboratories	-		2,268	

Table 2.1: Inventory of spent fuel in storage in Canada as of June 30, 2010.[34]

History of nuclear waste management

The history of Canada's nuclear waste management policy dates back to the mid-1960s.[35] In 1969, the Atomic Energy Control Board (AECB, which became the Canadian Nuclear Safety Commission in May 2000) officially requested AECL to conduct research on storing and disposing of nuclear waste. AECL joined with Ontario Hydro (which became Ontario Power Generation after April 1999) and Hydro Quebec to form a committee of waste owners. The committee initially advocated monitored retrievable storage on the grounds that permanent disposal had yet to be proven and that retrievability allowed greater flexibility.[36]

Retrievability also kept open the option of reprocessing. AECL had considered reprocessing spent fuel in the 1950s because of concern that uranium reserves were limited.[37] By the 1960s, however, abundant domestic uranium resources had been identified and the focus shifted to a once-through fuel cycle. Interest in reprocessing persisted within AECL's nuclear-energy R&D establishment, fueled in part by the assumption that nuclear power would expand rapidly in Canada.[38] This changed after the Indian nuclear test of 1974, which used plutonium from a research reactor supplied by Canada. After that, retrievability "became a political liability for commercial nuclear power, while permanent disposal lent support by removing waste from possible military uses."[39] Deep geological disposal was first endorsed in a joint statement by the federal government and the government of Ontario in 1974 after India's test.

In August 1977, the Federal Department of Energy, Mines and Resources released a report that surveyed various spent-fuel management and disposal options, including reprocessing and immobilization; surface storage; and disposal in ice sheets, in space, on or beneath the sea floor, or in various types of underground rock.[40] This report, which became known as the Hare report, after its Chairman F. K. Hare, recommended burying the spent fuel at depths of 800 to 1000 meters in the Canadian Shield, a large area of ancient igneous rock in eastern and central Canada and called for an "effective interchange of information and ideas" among the public, industry, and government.[41]

The Hare report drew much criticism and started a public debate over nuclear waste disposal that may have played some role in reducing public support for expanding Canada's nuclear-power capacity.[42] Attempts by the AECL to investigate locations in Ontario for waste disposal resulted in considerable local opposition.[43] Petitions against repository proposals garnered tens of thousands of signatures and Ontario parliamentary support dwindled.[44] This led the Governments of Canada and Ontario to announce in 1981 that no disposal site selection activities would be undertaken until after the repository concept had gone through a full federal public hearing and approval by both governments.[45]

In the early 1980s, AECL set up an underground research laboratory in the province of Manitoba.[46] A shaft was sunk to a depth of 445 meters in granite and a number of galleries and rooms were excavated in which various experiments were carried out.[47] The laboratory was also used for joint international work on waste management and included participation from France, Japan, South Korea, Sweden, and the United States. The United States repository program, for example, spent millions of dollars each year on work at the laboratory because at that time, the U.S. repository program was not allowed by law to work at Yucca Mountain.[48]

In June 1978, the Governments of Canada and Ontario established the Canadian Nuclear Fuel Waste Management Program.[49] AECL, with the assistance of Ontario Hydro, was directed to develop a generic concept for the deep geological disposal of nuclear waste.[50] The program's goals were "to develop and demonstrate technology to site, design, build and operate a disposal facility", "to develop and demonstrate a methodology to evaluate the performance of a disposal system against … safety criteria", and "to show that suitable sites in plutonic [igneous] rock are likely to exist that, when combined with a suitably designed facility, would meet the safety criteria."[51]

After 10 years of research and development, in 1988, AECL and Ontario Hydro submitted their concept to the government, and this was then put to a public assessment. The repository concept submitted by AECL followed the recommendation of the Hare Report and involved burying the waste 500 to 1000 meters deep in the Canadian Shield.[52] The rationale for the choice of the Canadian Shield was its relatively geological stability for at least 600 million years.[53] Following a Swedish design proposal, the waste would be held in containers made of copper with an inner steel vessel.[54] These containers would be emplaced in boreholes in the surrounding rock or in the tunnels themselves with a layer of compacted bentonite clay placed between the container and the rock mass.[55] Thus the AECL concept included the use of both geological and engineered barriers, and envisioned no provisions for monitoring or retrieval.

The fundamental safety requirement imposed on the disposal concept was that, for the first ten thousand years following closure of a potential facility, the predicted probability that an individual in a "critical group" would incur a fatal cancer or serious genetic defect due to exposure to radiation from the waste should be less than one in a million per year. The critical group is a hypothetical set of people assumed to live at a time and place such that their risk from the repository is likely to be the highest.[56] In developing its models for doses, AECL has assumed that the critical group lives "above the vault location where nuclides are expected to enter the surface environment from below with discharging groundwater and where dilution and dispersion of nuclides are minimal" and consists of "a series of self-sufficient rural households that derive all their needs from local, potentially contaminated sources."[57] In addition to radiation doses, a study commissioned by NWMO lists about 17 chemical elements in CANDU spent fuel that could potentially reach concentrations in excess of guideline values for drinking water, surface water, soil, or air at point of discharge to soil.[58]

Because of its concerns about opposition from local communities at individual sites, AECL decided to use a two-stage model for the environmental assessment that is mandatory under the Federal Environmental Assessment and Review Process introduced in 1973.[59] First, an Environmental Impact Statement (EIS) would be prepared to compare the different approaches to radioactive waste management without any specific site identified.[60] Then, after approval of a recommended disposal technology, a separate environmental assessment process would be initiated for a specific site.

In 1989, the federal Minister of the Environment appointed an independent environmental assessment panel chaired by Blair Seaborn to examine the disposal concept proposed by AECL.[61] The panel initiated its review by holding public "scoping" meetings in the provinces of Ontario, New Brunswick, Quebec, Saskatchewan, and Manitoba, which all mine uranium or fabricate it into fuel or host nuclear reactors, and worked to develop guidelines for AECL's impact statement. The panel finalized these guidelines and issued them to AECL in 1992.

In 1994, AECL submitted an Environmental Impact Statement (EIS) on the impacts both after and before closure of the repository, including interim storage and transportation.[62] This EIS was then the subject of a second round of public hearings in 1995. While these public hearings were underway, in 1996 the Government of Canada issued a *Policy Framework for Radioactive Waste* defining the roles of the government and the waste producers. It stated that:[63]

- The federal government has the responsibility to develop policy and regulate and oversee radioactive waste producers and owners so that they meet their operational and funding responsibilities in accordance with approved long-term waste management plans, and

- Waste producers and owners are responsible, in accordance with the "polluter pays principle", for the funding, organization, management and operation of long-term waste management facilities and other facilities required for their waste.

The policy framework recognized that arrangements may be different for the four broad categories of radioactive waste found in Canada: spent fuel, low- and intermediate-level radioactive waste and uranium-mine waste rock and mill tailings.

The Seaborn Panel submitted its final report to the federal government in March 1998. Its key conclusions were:[64]

- Broad public support is necessary to ensure the acceptability of a concept for managing nuclear fuel wastes;

- Safety is a key part, but only one part, of acceptability. Safety must be viewed from two complementary perspectives: technical and social;

- From a technical perspective, the safety of the AECL concept had been on balance adequately demonstrated for a conceptual stage of development, but from a social perspective, it had not;

- The AECL concept for deep geological disposal did not have the required level of acceptability to be adopted as Canada's approach for managing nuclear fuel wastes.

The Panel discussed the concept of social safety pointing out the many ways in which society at large might have different ideas on what constitutes safe disposal as compared to technical experts. An example that the Panel discussed was in the range of scenarios considered because the public will likely be focused on extreme cases, or worst-case scenarios and would not want to exclude scenarios with a low probability of occurrence. Similarly, a social safety perspective would call for regulatory standards to be developed "through consultation processes involving varied groups" and "protect generations living in the distant future."[65] Another important social criterion laid out by the Panel was that any concept involving the use of Aboriginal lands would have to respect Aboriginal rights and concerns through a process that is appropriate to their cultural practices, values and language.

The Panel's chief recommendation for how to proceed was that a nuclear fuel waste management agency should be created "at arm's-length from the utilities and AECL."[66] It recommended that the board of directors appointed by the federal government be representative of key stakeholders. The Government of Canada, which commended "the Panel for its public consultation effort," rejected this recommendation. Instead, it reiterated its 1996 Policy Framework decision that the management organization should be established by the producers and owners of nuclear fuel waste, specifically the three utilities that operated nuclear reactors and that the utilities should appoint the organization's board of directors.[67]

The Government's rationale was that such an arrangement would facilitate cooperation among producers and owners to find a solution that would, *inter alia*, be cost effective and integrated.[68] The government seemed content as long as the organization was "incorporated as a separate legal entity" from the producers and owners of the waste. This response was codified through the 2002 Nuclear Fuel Waste Act (NFWA) that requires the nuclear utilities to establish a waste management organization as a separate legal entity to "provide recommendations to the Government of Canada on the long-term management of used nuclear fuel" within three years, and "establish segregated funds to finance the long-term management of used fuel."[69]

The Nuclear Waste Management Organization (NWMO)

In 2002, Ontario Power Generation, Hydro Quebec, New Brunswick Power Corporation, and AECL created the Nuclear Waste Management Organization (NWMO) in accordance with the NFWA. The NWMO launched a national consultation process aimed at identifying a waste management option "that would be socially acceptable, technically sound, environmentally responsible and economically feasible."[70]

NWMO described the consultation process as a "dialogue" and used a variety of means, including "nation-wide surveys, focus groups, issue-focused workshops and roundtables, e-dialogues and deliberative surveys, and public information and discussion sessions," to reach out to people.[71] It specifically consulted with a number of Aboriginal organizations. Even critics of the nuclear establishment had to admit that "this was, by far, the most open, participatory, democratic, independent, attempt to find wisdom that this subject had ever had in Canada."[72]

The consultation involved four phases. The first explored what expectations Canadians had for the study and identified the key questions that might be asked of the chosen waste-disposal option. The second phase tried to explore these questions for all the options. The third phase then went further in assessing the various disposal options and the fourth phase finalized the study findings. At the end of each phase, NWMO released a document summarizing the findings of the previous stage.

NWMO considered three options:

1. Deep geological disposal in the Canadian Shield,

2. Continued storage at nuclear reactor sites, and

3. Centralized storage, above or below ground.

At the end of the three year process, in 2005, NWMO recommended what it described as "Adaptive Phased Management" (APM).[73] The idea is essentially the geological disposal option, but with a very long period of monitoring after emplacement. NWMO envisions three phases, with the first two phases each being 30 years long and the final phase lasting 240 years.

During the first phase, spent fuel would be stored and monitored at nuclear reactor sites while a central site "that has rock formations suitable for shallow underground storage, an underground characterization facility and a deep geological repository" is selected.[74] In parallel, the NWMO would decide "whether or not to proceed with construction of a shallow underground storage facility and to transport used fuel to the central site for storage." Should it be decided to construct a shallow storage facility, then the construction and operating licenses also would be obtained during the first phase.

The second phase would focus on completing the final design and safety analyses required for the repository. If shallow underground storage is approved, this phase would involve transport of used fuel from the reactor sites to the central site for extended storage.

The third and final phase would involve transferring spent fuel from the centralized underground shallow storage or reactor sites, repackaging it, and placing the used fuel containers into the deep geological repository for final containment and isolation. Then, for approximately 240 years, access to the deep repository would be maintained and it would be monitored to assess the performance of the repository system and to allow retrieval of used fuel, if required. During this phase, however, the long-term isolation containers would be backfilled and sealed within the placement rooms, making retrieval more difficult.

For a scenario involving the disposal of 3.6 million spent fuel bundles,[75] NWMO estimated the cost of the 300 year APM program at about $24 billion (2002 Canadian Dollars or approximately 25 billion in 2009 US Dollars) if it included interim spent fuel storage in a centralized underground facility. When discounted, the present value is estimated at $6.1 billion (2004 Canadian Dollars).[76] If the spent fuel remained at reactor sites prior to operation of the deep repository, these figures come down to $21 billion (2002 Canadian dollars) with a present value of about $5.1 billion (2004 Canadian Dollars). Thus, leaving spent fuel at the reactor sites is a cheaper option.

On June 14, 2007, the Canadian government accepted the recommendations of NWMO and gave the organization the responsibility for implementing the program.[77] In the interim, the utilities and AECL continue to be responsible for spent fuel at their respective sites.

The first step adopted as part of the APM approach was to develop the process through which sites would be selected. In 2008, NWMO invited "interested organizations and individuals to contribute their suggestions and expectations for the principles, objectives and key elements that should guide the development of a fair and inclusive site selection process."[78] The following year, NWMO put up a draft document with its proposal for comments, and finalized a multi-step process in 2010.[79]

In May 2010, NWMO began a multi-year process for selecting an informed and willing community to host the deep geological repository for Canada's used nuclear fuel. The process involves nine steps, including a multi-step approach to assess and select sites, to perform a safety review, and to oversee construction and operation of the facility.

The first step in the process is "a broad program to provide information, answer questions and build awareness among Canadians about the project and the siting process."[80] NWMO described the initiative as a "multi-billion-dollar project … also [involving] the creation of a centre of expertise for technical, environmental and community studies" and predicts that it "will become a hub for national and international scientific collaboration, and … will generate thousands of jobs in a host region and hundreds of jobs in a host community for many decades."[81] In their public presentations on the project, NWMO spokespersons have emphasized the economic benefits ("thousands of jobs," "hundreds of millions of dollars for many years," and "transformational impact") that would flow to the communities hosting the project.[82]

The first results of these presentations are becoming apparent. A few villages and small towns have started cautiously exploring the possibility of becoming home to a repository.[83] A typical example is Ignace in northern Ontario, a town of 1200 people whose economy used to be based on forestry. But in recent years, the industry's earnings had declined and this had resulted in people migrating away from the community. Town officials see waste disposal as an economic engine generating hundreds of jobs for several years and a somewhat smaller number over the long term.[84] After the initial screening, in March 2011, NWMO wrote to town officials saying that they "did not identify any obvious conditions that would exclude the Township of Ignace from further consideration in the NWMO site selection process."[85] If the town were to express an interest in going further, NWMO would initiate "several years of studies" to confirm if the site is suitable.

In Ignace and other places, there has been local opposition, with the familiar dynamic of the need for economic growth and jobs being pitted against environmental and health concerns. Also apparent has been the tension between specific localities, which may desire waste disposal for economic reasons, and the provinces in which they are sited. At least one provincial government, Saskatchewan, has opposed the idea of hosting a repository, in part because it does not have any nuclear power plants.[86] Transportation of spent fuel and other forms of nuclear waste has also been a widely expressed source of concern.[87] This is despite the over 500 shipments of spent fuel that have been made in Canada, with about 5 to 10 shipments carried out each year, mostly between the operating nuclear reactors in Ontario, Quebec and New Brunswick and the AECL research facilities in Chalk River, Ontario.[88]

Ontario Power Generation (OPG) proposes to construct a geological repository solely for low- and intermediate-level radioactive wastes produced at its Bruce, Darlington, and Pickering nuclear power stations (see Figure 2.2). These wastes are already in interim storage at the Western Waste Management Facility in the same location. The long-term proposal resulted after a 2002 Memorandum of Understanding between the Municipality of Kincardine, the host community for the Bruce nuclear complex, and OPG. In 2005, a poll of all Kincardine permanent and seasonal residents, 18 years of age and older, who constituted 71 percent of all residents in all, found that 60 percent of the respondents were in favor of the project. OPG is proposing that a deep rock vault be constructed in a layer of limestone, at a nominal depth of 680 meters beneath the surface. The storage capacity will be approximately 200,000 cubic meters. The project's environmental impact statement was submitted to the Canadian Nuclear Safety Commission in April 2011.

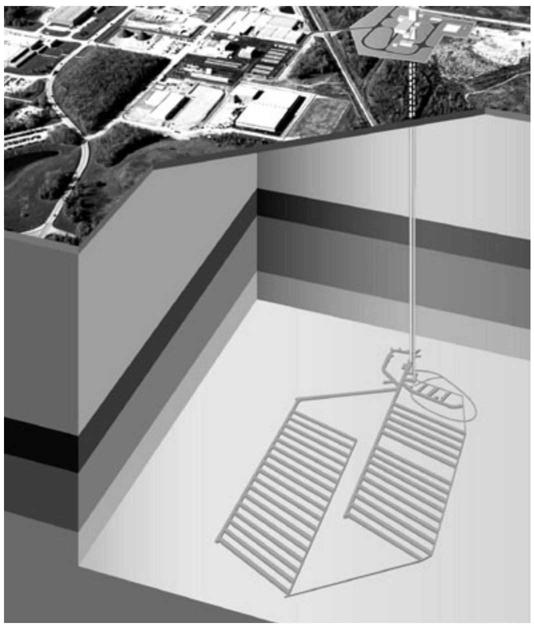

Figure 2.2: The Bruce Nuclear Complex in Ontario is proposed as a possible site for a geological repository for low-level and intermediate-level waste. *Source: Ontario Power Group.*

Future

Canada seems to have achieved a successful process to move forward with nuclear waste management. The government has approved the "Adaptive Phased Management" (APM) approach that the NWMO came up with after extensive public consultation. NWMO can therefore claim to have taken the first few steps towards dealing with the social opposition towards nuclear waste disposal in Canada. This appears to have had positive effects in the search for a repository site, and a few localities have come forward to explore the possibility, albeit somewhat tentatively, of hosting such a site.
The earliest date that is envisioned by the NWMO for the commencement of construction on a geological repository is 2035.[89] It may well take longer, especially if the option of interim shallow underground storage of nuclear wastes is chosen.

One potential problem is the radioactive-waste implications of an expansion of nuclear power in Canada. Those sites that have volunteered to explore the possibility of a repository have come forward under the understanding that the amount of spent fuel to be disposed of in the repository will be limited to what will be produced by the reactors already constructed over their lifetimes.

As part of setting up the process for spent fuel disposal, the NWMO took a narrow stance on what its mandate was, arguing "Used fuel exists today and will continue to be produced to the end of the lives of Canada's existing nuclear facilities. The focus of our study is to recommend a responsible path forward for addressing the used fuel that requires management for the long term. Our study process and evaluation of options were intended neither to promote nor penalize Canada's decisions regarding the future of nuclear power."[90] However, this was clearly not the government's view.[91]

Should there be concrete movement towards the construction of new nuclear reactors, it is possible that the seeming consensus on the current strategy for siting a repository might break down. The NWMO's 2005 report referred to "the impassioned arguments we heard about energy policy and the future of nuclear power." The reason that the nuclear waste issue was tied to the future of nuclear power in the country was also clarified: "While some worried that the identification of a long-term management approach would serve as a *de facto* licence for the expansion of nuclear energy without adequate public discussion, others acknowledged that it was important for the current economic viability of the industry that decisions be taken."[92] Currently, however, prospects for a revival of nuclear power in Canada seem bleak.[93]

M. V. Ramana

3 France

France's nuclear program started as a military effort for the production and separation of weapons plutonium. Gas-graphite reactors were built for the production of weapons plutonium and began operation in 1956 at the Marcoule military nuclear site in the south of France. In 1958, the first batches of its spent fuel were reprocessed on the same site in the UP1 (Usine de Plutonium or Plutonium Factory Number 1). This legacy has cast a shadow over the subsequent civilian program and especially over policy for the management of spent nuclear fuel even though military production of plutonium ended in 1993.

France's spent fuel management system today revolves around the civil nuclear program—now comprising 58 power reactors with a combined installed capacity of 63 GWe—and involves reprocessing spent uranium fuel and using the separated plutonium in mixed oxide fuel (MOX) for light-water reactors. The spent MOX fuel is not being reprocessed.

Planning for a geological repository for high-level and long-lived intermediate-level waste has been an issue almost since the beginning of the French nuclear program. Currently, it is being implemented by the National Radioactive Waste Management Agency (ANDRA) under legislation passed in 2006. The disposal facilities are to be developed on the basis of studies at a geological laboratory in a clay formation at Bure, in the east of France, with the repository to be located in a limited area around the Bure site and is expected to start operations by 2025.

Legislative framework for spent fuel management

In 1991, an effort to identify a site for an underground repository on land triggered a debate that resulted in the "Bataille Act," which required fifteen years of R&D, including an analysis of schemes to separate and transmute long-lived radioisotopes to shorter-lived radioisotopes.[94]

In 2006, two important pieces of legislation were enacted to provide a new legal basis for spent fuel and nuclear waste management in France: the "Act on Transparency and Safety in the Nuclear Field" (TSN Act, 13 June 2006) and the "Act on Sustainable Management of Radioactive Materials and Waste" (Planning Act, 28 June 2006). France is also a signatory to the international Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. A European Directive on Radioactive Waste Management was adopted in July 2011.[95]

France's classification of radioactive wastes (Table 3.1) distinguishes between isotopes of very-short (<100 days), short (≤31 years) and long (>31 years) half-lives and four levels of radiation intensity (very low, low, intermediate and high). Spent nuclear fuel is categorized as high level, long-lived waste.

Activity	Half-life: very short (less than 100 days)	Half-life: short (100 days to 31 years)	Half-life: long (more than 31 years)
Very low level (VLL)	Decay during interim storage	Shallow disposal (CSTFA)	
Low level (LL)		Shallow disposal (CSFMA)	under study
Intermediate level (IL)			under study
High level (HL)		(pursuant to 2006 Planning Act)	

Table 3.1: Classification of radioactive waste in France and disposition plans. CSTFA is the Centre de l'Aube Disposal Facility for VLL Waste and CSFMA is the Centre de l'Aube Disposal Facility for LIL Waste. *Source: Nuclear Safety Authority (ASN).*[96]

There is no legislation or binding specific regulation in France that would define these categories. They are in "common use." The national nuclear safety authority defines them in the following way:[97]

- High-level (HL) waste consists mainly of vitrified-waste from reprocessing spent fuel. These wastes contain both fission products and minor transuranics and are stored in stainless-steel containers. The activity level of the vitrified waste is on the order of several billion becquerels per gram and is cooled with convective air circulation. A becquerel (Bq) is one radioactive disintegration per second.

- Intermediate-level, long-lived (IL-LL) waste originates mostly from the reprocessing of spent fuel and consists of structural residues from spent nuclear fuel (i.e., cladding hulls and fuel-assembly nozzles). These wastes were initially conditioned into cemented waste packages, but current practice is to compact them into stainless-steel containers. It also includes technological waste from reprocessing and MOX fuel fabrication (e.g., used tools and equipment) and residues resulting from the processing of effluents, such as bitumenized sludges. Minor quantities of IL-LL wastes are generated during reactor operations (e.g., absorber rods). The activity of those residues ranges between 1 million and 1 billion becquerels per gram. There is negligible heat release.

- Low-level long-lived (LL-LL) waste consists mainly of graphite and radium-bearing waste. The activity of graphite waste lies between 10,000 and 100,000 becquerels per gram. Its long-term activity derives predominantly from beta-emitting radionuclides. Radium-bearing wastes contain long-lived alpha-emitting radionuclides and their activity ranges between a few tens to a few thousand becquerels per gram.

- Low-level and intermediate-level short-lived (LIL-SL) wastes result mainly from the operation and dismantling of nuclear power plants, fuel-cycle facilities and research facilities. Most residues in that category were until 1994 disposed of in a surface facility at the Centre de la Manche Disposal Facility (CSM) and, since 1992, at the Centre de l'Aube Disposal Facility for LIL Waste (CSFMA).

- Very-low-level (VLL) waste is mostly due to the operation, maintenance and dismantling of nuclear power plants, fuel-cycle facilities and research establishments. Its activity level is generally lower than 100 becquerels per gram. All residues of that category are disposed of at the Centre de l'Aube Disposal Facility for VLL Waste (CSTFA).

- Very-short-lived waste includes residues that result notably from medical uses.

- The 2006 Act on Transparency and Safety in the Nuclear Field established the national Nuclear Safety Authority (ASN) as an administrative body independent of the government. Together with ANDRA, which was established in 1979, ASN uses the principles defined in the 2006 Planning Act to elaborate the National Management Plan for Radioactive Materials and Waste (hereafter referred to as National Plan).

The Planning Act established three areas of research and development relating to the disposition of high and intermediate-level wastes:

1. Partitioning and transmutation of long-lived isotopes;

2. Reversible waste disposal in a deep geological formation; and

3. Long-term storage.

A National Review Board (CNE) assesses progress of these studies annually. The CNE consists of twelve individuals, including international experts, nominated by the Office for Evaluation of Scientific and Technological Options (OPECST) and the Academy of Moral and Political Science and appointed by the two chambers of parliament and the government.[98]

The 2006 Planning Act also attempts to ensure long-term funding for decommissioning and waste management. ANDRA is required to set up a "dedicated fund in order to build, operate, shut down definitively, maintain and monitor the storage and disposal facilities for high-level and long-lived waste."[99] All operators of nuclear installations must estimate the future costs for the management of their spent fuel, decommissioning operations and the management of radioactive waste, and must allocate "the required assets to the coverage of those provisions." The operators must submit to the authorities every three years new estimates of future charges and provide annual updates in intermediate years.

A National Commission for the assessment of spent fuel management, decommissioning and waste management costs has been constituted. Its membership includes the presidents of the responsible committees of both chambers of Parliament and eight experts appointed by the Parliament and the government (four each). The Commission may "require operators to provide any relevant documents for the fulfillment of its missions" and may hear the administrative authorities.

According to the 2006 Planning Act, "radioactive waste shall include any radioactive substance for which no further use is prescribed or considered." Article 8 explicitly stipulates that "no radioactive waste originating from a foreign country or from the processing of foreign spent fuel and foreign radioactive waste shall be disposed of in France" and "no spent fuel or radioactive material shall be introduced into France except for processing (e.g., reprocessing and MOX-fuel fabrication), research or transfer between foreign countries."

Commercial reprocessing, although originally introduced to obtain plutonium fuel for starting up fast-neutron reactors, is now clearly established as the national policy for spent-fuel management. Article II.1 stipulates that "the reduction of the quantity and toxicity of radioactive waste shall be sought notably by processing spent fuel and by processing and conditioning radioactive waste."

A disposal facility for long-lived intermediate and high-level wastes is required to be in operation by 2025. No license shall be granted, however, "if the reversibility of such a facility is not guaranteed." While the conditions of reversibility will be defined in a subsequent law, its minimum duration is one hundred years.

Spent fuel management system

The French nuclear establishment appears more committed to spent fuel reprocessing than that of any other country. Reprocessing of power reactor spent fuel started at the UP2 facility at La Hague in 1966. The original rationale for civilian reprocessing in France, as elsewhere, was as part of a strategy for the rapid introduction of fast breeder reactors because of concerns that uranium was scarce and that low-cost deposits would be rapidly depleted.[100]

Even though, the real price of uranium on the spot market dropped by almost two thirds between its peak in the late 1970s and 1985, and the costs of reprocessing and breeder reactors proved to be much higher than expected, reprocessing remained central to France's spent fuel management. The highly centralized French nuclear decision-making process always guaranteed that democratic debates and parliamentary votes did not interfere with the strategic orientations essentially elaborated, carried out, and supervised by elite technocrats.

There has, however, been discord between the two chief organizations involved in the generation and management of spent fuel, namely the electric utility, Électricité de France (EDF), and AREVA, the operator of the La Hague reprocessing plants, both government owned.[101] In December 2008, the two signed a "framework agreement for the recycling of used nuclear fuel from 2008 to 2040."[102] The agreement provides EDF with the possibility to increase the annual quantity of spent fuel sent to La Hague from 850 to 1,050 tons per year and to increase MOX fuel purchases from 100 to 120 tons per year.[103] But, on 5 February 2010, the two companies released a joint press release announcing that they had "reached an agreement covering the transportation, treatment and recycling of used nuclear fuel, for which a contract will be signed before the end of the first quarter of 2010."[104]

In a letter to the author dated 30 March 2011, EDF states that an "Agreement Processing-Recycling" has been signed on 12 July 2010. According to EDF the agreement covers the period 1 January 2008 to the end of 2012, including reprocessing of 850 tons per year and MOX fabrication of 100 tons per year for 2008-2009 and reprocessing of 1,050 tons per year and 120 tons per year for 2010 – 2012. Additional contractual conditions allow for the adaptation, "if necessary" of the various quantities to the quantities "effectively recycled."[105] It is remarkable that the period covered by the agreement is post-dated and only covers a period of five years in total (less than three years ahead) and falls far short of the ambitious 2008 announcement of a 32-year period.

In France, nuclear power reactor spent fuel is cooled in pools on the reactor sites for several years before being shipped by train to the Valognes station where the 100-ton-shipping casks are loaded onto heavy trucks that carry the fuel assemblies 30 km to the

La Hague reprocessing plant (Figure 3.1). The spent fuel is stored for another period of several years in the massive cooling ponds at La Hague before being reprocessed and separated into three principal products: uranium, plutonium, and high level wastes containing most of the fission products and the minor transuranics, neptunium, americium and curium. In addition, a whole range of low- and intermediate-level wastes are being generated in the process (Figure 3.2).

Part of the recovered uranium, about 990 tons per year as of 2010, is shipped to the Pierrelatte/Tricastin site in the Rhône valley for conversion (from uranium nitrate into stable U_3O_8) and long-term storage. As of the end of 2008, about 23,000 tons of reprocessed uranium are stored at Tricastin.[106] In the past, about 300 tons per year (average for 2007 to 2009) were re-enriched in Russia and fabricated into approximately 37 tons of new fuel,[107] which was used in two reactors at the Cruas site starting in 1994. After a television documentary triggered a public controversy in 2009, the shipments were halted in 2010.[108] According to the new strategy, 600 tons of reprocessed uranium are to be re-enriched annually and fabricated into approximately 75 tons of reprocessed, re-enriched uranium fuel to be used in all four Cruas reactors (see Figure 3.1).[109]

After processing, the separated plutonium is converted to plutonium oxide and stored in a large dedicated bunker onsite at La Hague. On average two truck shipments per week with about 100 kg or more of separated plutonium oxide each go on a 1,000 kilometer road trip from La Hague to the MELOX mixed oxide (MOX) fuel fabrication facility at Marcoule. Currently, twenty 900 MWe reactors at six nuclear power plants are loaded with up to 30 percent MOX fuel in the core. Two more 900 MWe units are licensed to operate with MOX and will be loaded with MOX in the future. EDF has requested a license for yet two more 900-MWe reactors (at Blayais) to be loaded with MOX, adding more flexibility to the fuel management scheme.[110]

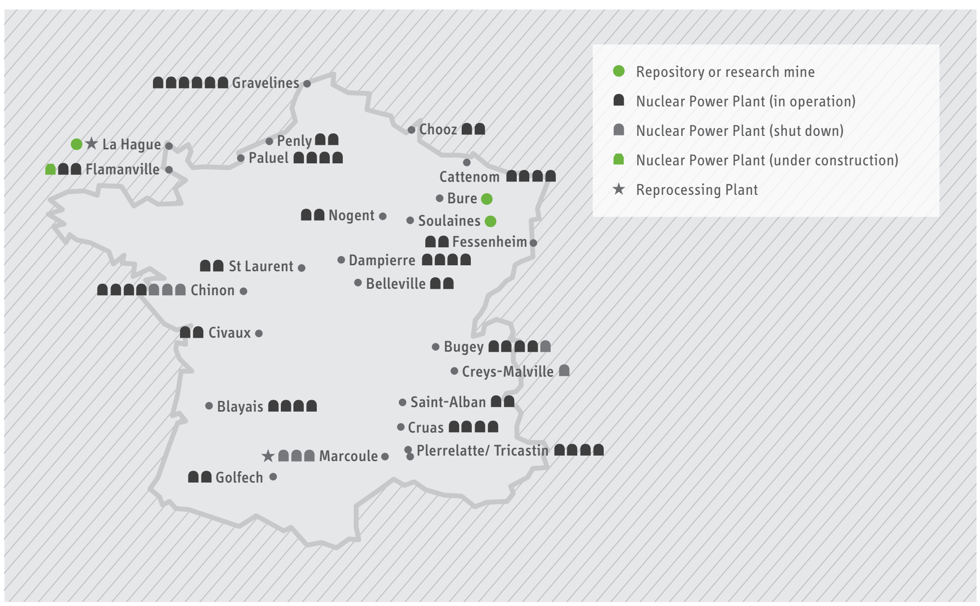

Figure 3.1: France's nuclear power plants, reprocessing plants, and sites of disposal projects. *Source: Adapted from WISE-Paris.*

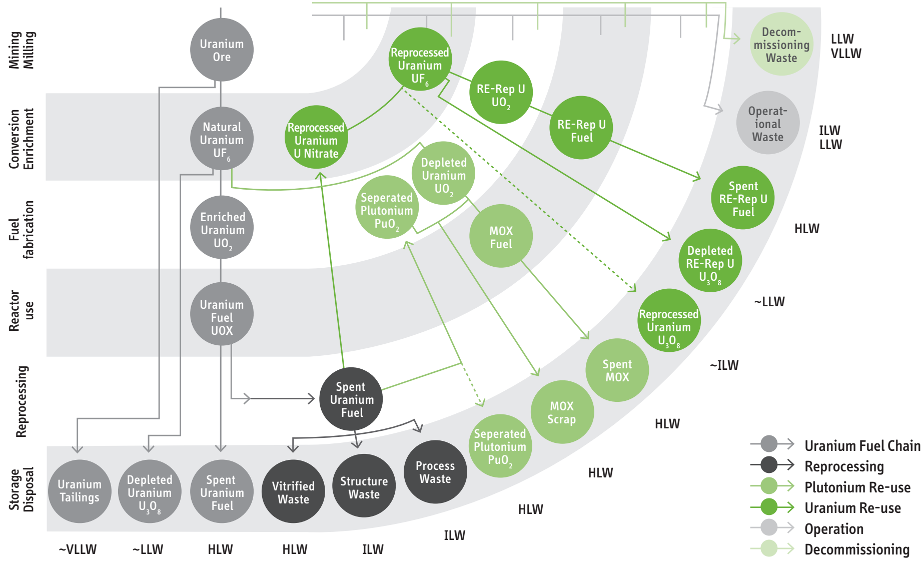

Figure 3.2: Generation of different radioactive-waste streams by nuclear power in France. *Source: WISE-Paris.*

The fresh MOX fuel is shipped by truck (see Figure 3.3) to the six sites with reactors licensed for MOX. At an average plutonium content of 8.65 percent in the plutonium-uranium mix, the approximately 120 tons of MOX loaded into reactors annually as of 2010 contained around 10 tons of plutonium. All these road shipments constitute a significant security challenge.[111]

Once irradiated, the spent MOX fuel is shipped to the La Hague reprocessing plant and stored there.[112] The plutonium in spent MOX fuel is relatively low quality for use in slow-neutron water-cooled reactors because it contains a reduced fraction of fissile Pu-239 and Pu-241 compared to the plutonium in spent low-enriched uranium fuel. The MOX fuel is therefore to be stored pending the construction of a fleet of fast-neutron plutonium breeder reactors, currently planned beginning around 2040, which would provide an incentive to separate the plutonium in spent MOX fuel to use as startup fuel for the breeders.

Figure 3.3: Fresh MOX shipment escorted by police vans on a French country road, 27 January 2011. *Source: Yannick Rousselet – Greenpeace.*

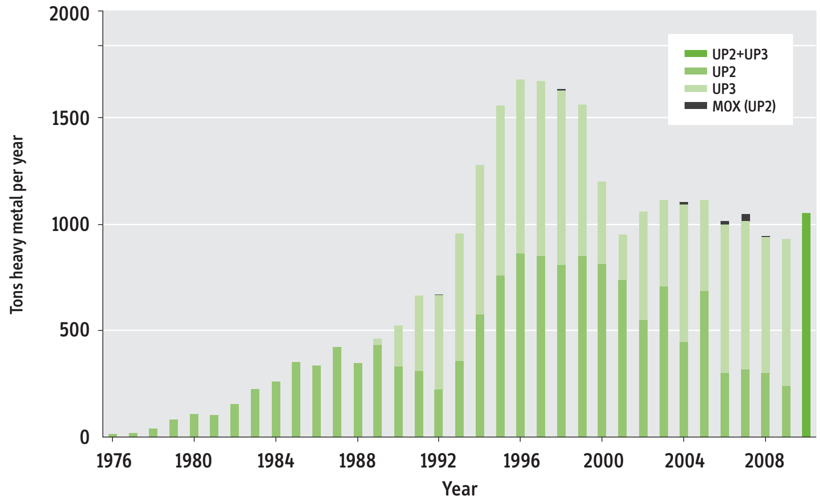

Figure 3.4: LWR Reprocessing at La Hague 1976 – 2010. UP3 was originally built to reprocess foreign spent fuel. Today, however, virtually all spent fuel being reprocessed is domestic. *Source: Mycle Schneider Consulting.*[113]

Over the entire operational period of La Hague, 1976 – 2010, AREVA has reprocessed about 26,550 tons of LWR fuel, including 72.5 tons of MOX fuel (see Figure 3.4). EDF also has accumulated a backlog of more than 13,000 tons of spent fuel, however, of which roughly three quarters (9,421 t as of the end of 2009) is stored at La Hague. In recent years, the spent fuel storage capacity of the four massive spent-fuel storage pools at La Hague has been increased through re-racking to dense packing from 13,600 to 17,600 tons. The spent-fuel backlog is not expected to decrease significantly until the reactors reach the end of their lives in 2030 (see Table 3.2).

At the same time, France has accumulated a large stockpile of separated plutonium (55.9 tons as of the end of 2009) mainly as plutonium oxide (PuO_2).[114] This is contrary to repeated government and industry statements of a policy of balanced production and consumption of plutonium.[115]

Current and future inventories of spent fuel

The 2010 National Plan indicates that, as of the end of 2007, about 13,000 tons of spent fuel was in storage, most of it spent low-enriched uranium fuel but also including 1,000 tons of MOX, 250 tons of fuel fabricated from re-enriched reprocessed uranium, 100 tons of fast breeder (FBR, Superphénix reactor) fuel, 40 tons of research reactor fuel and 140 tons of defense-related (mostly naval-reactor) spent fuel. In addition there were about 4,500 tons of low-enriched uranium fuel in the cores of France’s 58 light water reactors (LWRs), 290 tons of MOX fuel in the cores of 20 of those same LWRs, 80 tons of reprocessed and re-enriched uranium fuel in the cores of the four 900-MW LWRs at Cruas, and 5 tons of fuel in various research reactors. France discharges annually about 1,200 tons of spent fuel from its LWR fleet, including MOX fuel that will increase to 100 – 120 tons starting in 2012 (see Table 3.2).

	Type of fuel	End of 2007 (tHM)	End of 2010 (tHM)	End of 2020 (tHM)	End of 2030 (tHM)
Fuel in reactor cores	UOX	4,500	4,500	3,860	1,100
	REPU	80	100	290	0
	MOX	290	300	440	0
	Subtotal	4,870	4,900	4,590	1,100
Spent fuel awaiting reprocessing	UOX	11,504	11,900	13,450	11,000
	REPU	251	300	1,020	1,320
	MOX	1,028	1,200	2,320	2,550
	FBR	104	104	104	104
	Subtotal	12,887	ca. 13,500	16,894	14,974
In core + Spent fuel	Total	17,757	ca. 18,400	21,484	16,074

Table 3.2: Spent fuel estimates 2007–2030. UOX is uranium oxide, REPU is reprocessed uranium, MOX is mixed oxide fuel, and FBR is fast breeder reactor. *Source: ASN.*[116]

ANDRA's estimates of future spent fuel stocks are based on the current reactor fleet plus one additional unit under construction (the 1600-MWe EPR at Flamanville). It is remarkable that the projection envisages that the stock of spent UOX fuel awaiting reprocessing by 2020 will still be higher than today (see Table 3.2). There is no plan before at least 2030 to reprocess any significant amount of spent MOX, reprocessed uranium fuel (REPU), or fast breeder reactor fuel.

The National Plan states that MOX reprocessing diluted with UOX and REPU fuels should "start" in the decade between 2025 and 2035. Other sources, including the National Review Board, do not expect MOX reprocessing before 2035. The main reason for the delay is that there is no plan to reuse the MOX plutonium or the associated reprocessed uranium in LWRs again; the National Review Board has noted that "[N]umerous plutonium multi-recycling options for PWRs have been explored and abandoned."[117] While feasibility of MOX reprocessing has been demonstrated in the UP2 plant, because of the high plutonium content of spent MOX fuel, throughput must be reduced to about 50 percent of that for uranium fuel in order to avoid criticality problems.

According to the National Review Board, separating enough plutonium to launch a 1 GW fast breeder reactor would need the reprocessing of 285 tons of MOX fuel and would take about 140 days of operation for one of the two reprocessing plants at La Hague, UP2-800.[118]

Some 50 m^3 of spent research reactor fuel—which is supposed to increase to a maximum of 74 m^3 (4,374 packages) by 2030—are stored in the CASCAD facility at Cadarache. Opened in 1990, the facility is supposed to operate for 50 years. The fuel held in the CASCAD facility is to be disposed of directly, i.e., not reprocessed.

Plans for spent fuel and waste management

The nuclear power program has generated about 80 percent of the overall high-level waste volumes in France, while the defense program (plutonium and tritium production and naval reactors) and the research sector have contributed about 10 percent each.[119]

The high level waste from reprocessing spent fuel is vitrified and stored at La Hague. Currently, there are three such stores, with a combined capacity of 2,174 m^3, which will be full by 2013. AREVA plans to expand their capacity to 3,648 m^3 by 2012 and another expansion is planned for 2022. The design lifetime of the stores is until 2040.

There remains a significant backlog of other types of reprocessing wastes at La Hague to be conditioned, including 9,300 m^3 of sludge from over 30 years of operation (1966-1997) of the STE2 effluent treatment plant and 2,100 tons of hulls and nozzles (IL-LL), resins and technological wastes from operation of the old UP2-400 plant between 1976 and 1997.

Planning for a geological repository

ANDRA is required, before the end of 2012, to present various scenarios for all the intermediate- and high-level waste packages intended for disposal in a deep geological repository. In particular, ANDRA is to study the timeline for intermediate storage, conditioning, shipment and introduction of the waste into the disposal facility. The assessment is to include the possibility of intermediate-waste storage in the same geological repository.

There are no disposal facilities currently operating in France for any kind of long-lived wastes, whether low-, intermediate- or high-level. France does have three shallow disposal sites for short-lived waste, however.[120] One major low- and intermediate-level short-lived waste repository, the Centre de Stockage de la Manche, adjacent to the La Hague reprocessing site, now closed, operated between 1969 and 1994. In 2003 it entered a "surveillance" phase that is to last at least 300 years. However, the cover had to be repaired after a few years and the site is leaking tritium. The Centre de l'Aube Disposal Facility for Low- and Intermediate Level Waste (CSFMA) at Soulaines opened in 1992 and the Centre de l'Aube Disposal Facility for Very Low-level Waste opened in 2003 at Morvilliers, only a few kilometers from the CSFMA.

The Planning Act calls for the commissioning by 2013 of a storage facility for low-level *long-lived* wastes, including 4,615 m^3 of irradiated graphite sleeves currently stored at La Hague from the reprocessing of spent gas-graphite reactor fuels.[121] The opening of this new 150,000 m^3 sub-surface (15 m to 100 m depth) facility has been seriously delayed, to at least 2019, by massive protests in the areas considered as possible sites.

ANDRA launched a public call to 3,115 communities in 2008 for volunteers to host the facility. Forty-one applied for consideration and, in June 2009, the government selected two: Auxon (population 230) and Pars-lès-Chavanges (population 75), both in the Aube department that already houses the two operating disposal facilities for short-lived wastes. But both communities withdrew "under the pressure of the opponents."[122] Currently, the project is suspended and ANDRA and the government are looking for a new approach.

France's project for geological storage of high and intermediate-level waste is called the Centre industriel de stockage géologique (Cigéo), which would hold all such wastes to be generated through 2052 by the operation of the current fleet of 58 reactors, and the power reactor currently under construction as well as defense and other historic wastes. The total volume has been estimated at around 100,000 m^3. The disposal facilities are to be developed on the basis of the 500 m deep geological laboratory in a clay formation at Bure in the Meuse Department, which like the Aube Department, is located in the east of France. The repository is expected to underlie a storage surface area of about 15 km^2 (100 km of galleries and 200 km of horizontal boreholes for the emplacement of high level waste into the walls of the galleries, plus 20 km of horizontal boreholes for intermediate level waste).[123]

ANDRA is expected to submit a license request for the creation of Cigéo in 2015 in order to allow for the start up of operations by 2025, as stipulated by the Planning Act. In 2009 ANDRA proposed a so-called "Zone of Interest for In-depth Exploration" (ZIRA), a limited geographical area around the Bure laboratory, where more in-depth research is to be conducted prior to the underground installation of the repository. ANDRA has asked the government not to determine the exact site location prior to a public debate that is to be organized by the end of 2012 or the beginning of 2013. In the meantime, ANDRA has to demonstrate that the site will be safe for one million years. The parallel activities during the operational period of excavating tunnels and putting waste into storage will be a challenge. "This has never been done in the world, at least not in clay", ANDRA's Director General Marie-Claude Dupuis told Parliament, noting that "No benchmark exists today, for example, for the handling of fire."[124]

The high-level reprocessing wastes have to cool down for "several decades" (60 years, according to the National Review Board) prior to disposal. No waste packages with temperatures exceeding 90 °C are to be allowed to contact the clay environment lest the clay dry out, crack and become more permeable. According to EDF, the thermal load of spent MOX fuel is about three times as high as that of spent uranium fuel. Accordingly, it is estimated that spent MOX fuel will have to be cooled at least 100 years longer than spent LEU fuel or it would need to be placed in four or five times as many disposal casks as the equivalent amount of spent LEU fuel.[125]

ANDRA has developed four different scenarios to establish the necessary capacity for Cigéo. The most important assumption is that it will be necessary to deal with the radioactive waste from 45,000 tons of spent fuel. According to ASN, this corresponds approximately to an operational period of 40 years for each reactor. The scenarios are as follows:[126]

- Scenario 1a. All spent fuel, including MOX and reprocessed uranium fuel is reprocessed, resulting in 6,300 m^3 of high-level waste (HLW) and 81,100 m^3 of intermediate-level long-lived waste (ILW-LL);

- Scenarios 1b and 1c. All spent fuel except spent MOX is reprocessed, resulting in 6,300–7400 m^3 HLW + 80,600 m^3 ILW-LL and 2,000 tons of spent MOX fuel; and

- Scenario 2. Spent fuels reprocessing ends after 2010. In this scenario 29,000 tons of unreprocessed spent fuel will have to be disposed (12,500 tons of UOX with an average burn-up of 45 GWd/tHM, 14,000 tons of UOX with an average burn-up of 55 GWd/tHM, 500 tons of reprocessed uranium fuel, and 2,000 tons of MOX with an average burnup of 48 GWd/tHM) plus 2,600 m^3 HLW and 73,100 m^3 ILW-LL. "This scenario is included as a precaution," ASN states.

The costs of Cigéo remain extremely uncertain. According to ANDRA's Director General Marie-Claude Dupuis, the "only official figures that we have" have been determined by the Industry Minister as € (2002) 13.5 to 16.5 billion.[127] Inflating to current value, Dupuis added, would bring the range to € (2011) 21 to 26 billion. ANDRA's DG did not deny figures cited in recent media reports, putting a new estimate of the repository at € 35 billion, but called them "very premature."[128] A new official cost estimate is to be provided by the government prior to the 2012-13 public debate.

A substantial amount of historic intermediate-level long-lived wastes (bituminized, concreted and to-be-conditioned sludge) that is destined to be buried in a French geological repository is of foreign origin. AREVA sends back to foreign customers small volumes of equivalent (calculated according to a complex formula) high and intermediate level wastes conditioned according to the latest state of the art. The large volumes of "old style" conditioned wastes, including tens of thousands of tons of low-level wastes, will remain in France. Much of the low-level and short-lived intermediate level wastes have already been buried.

Open questions

France's spent fuel management policy has not yet dealt adequately with a number of open questions.

Reprocessing policy is being implemented in the expectation of the development and post-2040 deployment of fast-neutron plutonium breeder reactors. While French authorities state that direct disposal options are being studied, cost assessments and fund management do not adequately account for the possibility that any of the theoretically "reusable" materials (separated plutonium, reprocessed uranium, spent LEU fuel, re-enriched reprocessed uranium and spent MOX fuels) might be declared waste in the future for political, technical or economic reasons. OPECST urges that the National Plan "must envisage in a more complete way all strategic options of the nuclear sector that could be selected following a new political choice of the nation."[129]

France will have to deal with massive stocks of irradiated MOX fuel containing six times the percentage of plutonium as spent low-enriched uranium fuel and generating significantly more heat. If this fuel is not reprocessed, it will need significantly more space in the final repository or a century or more additional surface storage to cool down to levels comparable with spent uranium fuels.

As noted by the National Review Board, the "number of families of primary waste packages"— especially in the intermediate-level category— "is considerable."[130] This makes the repository design extremely complex.

Design and engineering of the Cigéo repository project are in the early stages and have been significantly revised several times. Underground rail transport has been abandoned, for example. This makes cost assessments highly speculative at this point. OPECST has recommended that the future National Plan include a financial assessment of nuclear material and waste management that provides ranges of uncertainties and clarifies financing mechanisms.[131]

A reactor operating life expectancy of 40 years provides the current design basis for the future repository. But EDF plans lifetime extensions beyond 40 years, which would significantly change quantities of waste to be disposed of. While ANDRA has assumed a 50 percent increase in waste by 2052 in some of its modeling, it has not provided detailed data and analysis.

Published cost assessments pre-date the 2006 Planning Act and did not take into account the fact that retrievability of high- and intermediate-level long-lived waste from a geological repository has been rendered obligatory rather than optional. Also, these cost estimates have never been discounted and the question of which discount rate to adopt in the longer term has not been solved yet.

Public opinion

A final open question about planning for the future of France's nuclear program, including management of spent fuel and final disposal, is public support. The management of radioactive wastes in particular has always played a major role in influencing public opinion on the issue of nuclear power.

Contrary to conventional wisdom, there has never been a "nuclear consensus" in France. Public opinion has always been split when it comes to the use of nuclear power. Prior to the March 2011 accidents at the Fukushima nuclear reactors in Japan, slightly less than half of the people polled were convinced that France's choice of nuclear power presents more advantages than disadvantages, while a roughly equal number were of the opposite view—the percentage of critics had increased from less than 30 percent in 1995 to 40 percent in 2010.[132]

In a recent, but still pre-Fukushima survey for the European Commission, the French seem unconvinced that the disposal of radioactive waste "can be done in a safe manner" (see Figure 3.5).

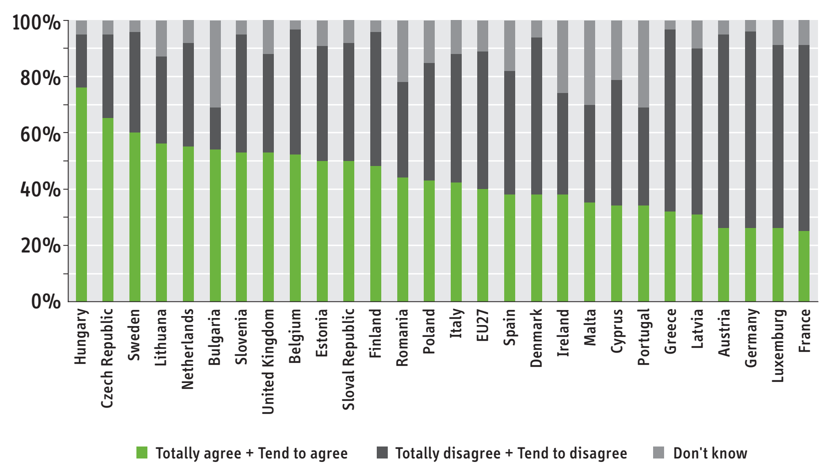

Figure 3.5: Responses to March 2010 opinion poll question: "The disposal of radioactive waste can be done in a safe manner…" The public in France is less confident than that in any other country in the EU that radioactive waste can be disposed of safely. *Source: European Commission.*[133]

Only a quarter of the French people polled believed that there is a safe way to dispose of nuclear waste.

As in most countries, the Fukushima crisis has a profound effect on French public opinion and political leaders. A June 2011 poll found that up to 77 percent of people polled were in favor of phasing out nuclear power.[134] However, while the French public was always split about the merits of nuclear power, there was a political party consensus in favor of nuclear power that excluded only the Green Party. After the Fukushima disaster, for the first time, top leaders of the Socialist Party, including party chairwoman Martine Aubry and vice-chairman Harlem Désir, explicitly stated the country should phase out nuclear power. Given that it is not unlikely that the Socialist Party and the Green Party might form the government after the 2012 elections, the country might be on the eve of a very major shift in energy policy.

Mycle Schneider

4 Germany

Germany's nuclear power program started in 1955 after the country officially renounced the development and possession of nuclear weapons. Germany's first nuclear power plant, the prototype reactor VAK at Kahl, Bavaria, began operating in 1960. At the start of 2011, there were 17 nuclear power reactors in operation at 12 sites with a total capacity of 21.5 GWe, producing around 23 percent of Germany's electrical power. Following the March 2011 Fukushima accidents, the government shut down eight reactors immediately and announced plans to close the remaining nine by 2022.

Germany's current spent fuel policy has been shaped by:

1. The nuclear phase-out law of 2002 and subsequent policy changes in 2010 and 2011;

2. The end of foreign reprocessing of Germany's spent fuel; and

3. The search for a repository.

Until 2005, utilities had the option of sending spent fuel for reprocessing in France or the UK or to a central interim storage facility at Gorleben for eventual direct disposal. Since 2005, as part of the Atomic Energy Law 2002 amendment, the only option has been interim storage of spent fuel at the reactor site where it has been produced and subsequent geological disposal. The only shipments have been to Gorleben of high level waste from reprocessing in the UK and France. A site for geological disposal of spent fuel and high level waste has not yet been determined. Exploration and research activities continue to focus on the Gorleben salt dome in Lower Saxony, but the site remains politically and socially controversial.

The nuclear phase-out law of 2002 and policy changes in 2010 and 2011

On 14 June 2000, under a federal coalition government of Social Democrats and the Green Party, Germany adopted a policy to phase out nuclear energy that came to be known as the "nuclear consensus." The primary rationales were the risks of reactor accidents and the problem of nuclear waste management. It was argued that the consensus decision would help calm the prolonged and severe social and political conflict over nuclear energy in Germany.

The "Nuclear Phase out Law" of 2002 amended Germany's Atomic Energy law to ban the construction of new nuclear power plants in Germany.[135] It also fixed a maximum production of electrical energy from each existing plant to approximately the amount that would be generated in a total operating time of 32 years.[136]

The federal elections of 2009, however, brought to power a coalition of Christian Democrats and Liberals that decided to delay the nuclear phase-out so that nuclear energy would be available as a bridge to a carbon-free, renewable-energy electricity supply. An amendment to the Atomic Energy Act was published in December 2010.[137] It extended the average operating times of the reactors by the equivalent of about 12 years.[138]

After the Fukushima Daiichi nuclear-power plant accident of March 2011, the German Government reversed itself and decided to shut down eight reactors immediately and the remaining nine between 2015 and 2022.[139] The amount of spent fuel that will be discharged will be similar to that expected under the original phase-out plan.

Figure 4.1 shows the locations of Germany's nuclear power plants, spent fuel interim storage facilities, nuclear research centers and sites of disposal projects.

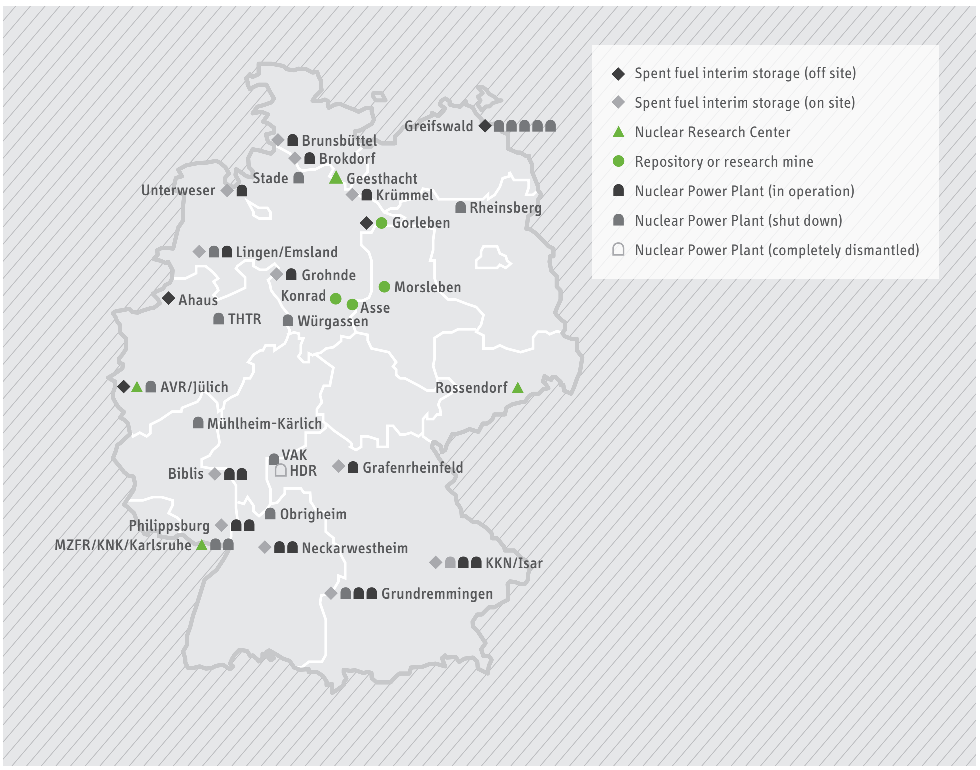

Figure 4.1: Locations of Germany's nuclear power plants, spent fuel interim storage facilities, nuclear research centers and sites of disposal projects. *Source: Öko-Institut.*

The quantities of spent fuel that would be discharged for average operating times of 32 years are shown in Figure 4.2.

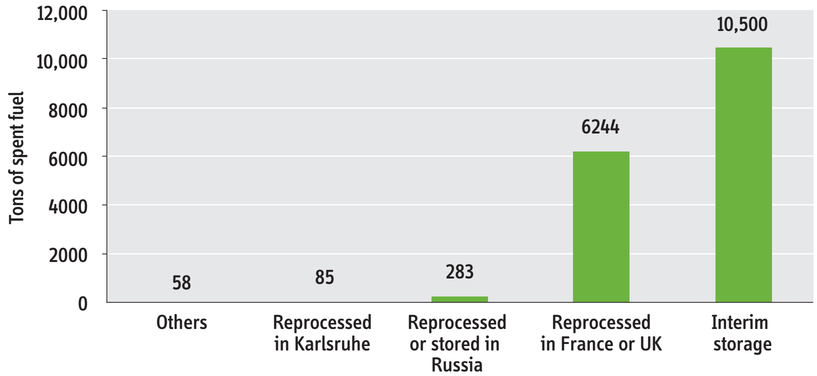

Figure 4.2: Disposition of German spent fuel by 2022 for phase-out shown by amounts of original heavy metal in the fuel. Interim storage is the only option open for spent fuel management today.

More than 75 percent of the spent fuel currently stored for direct disposal is at the reactor sites. The remainder, which is stored in centralized storage facilities, is mostly spent fuel from Soviet-designed East German nuclear power plants at Greifswald and Rheinsberg. This fuel is stored in the "Zwischenlager Nord" (ZLN, Northern Interim Storage) at Greifswald in Mecklenburg-West Pomerania.[140]

The management of spent fuel from research and prototype reactors with a total mass of 187 tons (heavy metal) is discussed below.

An additional 280,000 m^3 of radioactive waste of other types, generated by nuclear-power-plant decommissioning, operation, research, etc. is expected by the year 2080 (assuming an average nuclear power plant operating time of 32 years).

The rise and fall of reprocessing

Reprocessing was part of the plan for Germany's nuclear program from the very beginning. The French and the UK nuclear programs, where reprocessing was originally introduced to recover plutonium for weapons, no doubt influenced these developments. In the 1950s and 60s, Germany's powerful chemical industry was a driving force in the development of its reprocessing capabilities.

As in other countries with advanced nuclear programs, Germany's interest in reprocessing was driven by the idea of plutonium breeder reactors and a "closed fuel cycle" in which plutonium would be produced from uranium-238 and recycled as fuel. This vision was laid out in the 3rd German Atomic Program for nuclear activities for the period 1968-1972, which included the construction of a prototype fast-neutron breeder reactor and a pilot reprocessing plant in Karlsruhe.

The Karlsruhe pilot reprocessing plant (WAK) started operation in 1971. During its first years, it reprocessed spent fuel from research and pilot reactors. Later spent fuel from commercial nuclear power reactors was reprocessed as well. In parallel, Germany's nuclear utilities negotiated contracts with the French and UK reprocessing industries.

Starting in 1973, Germany's government began to require the nuclear utilities to prove that they had made provisions for spent-fuel management as a condition for the licensing of new nuclear power plants for construction and operation.[141] In 1974, in connection with its commitment to KNK I and KNK II breeder reactor projects in Karlsruhe, the government embraced "integrated waste management," with uranium and plutonium recycling presented as a solution both for waste management and for reliable nuclear fuel supply.[142] Thus, reprocessing became a central part of the German nuclear program and remained so despite the high costs of reprocessing which became evident in the following years.

The reprocessing of about 85 tons of spent power reactor fuel and about 104 tons of research and prototype reactor spent fuel was carried out at WAK between 1971 and 1990.[143] Sixty cubic meters of liquid high-level waste from these activities was vitrified between September 2009 and December 2010 as part of the decommissioning of WAK, resulting in 140 canisters of vitrified high-level waste. These canisters were shipped in five transport and storage casks to the ZLN at Greifswald in February 2011 for storage until a geological repository is available.

The total cost of the decommissioning and waste management from WAK, including waste disposal and other waste management activities is estimated at € 2.6 billion (US$ 3.5 billion). As of January 2008, € 2.2 billion (US$ 3.0 billion) had been spent on the decommissioning project.[144]

A first attempt to construct a commercial reprocessing plant in Germany failed in 1979. After intense public and political debate, plans for a so called "nuclear waste management center," including reprocessing, conditioning, storage and disposal facilities, in Lower Saxony were reduced to plans for a geological repository.

At the beginning of the 1980s, Bavaria offered to provide a site for a reprocessing plant. Construction at Wackersdorf started in 1987 but was halted in 1989 because of strong public resistance and economic reasons. Instead, Germany's nuclear utilities invested in France's reprocessing facility at La Hague. Until 2005, they sent about half of their spent fuel to France and the UK for reprocessing and placed the other half in domestic interim storage, mainly in wet or dry storage at reactor sites, for direct disposal.

The Nuclear Phase Out law of April 2002 terminated spent fuel shipments to reprocessing facilities abroad as of June 2005.[145] The safety risks and costs associated with such shipments were given as the main reasons.[146] The Environment Minister also pointed to the benefits of abandoning the plutonium economy and minimizing spent fuel and high-level waste transport.[147]

The plutonium that has been separated from reprocessed German spent fuel is being recycled in mixed oxide (MOX) fuel for use in Germany's nuclear power reactors. Germany's entire stock of separated plutonium is to be eliminated before the power reactors complete their previously planned operational times of 32 years.[148] As of the end of 2008, the utilities hoped to load the last MOX fuel into a reactor in 2016.[149] Should reprocessing of Germany's remaining spent fuel at the UK's THORP plant be further delayed due to technical problems, there still would be six years, according to the 2002 phase-out schedule, before Germany's last nuclear power plant is shut down.

Ten German pressurized water reactors (PWRs) and two boiling water reactors (BWRs) have been licensed to use MOX fuel. For the PWRs, the limits on the MOX fraction of the core range from 9 to 50 percent. The two BWRs at Gundremmingen (KRB B and C) are licensed to use up to 38 percent. Thus far, a maximum of 33 percent of MOX fuel has been used in a PWR and 24 percent in a BWR.[150]

Vitrified high-level reprocessing waste is returned to Germany in dual-purpose transport and storage casks and stored in the centralized interim storage facility at Gorleben (Table 4.1).

Number of casks	From La Hague	From Sellafield
Total	108	21
Returned by November 2010	97	0
Planned	1 shipment of 11 casks in 2011	Start of shipments after 2013

Table 4.1: Casks of high level waste to be returned to Germany from reprocessing abroad. *Source: Federal Office for Radiation Protection (BfS).*[151]

Management of spent fuel and HEU from research reactors

The first research reactor to go critical in Germany was the FRM reactor at Garching near Munich in 1957. The most recent, which began operating in 2004, is the FRM II reactor located at the same site.

Spent fuel from Germany's early prototype reactors (VAK, MZFR, KKN and KNK II, HDR) was reprocessed in Germany or abroad. Mixed uranium/plutonium oxide fuel was produced for the fast breeder prototype reactor SNR 300 but never used. This fuel was reprocessed in France and the plutonium is being used in light water reactor MOX fuel.

The fuel of the helium-cooled, graphite-moderated "pebble-bed" AVR and THTR reactors was highly-enriched uranium fuel and thorium in particles embedded in graphite balls 6 cm in diameter. The irradiated fuel is stored in transport and storage casks at the Research Center in Juelich and the interim storage facility at Ahaus.

Germany's other research reactors were fueled with low or highly enriched uranium. Low-enriched uranium fuel has been reprocessed in Germany and the recovered uranium blended and reused as light water reactor fuel. Highly enriched uranium (HEU) has been returned when possible to the country of origin for disposal.

Spent fuel of Russian origin of the former eastern German Rossendorf research reactor is currently stored at Ahaus. In 2010, a license for the return of this fuel to the Mayak reprocessing plant in Russia was requested in the context of the Global Threat Reduction Initiative, one of whose missions is to clean out global stocks of HEU spent fuel. Due to concerns about the environmental conditions at the Mayak plant, however, no license was granted by the German federal government.

For U.S.-origin HEU fuel from research reactors that have agreed to be converted from HEU to LEU fuel, U.S. law currently allows a return for HEU fuels irradiated by May 2016. Some German research reactors that have been converted will still be online after that. Also the FRM II reactor is currently being fueled with highly enriched uranium of Russian origin. No return of its spent HEU fuel to the United States is therefore possible. Current plans foresee the storing of wastes that are not returned to the country of origin at the interim storage facility in Ahaus followed by disposal in a geological repository.

Repositories: the Asse and Gorleben projects

The Asse facility was established in 1965 as a mine for research into waste disposal but became, in fact, a repository for low- and intermediate- level waste. The mine is now endangered by an inflow of brine and possible structural instabilities.

Over the past forty years, there have been major efforts in Germany to site a geological repository for the disposal of high-level waste and spent fuel. To date, however, no site has been officially selected.

The Asse repository for low- and intermediate-level waste. From 1967 to 1978, low- and intermediate-level waste in the Federal Republic was disposed of—nominally for research purposes—in the former Asse salt mine. In the former German Democratic Republic, another salt mine located at Morsleben was used for disposal of low- and intermediate-level waste. Its operation started in 1970 and was continued after German unification until 1998. Both projects have been stopped for safety reasons.[152]

In the Asse repository, 131 salt chambers at thirteen levels were dug through 1964. In the years 1965 till 1978 about 125,800 barrels of low- and intermediate- level waste with total radioactivity at time of emplacement of about 10^{16} Bq (270,000 Ci) were disposed in 13 chambers at 511 m, 725 m and 750 m depth. Due to poor documentation, uncertainties exist regarding the exact inventories.

Since 1988 an inflow of brine at a rate of about 12 cubic meters per day has been measured in the southern area of the mine. If this flow should increase, there would be dangers of flooding and of a collapse due to salt weakening and dissolution.

The main cause of this problem is that the Asse mine was excavated close to the outer boundary of the salt dome and not backfilled before it was converted into a repository. Being operated under the mining law, inadequate attention was paid to nuclear matters, and no assessments of long term radiological consequences were performed, although there were no plans for retrieval of the waste. Warnings from a regional NGO, which stressed the dangers of flooding and collapse, were ignored.[153]

Planning for the closure of the Asse repository started in 1997. The objective is to prevent the flooding and collapse of the mine and the release of radioactive substances to the biosphere. A group of regional representatives has been involved in the discussion of options for the closure since late 2007. In 2009, the status of the Asse mine was officially changed from a research project to a radioactive waste repository. It now has to be operated according to the atomic law. As a result appropriate attention is now paid to radiation protection. Furthermore the licensing procedure for the closure of the repository requires providing the inhabitants of the region opportunities to express their concerns.

An assessment of the feasibility of retrieving the waste packages in Asse began in 2010. In parallel, measures to increase the stability of the mine are being undertaken. Due to uncertainties regarding the condition of the waste packages and chambers, possible retrieval techniques and the time required, a final decision to start the retrieval of all the waste will not be taken before a three-phased feasibility study is completed. The first phase was licensed in spring 2011 after a one-year period of planning.

The Federal Ministry of the Environment which is responsible for the Asse budget announced recently that costs for waste retrieval and closure of the mine cannot be predicted until the plan for closure is finalized[154] Costs of € 2 to 4 billion (US$ 2.7 to 5.4 billion) have earlier been quoted in the media. The fees totaling about € 8.5 million that were paid by waste producers when the waste was delivered to the site do not come anywhere near covering these costs.[155]

The problems in the Asse repository have stirred up the public debate on the suitability of salt formations and of the concept of geological disposal in general. This has influenced the debate over high-level waste disposal in general and the Gorleben salt dome in particular.

The saga of Gorleben. German initiatives to locate a geological repository for spent fuel have focused on the Gorleben exploration mine in Lower Saxony adjacent to the Gorleben interim storage facility. Originally, in the 1970s, Gorleben was proposed as the location of a "national waste management centre" where reprocessing, waste conditioning, interim storage and disposal would all take place. Political considerations, such as its location near the border with East Germany, played a role in the selection of the site. When that plan proved to be politically infeasible, Gorleben became in 1977 a candidate site for a repository for all types of radioactive waste. Later, its purpose was narrowed further to the disposal of heat generating waste, i.e., mainly spent fuel and high-level reprocessing waste.

Because of this history, there was no official process by which alternative sites in Germany were ranked on the basis of their potential suitability for a radioactive waste repository.

Above-ground studies of the suitability of the Gorleben site started in 1979 and underground exploration began in 1986. Two vertical shafts in the center of the salt dome provide access to the exploration mine. The main horizontal tunnel is at a depth of 840 m.

There are plans to explore nine areas. By 2000, exploration of the area "EB 1" had been nearly completed and about € 1.5 billion (US$ 2.0 billion) had been spent.

The selection of Gorleben has been controversial since the very beginning. The nuclear consensus of October 2000 therefore included a moratorium on further exploration there. Instead, the Federal Office for Radiation Protection (BfS), which is responsible for nuclear waste disposal in Germany, started a research program with the intention of clarifying generic safety-related issues that are independent of specific sites. BfS published the results of this research program in November 2005.[156] A key conclusion was that:

> "There is no host rock that will always guarantee the highest level of repository safety. … Different options can only be compared if the comparison is made between specific sites and repository concepts. This leads to the conclusion that a comparison of sites is necessary."

The new federal government elected in 2009 decided to end the Gorleben moratorium. The Christian Democratic minister of the environment announced the decision to

- Restart exploration activities, and
- Perform a preliminary safety assessment on the basis of existing data within 2 years.[157]

The selection of the areas of the Gorleben salt dome that are to be explored is being influenced by private salt mining rights. The Atomic Energy Act of 2010 allows for the possibility of compulsory government purchase of such rights, but there has been as yet no indication that the Government will make use of this right within the next several years. Exploration activities are being performed under the German mining law until the decision to construct a repository has been taken. The use of the mining law in this way has been criticized by some groups as a way to avoid the formal public involvement that would be required under the atomic law.

In contrast to other countries, where political setbacks in the siting process led to revised procedures and a re-start, the lack of political consensus in Germany has thus far prevented the establishment of a site-selection process based on broadly-accepted standards. The 2010 extension of the operational times of Germany's nuclear power plants made such a consensus more difficult by increasing the political and societal tensions relating to nuclear power. The June 2011 decision to return to a rapid phase-out may have created the conditions for a site-selection process to go forward. Several state premiers announced their support of a countrywide site selection process.[158]

Designing a siting process

In 1999, prior to the passage of the Nuclear Phase-out Law, the Federal Minister of the Environment, who belonged to the Green Party, constituted a "Committee on a Site Selection Procedure for Repository Sites" (AkEnd) charged with developing a new framework for a siting procedure that would be transparent and impartial.[159] AkEnd worked from February 1999 to December 2002. Its basic recommendation was a criteria-based approach that would take into account long-term safety, regional development interests and the willingness of the regional population to participate in the process.

AkEnd also recommended that the site selection procedure should include public and independent expert involvement at both the national and potential host region levels.[160] The AkEnd process ended in 2003, however, with the failure to establish a negotiation group representing the Federal and State (Länder) governments, industry and stakeholder groups to carry out the next phase of specifying the site-selection process.[161] There was no single reason for this failure but the following considerations may have contributed:

- For the states (Länder), it is not very appealing to host a potential disposal site. Their preparedness to open up a selection process on the basis of a "blank map", as recommended by the AkEnd, was therefore not very high;

- For the nuclear industry, the expected cost of a broad site selection process may have been an important consideration;

- The Federal ministries may also have been reluctant to join in negotiations that were completely open but whose conclusions would be binding on them.

In November 2008, the Federal Ministry for the Environment, Nature Protection, and Nuclear Safety (BMU) organized a stakeholder symposium on nuclear waste disposal that brought together a broad range of stakeholders as a first but very small and fragile step towards further dialogue.

A Disposal Dialogue Forum (FED) was established as an inter- and intra-disciplinary group of members of the planning team for the 2008 stakeholder symposium. This forum has held regular meetings for about 2 years. Two members of the FED, both representatives of the Gorleben region, ended their participation, however, in protest over the extension of the nuclear power plant operational times, the restart of the exploration of the Gorleben salt dome on the basis of mining law instead of the atomic law,[162] and the continuation of shipments of high-level waste from La Hague to the Gorleben interim storage facility. As a result, the FED's future is unclear.

At the beginning of 2011 the "Gorleben Dialogue" was started by the BMU[163] In a first stage, an online survey was performed that offered a public opportunity to express expectations and provide recommendations regarding topics and measures for public participation during exploration activities and preliminary safety assessments. Subsequently a proposal for the organizational structure was published by the BMU.[164] The central forum is the so called Confidence Committee that is empowered to co-decide on: relevant questions for the safety assessment, the necessity of additional exploration measures, independent assessments and research, organization and topics of peer review, and on public relations. Half of the seats in this committee will be filled by representatives of the Gorleben region.

An Information Forum and an Expert Committee will support the process by providing information to the public and scientific support to the Confidence Committee respectively. Half of the members of the Information Forum are to be regional representatives and half of the members of the Expert Committee can be named by the region. A national Expert Committee is to be established to provide scientific support on all questions of disposal unrelated to the Gorleben project.

The success of this process will depend on the extent to which it can accommodate strong and well organized citizens' initiatives and the degree to which openness of outcomes of the preliminary safety assessment is assured and made transparent to stakeholders and the public.

Conclusion

Although the long history of the geological repository siting debate at Gorleben is complex, some general lessons can be extracted:

1. Successful implementation of a sustainable siting procedure, including broad acceptance of safety criteria takes much longer than the four-year interval between elections and, as a result, becomes liable to political reversals;

2. Implementation of a siting procedure is more complex in a federal system such as Germany's because many powers reside with the states (Länder) and the election cycles at the two levels are out of phase.

3. The siting process is further complicated if there is simultaneously a debate over new nuclear-generating capacity or over the question of extending the operating times of existing nuclear power plants.

4. Transparency of assessment and exploration activities and of decision-making processes is essential if a site selection process is to be politically sustainable. This becomes more difficult if, as was the case in Germany, such transparency is not designed in from the very beginning of the process.

Beate Kallenbach-Herbert
with contributions by Anne Minhans and Christoph Pistner

5 Japan

Japan's spent fuel management policy is to reprocess. At first, this was done by shipping spent fuel to reprocessing plants in France and the United Kingdom, with the high-level wastes and separated plutonium returning to Japan. Japan also built a domestic pilot reprocessing plant at Tokai-mura, and then a large commercial reprocessing plant at Rokkasho-mura that is currently expected to start commercial operation in 2012.

The original, and still-stated, ultimate purpose of reprocessing in Japan is to produce plutonium for fast-neutron plutonium breeder reactors. However, the Japan Atomic Energy Commission's latest long-term plan called "Framework for Nuclear Energy Policy" (hereafter referred to as the Framework), adopted by the Cabinet in 2005 projects that fast breeder reactor commercialization will not occur until around 2050.[165]

The plan now is to dispose of a large portion of Japan's already separated plutonium, and the additional plutonium to be separated at the Rokkasho reprocessing plant, by mixing it with depleted uranium to make MOX fuel for light water reactors. This plan too has experienced a series of delays. Nevertheless, plans for full-scale reprocessing at Rokkasho are going forward. The major reason appears to be the need to find a destination for spent fuel accumulating in nuclear power plant cooling pools. The pools are becoming full and utilities would like to send this spent fuel to Rokkasho but the Rokkasho storage pool is now also full. Spent fuel could also be sent to offsite interim storage facilities, and one such facility is under construction. The vitrified high-level reprocessing waste is to be stored at the High-Level Radioactive Waste Storage Center at Rokkasho pending the availability of a 300-meter-deep geological disposal site. The goal is for the repository to begin accepting high-level wastes in the late 2030s, but so far no repository site has been identified despite the offer of financial incentives to encourage applications from local communities.

Whether and how the disaster at Tokyo Electric Power Company's Fukushima Daiichi nuclear power plant triggered by the earthquake and tsunami of 11 March 2011 will affect Japan's spent fuel policy remains to be seen.

Nuclear power in Japan

In June 2010, Japan's Cabinet approved the Basic (Strategic) Energy Plan put forward by the Ministry of Economy, Trade and Industry (METI) to add at least 14 commercial nuclear power reactors to the existing 54 (48.8 GWe) by 2030 (see Figure 5.1). The plan envisioned that Japan would have at least 67 power reactors (68.1 GWe) in 2030.[166] This ambitious plan was criticized as unrealistic before the 11 March 2011 earthquake. Following the disaster, Tokyo Electric Power Company (TEPCO) decided to decommission

Fukushima Daiichi's Units 1-4 and cancel plans for Units 7 and 8 and Prime Minister Kan stated that "it is necessary to go back to the drawing board in reviewing the Basic Energy Plan."[167]

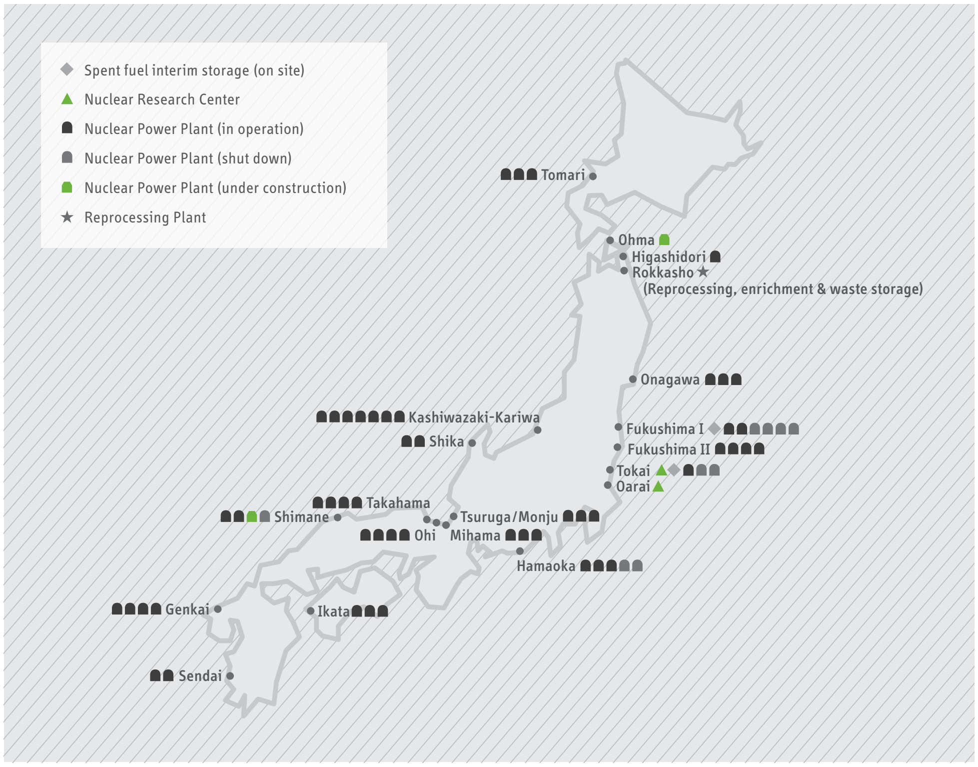

Figure 5.1: Locations of Japan's nuclear power plants, research centers, spent fuel storage facilities, and reprocessing plants.

The earthquake and tsunami have had a devastating impact on the operation of Japan's nuclear power plants. As of 7 May 2011, 33 of Japan's 54 reactors were out of operation—14 due to the March 2011 earthquake and tsunami and the others due to seismic upgrades required following the 2007 earthquake, other safety issues, and previously planned inspections.[168] Subsequently, in response to Prime Minister Kan's request, Chubu Electric Power Company shut down Hamaoka Units 4 and 5 for earthquake and tsunami-related upgrades.[169] Ten more power reactors were scheduled to go into periodic inspection by the end of 2011.[170] Governors of different prefectures have said they will not allow power reactors that are out of operation to restart until clear guidance on revised safety requirements is provided by the central government.

Rokkasho Reprocessing Plant

The Rokkasho Reprocessing Plant has a design capacity to process fuel containing 800 tons of uranium per year. In March 2006, its operator, Japan Nuclear Fuel Ltd (JNFL), started active testing using actual spent fuel. The melting furnace for immobilizing high level radioactive reprocessing waste in glass experienced a series of problems, however, including flow blockage due to plate-out of platinum group fission products, damage to the brick-covered ceiling of the furnace, and problems in recovering a piece of brick that fell into one of the two furnaces. In September 2010, JNFL changed the scheduled date of completion of the Rokkasho reprocessing plant from October 2010 to October 2012. This was the eighteenth postponement of the schedule. The construction of the plant started in 1993 with start-up scheduled for 1997. The plant is therefore 15 years behind schedule at this point.[171]

Program to use MOX fuel

In 1997, Japan's Federation of Electric Power Companies (FEPC) and the government announced plans for using MOX fuel in 16 to 18 light water reactors (LWRs) by 2010.[172] On 12 June 2009, FEPC pushed back this goal to 2015.[173]

As of March 2011, MOX fuel produced in France from Japanese plutonium separated at France's La Hague Reprocessing Plant had been loaded in four reactors.[174] One of these reactors, Fukushima Daiichi Unit 3, was damaged by the 11 March 2011 accident, however, and will be decommissioned. Two others, Genkai Unit 3 and Ikata Unit 3, are under periodic inspection and it is not known when they will be restarted. Chubu Electric Power Company's Hamaoka Unit 4, a candidate for MOX use, will not be put back to operation for at least two years. The construction of the Ohma Advanced Boiling Water Reactor (ABWR) in Aomori Prefecture, which is designed to take a full core of MOX fuel and was planned to start operation in 2014, was halted after the earthquake. A recent poll found that only 25% of the residents in the prefecture supported continuation of the construction of Ohma and TEPCO's Higashidori Unit 1, the only other nuclear power reactor under construction in the Prefecture. Forty eight percent of those polled were in favor of cancelling both reactors.[175]

In October 2010, JNFL started construction of the MOX Fuel Fabrication Plant at the Rokkasho complex to use the plutonium that is to be separated there. The plant has a design capacity to produce annually MOX fuel containing 130 tons of heavy metal (uranium and plutonium) and is intended to accommodate all of the plutonium separated at the Rokkasho Reprocessing Plant. Originally the MOX fuel fabrication plant was supposed to start operation in 2012. Before the Fukushima accident, it was scheduled to start operation in March 2016.

It has not been decided what to do with Japan's spent MOX fuel. The JAEC's 2005 "Framework" stated that "[s]tudy on the measures to be taken for spent fuel stored at interim storage facilities and spent MOX fuel from LWRs will start around 2010." Although METI officials admit that this means nothing has been decided about a second commercial reprocessing plant, METI and other reprocessing proponents often act as if it is a foregone conclusion that a second plant will be constructed.[176]

Disposition of high level radioactive wastes

A total of 1,310 canisters (weighing about 500 kg each) of vitrified high-level waste (HLW) generated by reprocessing Japan's spent fuel were returned to Japan from France between 1995 and 2007. A first shipment of 28 canisters from the UK arrived in March 2010. The plan is for a total of about 830 canisters to be sent from the UK during the current decade.[177]

Canisters of vitrified high-level waste will also be produced at Rokkasho. The plan is to store the HLW canisters at the High-Level Radioactive Waste Storage Center at Rokkasho pending the availability of a geological disposal site.

The search for a repository site was initiated in Japan's 2000 Radioactive Waste Final Disposal Act. The Act established the Nuclear Waste Management Organization (NUMO). In December 2002, NUMO started to solicit applications from local communities to host a geological repository for vitrified high-level waste that would be at least 300 meters underground. The plan is to select a site by the late 2020s. The selection process is to go through three stages:

1. Literature survey: review of available information on the geology and other information relevant to the suitability of the site (about 2 years),

2. Preliminary investigation: borehole survey, geophysical prospecting, etc. (about 4 years), and

3. Detailed investigation: for selection of a repository site (about 15 years).

The facility would open to accept high-level wastes in the late 2030s.[178]

Due to a lack of response from municipalities, the amount of the money offered to incentivize applications for the literature-survey stage was raised in 2007 to a maximum of ¥2 billion ($25 million). Up to ¥7 billion ($90 million) would be provided during the preliminary investigation stage.

In January 2007, the mayor of Toyo-cho in Kochi Prefecture made the first and, as of this writing, only application — but without consulting his town council. This resulted in his forced resignation and a special election in April 2007 that resulted in the victory of a candidate opposed to the application. The application was withdrawn.

After this fiasco, the siting policy was changed to allow the government to actively solicit targeted municipalities to apply for a literature survey.

In March 2007 Minamiosumi-cho town in Kagoshima Prefecture invited NUMO to explain the program. Due to the opposition from the governor, however, the mayor gave up the idea of applying for a literature investigation. In December 2009, a group within the town was reported to be again considering an invitation but the governor expressed his opposition again and the mayor said he had not made any decision yet.[179]

Storage of spent fuel

Spent fuel pools at reactor sites. According to the nuclear utilities, 900 to 1000 tHM per year of spent fuel were discharged annually by Japan's reactors in the years before the post-Fukushima shutdowns.[180] The amount discharged between 1 October 2008 and 30 September 2009, however, was 859 tons.[181]

As of the end of March 2010, the total amount of spent nuclear fuel stored at Japan's nuclear power plants was 13,150 tons. This includes about 200 tons of spent fuel stored in dry casks at Fukushima Daiichi 1 and Tokai Daini 2. The total spent fuel "management capacity" was 20,410 tons.[182] "Management capacity" or effective storage capacity is defined as the capacity that would leave sufficient empty storage space in the pool to allow unloading of the full reactor core during an inspection of the interior of the pressure vessel plus sufficient empty space to hold one "reload" of fresh fuel at refueling time (one quarter to one third of the full core depending on the reactor type).[183] In the case of dry cask storage facilities, the capacity of the actual dry casks that have been placed in the building, not the amount permitted to be brought into the building, are included when calculating the management capacity. On-site "management capacity" at Japan's nuclear power plants grew over the last decade due to construction of new reactors, re-racking and expansion of the pool volume at existing reactors, and some dry cask storage (see Figure 5.2).

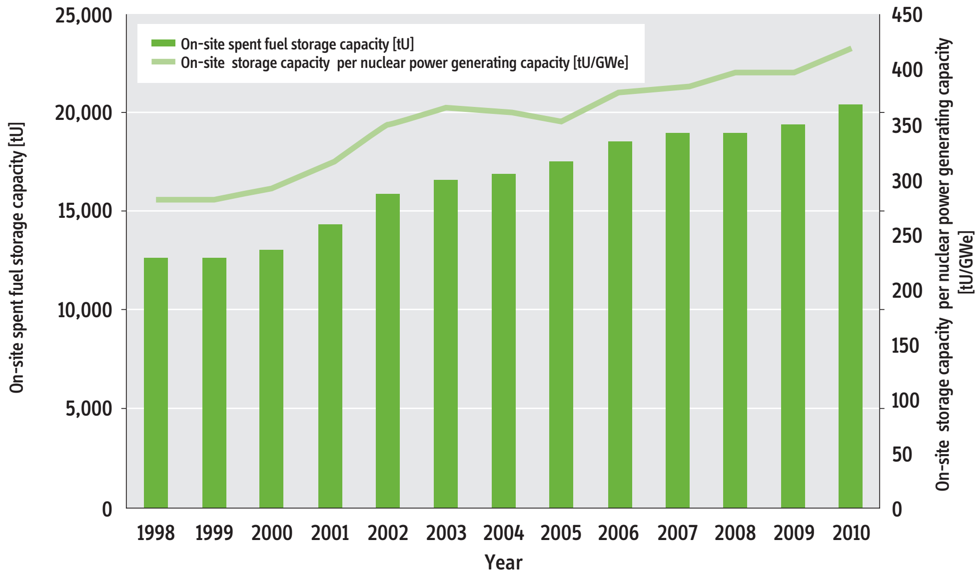

Figure 5.2: Spent fuel storage capacity ("management capacity") at Japan's reactor sites over time. As of March 2010, there were 13,150 tons of spent fuel at the reactor sites.

This growth in storage capacity is not enough, however, for continued operation of reactors. Given an annual discharge of 900 to 1000 tHM, the current collective capacity at the reactor sites would be reached in about 7 to 8 years, and sooner at some sites, if additional storage capacity did not become available. The post Fukushima Daiichi accident situation will probably extend this period with many reactors shut down for long periods.[184] The principal options for dealing with the capacity problem after the spent fuel pools have been re-racked to their maximum capacity are:

1. Send the spent fuel to Rokkasho;

2. Send it to offsite interim storage facilities, and/or

3. Build new storage capacity on site, most likely utilizing dry casks.

In the past, the reprocessing plants in the United Kingdom and France functioned effectively as virtual interim storage facilities for Japan, but this "storage method" is not available anymore—at least for now.[185]Also, the Tokai reprocessing plant stopped accepting spent fuel after it completed its operations in 2006.

Spent fuel storage at Rokkasho. The Rokkasho reprocessing plant has a storage pool with a capacity of 3,000 tHM but this pool is almost full. As of the end of February 2011, the plant had received a total of 3,352 tons HM,[186] of which 425 tHM was reprocessed during hot testing.[187] Until the plant starts to operate, it cannot accept much more spent fuel.

Off-site interim dry cask storage. The Long-Term Plan of 1987 pointed to the need for interim storage capacity and, in 1997, Japan's government made a decision to build off-site interim storage capacity by 2010. In 1998 a preliminary report on interim storage of the nuclear power working group of an advisory committee on energy noted that: "since the Rokkasho reprocessing plant under construction now has an annual capacity of [only] 800 tons, the amount of spent fuel to be stored will continue to increase in the long run" and therefore, in addition to the conventional method of storing spent fuel in the pools at the reactor sites, "it is necessary to have available facilities with the aim of storing spent fuel outside nuclear power plants by 2010."[188] An amendment to the Nuclear Reactor Regulation Law in 1999 established a system whereby companies can be licensed to operate such off-site facilities. According to the law, "interim storage" means "off-site (away-from-reactor) storage." On-site dry cask interim storage was and is possible without a change in the law.[189]

In 2005, TEPCO and its junior partner, Japan Atomic Power Company (JAPC) established the Recyclable Fuel Storage Company (RFS) in Mutsu city, next to Rokkashomura village to store a total of 5,000 tons of spent fuel in two buildings.[190] The combined capacity will be shared by the two utilities in accordance with the ratio of their shares in the company: 4,000 tons for TEPCO, and 1,000 tons for JAPC.[191]

The construction of the first building with a capacity of 3,000 tons (288 casks) began in August 2010 to start operation in July 2012. About 200 to 300 tons of spent fuel per year is to be transported to the facility in about four shipments. The period of use of each building is not to exceed 50 years and the storage period of spent fuel in each cask is not to exceed 50 years. Consultation with local communities is to begin no later than 40 years after the start-up of the operation concerning transportation of stored spent fuel out of the facility.

According to a calculation by the Central Research Institute of Electric Power Industry (CRIEPI), the cost of the transportation/storage cask system is about 60 percent less than that of pool storage, and this will result in more than ¥100 billion ($1.25 billion) cost reduction for storing 3,000 tons of spent fuel for 50 years.[192] RFS says that the cost for the metal casks accounts for 70–80% of the total construction cost of ¥100 billion (about $400 per kilogram of spent fuel).[193]

The spent fuel to be stored at the interim facility is supposed to be reprocessed later at a second reprocessing plant to follow the Rokkasho reprocessing plant. That is why the name of the company operating the facility is the Recyclable-Fuel Storage Company (RFS). The 2005 Framework states that, "intermediate storage of spent fuel makes temporal coordination possible until it is reprocessed, and it is therefore important as a means for contributing to the flexible operation of the overall nuclear fuel cycle. … Spent fuel will be reprocessed within the available reprocessing capacity of the time, and volume exceeding the capacity will be placed in interim storage."

The idea of long-term interim storage in Japan does not automatically mean a change of its rigid reprocessing policy. Indeed, the understandings around the Recyclable Fuel Storage Company ratchets up the pressure on Japan's nuclear utilities to operate the Rokkasho reprocessing plant and to build a second commercial plant. Right before signing the agreement on the Mutsu interim storage facility on October 19, 2005, Aomori Prefecture Governor Shingo Mitamura stated that one of his reasons for giving consent to RFS was the assurance given him by the responsible ministries that a second reprocessing plant would be built. He noted that, "It is vitally important that the reprocessing of all the spent fuel is the premise for the interim storage program. The spent fuel should not be kept in Mutsu city forever."[194]

In addition to TEPCO, other utilities also are expected to develop off-site storage facilities but none have any concrete plans yet. In the case of Kansai Electric Power Company (KEPCO), which has 11 reactors in Fukui Prefecture, there has been talk in a few communities in the prefecture about hosting an interim storage facility but no proposal has materialized. A special committee established by the city council of Gobo in Wakayama Prefecture asked KEPCO in December 2009 to examine the possibly of building an interim storage facility in the city. KEPCO responded positively in February 2010 saying that "siting is possible according to a literature survey" but avoided giving a definite answer.[195]

Dry cask storage at reactor sites. As already noted, small amounts of onsite dry cask storage capacity exist at two power plants: Tokyo Electric Power Company's Fukushima Daiichi and Japan Atomic Power Company's Tokai Daini.[196] Fukushima Daiichi has a permit to install 20 casks containing about 150 tons of spent fuel and has installed 9 casks containing 408 assemblies in all.[197] Tokai Daini has a permit to install 24 casks (about 250 tons of heavy metal), each holding 61 assemblies, and has installed 17, two of which were empty as of the end of 2010.[198]

Dry cask storage was introduced in 1995 at Fukushima Daichi (Figure 5.3). Since the building, with interior supporting structure, already existed for storing transportation casks, Fukushima Prefecture didn't consider it necessary for TEPCO to request the Prefecture's consent. At Tokai Daini, an onsite dry storage facility was built in 2001 to increase the spent fuel storage capacity (Figure 5.3).

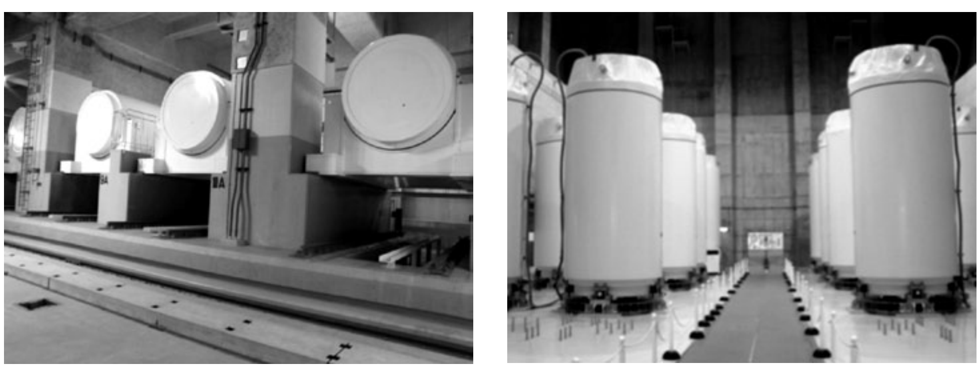

Figure 5.3: Dry metal cask storage facility at the Fukushima Daiichi nuclear power plant (left) and at the Tokai Daini nuclear power plant (right). The tubes are to monitor the casks for possible leaks. *Source: Japan Atomic Power Company.*

Following a 1992 suggestion from the Nuclear Safety Commission, TEPCO and JAPC both have conducted periodic inspections of sample storage casks and the spent fuel stored within them (in 2000 and 2005 at Fukushima Daiichi and 2009 at Tokai Daini) to provide assurance of integrity of both the fuel and the cask.[199] The Idaho National Laboratory is the only other place where such monitoring of spent fuel in metallic dry cask storage is being conducted.

In December 2008, the Chubu Electric Power Company announced a plan to build a 700-ton dry storage facility at its Hamaoka nuclear power plant around 2016. This plan was made as part of a package to terminate operation of Units 1 and 2 due to seismic design problems and build Unit 6 as a replacement. The company stated that "based on necessity to remove spent fuel from the fuel pools in Reactors Nos. 1 and 2, which are to be shutdown, Chubu Electric has adopted a plan to build a new dry storage facility inside the power station site for spent fuel from all Hamaoka reactors."[200] The plan for the new reactor itself, however, is in question now due to the Fukushima Daiichi situation and heated disputes about seismic risks near (or under) the Hamaoka site, which, as already mentioned, halted operation of all the remaining reactors on the site (Hamaoka 3-5) in May.

Dry cask interim storage vs. reprocessing

Additional interim spent-fuel storage capacity, either on or off the reactor sites, could provide an alternative to operating the Rokkasho Reprocessing Plant. The Council that wrote the 2005 Framework considered the possibility of direct disposal of spent fuel without reprocessing but argued against it with the following logic:

> "If we make a policy change from reprocessing to direct disposal, it is indispensable for the continuation of nuclear power generation to have communities that up until now have accepted selection as a site for nuclear facility, based on the assumption that spent fuel would be reprocessed, to understand the new policy of direct disposal and accept the temporary storage of spent fuel at the site."

The 2005 Council went on to say that:

> "It is clear, however, that it takes time to do so, as it is necessary to rebuild relationships of trust with the community after informing them of the policy change. It is likely that the nuclear power plants that are currently in operation will be forced to suspend operations, one after another, during this period due to the delay of the removal of spent fuel."

It therefore decided to reaffirm the reprocessing policy. In effect, those institutions that promoted the plutonium breeder reactors as just around the corner, are now saying that because it might be difficult for people to adjust to the disappearance of a rationale for reprocessing, we have to keep doing it.

A new Framework for nuclear energy is now under discussion to succeed that of 2005. At its first meeting on 21 December 2010, six out of 26 members of the new Council mentioned the need to work on interim storage both on and off site. None of them advocated postponing or stopping operation of the Rokkasho plant because they are supportive of reprocessing in general, but those few members that have been critical of reprocessing might call for dry cask storage as an alternative to reprocessing later in the process. The atmosphere may be different when they meet the next time after a pause since March 11.

After the Fukushima Daiichi accident, there will be more scrutiny about the financial aspect of reprocessing. There are people, including Taro Kono, perhaps the only anti-nuclear-power Diet member from the Liberal Democratic Party, which was almost continuously in power since its founding in 1955 until 2009 and supported reprocessing, who suggest that the 2.4 trillion yen ($30 billion) deposited by utilities into the fund managed by the Radioactive Waste Management and Funding and Research Center (RWMC) for reprocessing costs at Rokkasho should be used for compensation payments for the damages caused by the Fukushima Daiichi events. They argue at least that TEPCO's share, which is about 40 percent, should be used for such a purpose.[201]

Japan's debate over the separation of utility power generation and transmission/distribution operations might also affect the reprocessing policy. At present, the nine regional electric power companies operating nuclear reactors also have a monopoly over transmission/distribution.[202] At his 18 May 2011 press conference, Prime Minister Kan committed that a debate on separating generation from transmission would be carried out as part of the review of the Basic Energy Plan.[203] Separation of transmission/distribution would foster competition between different types of generation. In this context, the nuclear utilities probably would not want to pay for the extra cost of reprocessing and might try to change the government policy of requiring reprocessing.

Restarting Japan's prototype plutonium breeder reactor, Monju, scheduled for March 2014, also has become politically as well as technically more difficult after the Fukushima Daiichi accident. Commenting on Monju at a press conference after a Cabinet meeting on July 15, Yoshiaki Takaki, Minister of Education, Culture, Sports, Science, and Technology (MEXT), responsible for the Monju project, stated that "the direction will be formed through the process reviewing the nuclear policy/energy policy." Asked whether both continuation and cancelling will be considered as a possible direction, he replied affirmatively.[204]

As a prelude to this, the White Paper on Science and Technology 2011 of MEXT approved by the Cabinet on July 12 did not reaffirm the statement in the 2010 White Paper that: "The realization of the demonstration facility around 2025 and the commercialization of FBR before 2050 is aimed at." Furthermore, on 13 July 2011, in a televised statement to the nation, Prime Minister Naoto Kan had announced the goal to "phase out the dependence on nuclear power plants and achieve a society that can work without nuclear power plants."[205] These facts give more weight to a view that the government might discontinue the Monju project.

Faced with questions from ministers in the informal session after the abovementioned Cabinet meeting, however, Kan admitted that the nuclear power phase-out idea was his own personal view and not the policy of the Cabinet. And later on the same day, after media reports on Takaki's suggestion of the possibility of cancellation of Monju caused turmoil, the MEXT and Takaki himself denied that he mentioned cancellation at all.

Regardless of the intention of Takaki, however, the whole episode has certainly drawn attention to the possibility of cancellation of Monju. The rationale for reprocessing will likely be questioned more sharply. The logical conclusion would be to suspend the plans for operation of the Rokkasho reprocessing plant and to abandon plans for building a second reprocessing plant. It remains to be seen, however, whether logic will prevail.

Finally, the crisis over the spent fuel pools at Fukushima Daiichi dramatized the need to tackle the task of storing spent fuel more safely. The task remains regardless of the direction of the nuclear-phase-out discussion. Although internal sources say the structural building of the dry cask storage facility at the site was damaged, there have been no reports of any safety concerns with regard to the spent fuel stored in the dry casks. This might lead to more interest in dry cask storage. The trauma from the Fukushima Daiichi accident might, however, lead to opposition to building any new interim storage facilities—either at nuclear power plant sites or off-site. Even if only a small number or nuclear reactors are allowed to operate, continued operation will still result in intensification of the pool storage capacity problem. It would be ironic if the Fukushima events simply reinforced the status quo: a continuation of Japan's reprocessing policy.

Tadahiro Katsuta and Masafumi Takubo

6 South Korea

South Korea's first power reactor at Kori started generating electricity in 1978. As of January 2011, there were in operation 21 power reactors with a total capacity of 18.7 GWe, 8.6 GWe under construction, and additional capacity planned that would bring South Korea's total nuclear generating capacity up to 42.7 GWe by 2030.[206] All of these reactors are pressurized water reactors except for four CANDU heavy water reactors with a combined capacity of 2.8 GWe at the Wolsong nuclear power plant (Figure 6.1).

Despite this thirty-year history of nuclear power expansion, however, South Korea has as yet no concrete plans for spent fuel disposal. Attempts have been made to establish an off-site central spent fuel interim storage site but they have failed due to public opposition. In 2005, the government did succeed in siting a national low and intermediate radioactive waste disposal site by adopting a consultative approach and providing financial incentives to local governments. A public consensus-building process on spent fuel management, including issues of interim storage and final disposal, was planned in 2009 but has been suspended.

Figure 6.1: Locations of South Korea's nuclear power plants, research centers, and spent fuel and waste storage facilities.

The reprocessing controversy

As in other countries with nuclear power plants, South Korea's public has concerns about radioactive waste. As the reactor storage pools fill up, spent fuel management has become a hot political issue. South Korea's nuclear utility, Korea Hydro and Nuclear Power (KHNP), says it is facing a crisis with regard to on-site storage during the next ten years at all of its four nuclear power plant sites.[207] It claims that the storage pools at the Kori, Ulchin and Yonggwang sites, which have pressurized water reactors (PWRs), will fill up in 2016, 2018, and 2021 respectively, and both the spent fuel pools and the dry storage facilities associated with the heavy water reactors (HWRs) at the Wolsong site will be full in 2017.[208]

The Korea Atomic Energy Research Institute (KAERI) has used this alleged crisis as an argument for reprocessing—specifically pyroprocessing—South Korea's PWR fuel and recycling the recovered plutonium and other transuranic elements in fast-neutron reactors.[209] The argument has developed a nationalistic dimension because, in the 1988 U.S.-Japan Agreement of Nuclear Cooperation, the U.S. gave advance consent to Japan's reprocessing of spent fuel.[210] The politically inflammatory question is: why should South Korea not have the same rights as Japan?

The U.S. Government's response is that, if South Korea were to launch a reprocessing program, it would make much it more difficult to persuade North Korea to give up its reprocessing and enrichment programs. A more general concern is that the proliferation of national reprocessing plants would destabilize the nonproliferation regime because they would put an increasing number of countries within weeks of acquiring nuclear weapons once they decided to do so. At the moment, Japan is the only non-weapon state that reprocesses.

Pyroprocessing and fast-neutron reactors could not be deployed on a large scale rapidly enough to cap South Korea's spent fuel storage problem in the next few decades. KAERI argues, however, that the expectation that the spent fuel would be recycled could make it politically possible to build a central spent-fuel storage facility near the site where the pyroprocessing plant would be built.[211] This is, in fact, what happened in Japan. Although no prefecture has been willing to host a stand-alone central spent-fuel storage facility, a large interim spent-fuel storage facility is being built at Mutsu in Aomori Prefecture near the Rokkasho Reprocessing Plant.[212] KAERI also argues that reprocessing and fissioning of the recovered transuranic elements could reduce the area needed for a geological repository. This argument is discussed later.

On-site storage

In fact, the on-site storage crisis is not as imminent as KHNP has suggested. As has been noted by the Korea Radioactive Waste Management Corporation (KRMC), which was established in 2009 by South Korea's Radioactive Waste Management Act to manage the country's spent fuel and radioactive waste problems, the capacities of some of South Korea's PWR spent-fuel pools could be increased by installation of higher-density racks.[213] The KRMC also notes that, at two of the PWR sites (Kori and Ulchin), new reactors are being built with empty pools that could accommodate spent fuel from the older operating reactors. This could delay the spent-fuel storage crisis at these two sites for an additional decade or so. No new reactors are planned at the third PWR site (Yonggwang), however. The obvious way to expand on-site storage there—and at the Kori and Ulchin sites a decade later—would be to build dry storage for older cooler spent fuel, as is being done in the United States.

As of the end of 2008, about 4,870 tons (heavy metal) of PWR spent fuel was stored at South Korea's 3 PWR sites, including 1,768 tons at Kori, 1,732 tons at Yonggwang and 1,366 tons at Ulchin. At the Wolsong nuclear power plant, 6,082 tons of CANDU spent fuel was in storage—more than the combined discharges of the 16 PWRs at the other three sites (see Appendix).[214] This reflects the fact that natural-uranium-fueled HWRs discharge about seven times as much spent fuel per GWe-year as PWRs.

An additional 300 tons of PWR spent fuel and 380 tons of HWR spent fuel are discharged annually. Assuming 60-year lifetimes for the PWRs and 50-year lifetimes for the HWRs, approximately 51,000 tons of spent PWR fuel and 20,000 tons of spent HWR fuel will be generated over the entire lifetimes of the 35 PWRs and 4 HWRs units that are expected to be deployed by 2030.[215]

Dry storage has already been built at the HWR site, Wolsong, and more is being built there. Some argue that this is illegal because the national low- and intermediate-level waste (LILW) repository is adjacent to the Wolsong nuclear power plant and, according to the 2005 Special Act on Support for Areas Hosting Low and Intermediate Level Radioactive Waste (LILW) Disposal Facility, the same community cannot be required to host both the national LILW repository and interim spent fuel storage facilities. The KRMC argues, however, that the on-site dry storage facilities at Wolsong are "temporary," not the "interim" storage that is banned by the special Act. KHNP has expanded the dry storage capacity at Wolsong twice since the 2005 Act: by 1,080 tons in 2006 and 3,360 tons in 2010 (Figure 6.2).[216] Because of the rate at which HWRs discharge spent fuel, however, this dry storage will be full in 2017. Another 10,000 tons of dry storage will have to be constructed for the HWRs by 2040.

A PWR discharges about 20 tons of spent fuel per GWe-year. For Kori (3.1 GWe), Yonggwang (5.9 GWe) and Ulchin (3.9 GWe) the equivalent at each site of the 7,000 tons of dry storage that already has been installed at Wolsong would be enough for 110, 60 and 90 years of discharges respectively.

Politically, it is hard to believe that local communities would be implacably opposed to allowing the construction of dry on-site storage. They have an economic stake in the continued operation of the nuclear power plants that they host. In addition to the employment provided by the plants, the 1989 Act for Supporting the Communities Surrounding Power Plants provides host communities the equivalent of a few tens of millions of US dollars per year per site. If a host community forced the shutdown of a nuclear power plant reactor by blocking the construction of dry storage, this flow of funding might end. The government or utility could add an additional incentive for accepting interim storage by paying an extra "nuclear fuel storage tax" for dry storage with the money used for purposes that the local communities see as a real benefit.[217] The equivalent of a $10 million annual tax payment per site would add less than one percent to the cost of a nuclear kilowatt-hour.[218] As discussed later, the low-level waste disposal site offers a precedent for such payments.

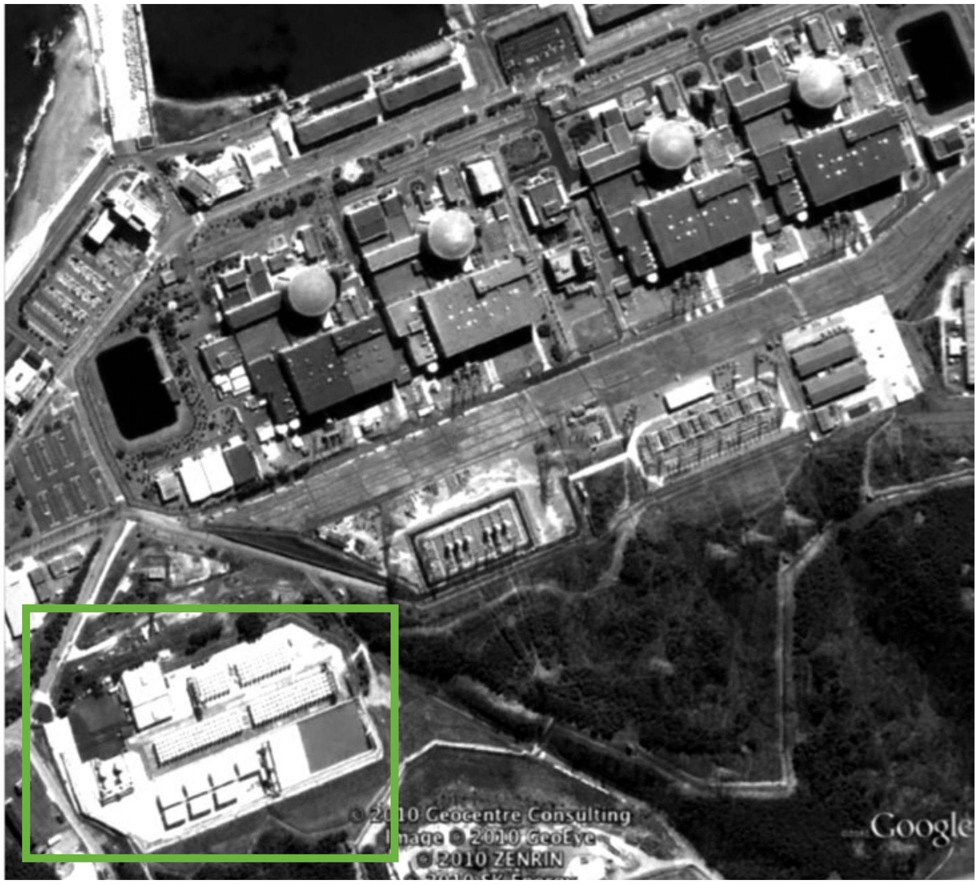

Figure 6.2: A satellite image of the Wolsong site (20 March 2010). Two types of dry storage are visible in the area at the lower left showing white rectangles. This includes about 300 individual casks containing about 10 tons of spent fuel each in rows of five in four groupings in the upper right of that area and seven MACSTOR monoliths at the lower left in each of which 40 canisters are embedded in a block of reinforced concrete that provides radiation shielding. Cooling air is drawn through channels in the monoliths by passive convection. *Source: Google Earth.*

Attempts to establish a central spent-fuel storage facility and a repository for low and intermediate-level waste

South Korea's attempts to site a central interim spent-fuel storage facility and repository for low and intermediate level waste (LILW) began in 1986 when the Atomic Energy Act was revised and the Ministry of Science and Technology (MOST, now the Ministry of Education, Science and Technology or MEST) and KAERI were assigned the responsibility for radioactive waste management. During the following decade, they made five failed attempts to acquire sites to host such facilities:[219]

1987– 1989. Based on a literature survey, MOST and KAERI selected Ulchin, Youngduk and Youngil on the east coast as potential sites for LILW disposal. They began on-site studies on the suitability of the geology at each of these sites in December 1988 but strong opposition from the local communities developed, drawing a great deal of sympathetic media attention. The site studies were abandoned in May 1989.

1990–1991. After an undisclosed study, MOST and KAERI selected Anmyundo on the west coast as a potential site for LILW disposal, describing it as a second Atomic Energy Research Facility. The decision was disclosed by the newspapers before the government made it public. Strong opposition developed among anti-nuclear organizations and local residents, who criticized the secrecy of the government's site selection process. The plan was officially withdrawn in October 1991.

1991–1992. Based on expert technical opinion, in 1991, MOST and KAERI selected six candidate sites, including Ulchin and Youngil on the east coast and Anmyundo, Changheung and Taean on the west coast for LILW disposal. There was strong opposition from the local communities—especially Anmyundo. The attempt was abandoned in 1992.

1993–1994. Anticipating financial incentives, in 1993, some regions, including Ulchin, Youngil and Yangsan on the east coast, offered themselves as candidate hosts for the LILW repository. In January 1994, the government passed an incentive law and announced a fund of 50 billion Won (about $45 million) for regional development around a radioactive waste management site. Unjin submitted a proposal to host the LILW repository supported by a 57 percent vote, but the site was found to be unsuitable.

1994–1995. A nationwide site-screening process selected 7 locations in coastal regions and 3 in island regions as potential sites for LILW disposal. In December 1994, the central government announced Kuleup-do, an island along the west coast, as the candidate site. In June 1995, a 50 billion Won Deocjeock Development and Welfare Foundation was established for the financial benefit of the host community. In October 1995, however, an active fault zone was discovered nearby. The government abandoned the site two months later.

In 1996, responsibility for radioactive waste management was transferred to the Ministry of Commerce, Industry and Energy (later renamed the Ministry of Knowledge and Economy or MKE) and KHNP's parent utility, the Korea Electric Power Corporation (KEPCO). In September 1998, South Korea's highest policy making body for nuclear power, the Atomic Energy Commission (AEC), announced a Radioactive Waste Management Plan in which a LILW disposal facility would be built by 2008 and an interim spent-fuel storage facility nearby by 2016.

This was followed by four more failed siting attempts, despite steadily growing incentive offers:[220]

2000–2001. In June 2000, the central government increased the financial incentive to 300 billion Won ($270 million) and invited bids from local communities to host a LILW disposal site. Seven regions along the east and west coasts indicated interest, but following internal debates over the costs and benefits, none of them applied.

2001–2003. In August 2001, the central government returned to its original approach: selection first and discussion later. In December 2002, the AEC announced four candidate sites, including Ulchin, Yonggwang, Kochang and Youngduk along the east and west coasts. The announcement was greeted by simultaneous protest demonstrations in all four regions.

2003. In April 2003, the government increased the incentive by offering a research center with a proton accelerator and offering to move the headquarters of KHNP to the host community. Eighty percent of the population of Pooan on the west coast signed a petition in favor of hosting the site but large-scale opposition developed. A joint conference was held in November 2003 to resolve the issue but collapsed in dissension.

2004. In April 2004, the government attempted for the first time to launch a public discussion of the costs and benefits of a national radioactive waste site but the subject was poorly defined and public acceptance was not increased.

In December 2004, therefore, the AEC decided to pursue separate sites for the LILW repository and the central interim spent-fuel storage facility, starting with the LILW site, which was seen as politically easier. In March 2005, a Special Act on Support for Areas Hosting Low and Intermediate Level Radioactive Waste (LILW) Disposal Facility was passed that guaranteed a local government hosting the national LILW facility an exemption from hosting a spent-fuel storage facility.

The central government required a local referendum on hosting the facility and offered as inducements:

- Three hundred billion Won ($270 million) upfront plus an additional 637,500 Won ($600) per waste drum accepted till the site reached its design capacity of 800,000 drums, and

- The relocation of KHNP's headquarters to the city that hosted the facility.

Success was finally achieved. Four cities competed to host the facility. Gyeongju City won after 89.5 percent of its voters approved hosting the site versus 67–84 percent pluralities in the other candidate cities.[221]

The challenge of siting a central spent-fuel storage facility remains but the need for such a facility is questionable. Most likely, as in other countries and as at Wolsong, it would be easier to build on-site dry storage at each of the nuclear power plants. This would also avoid having to transport the spent fuel before its final destination is determined.

Siting a geological repository

South Korea's key national laws relating to spent fuel and radioactive waste management are the Atomic Energy Act (AEA) and the Radioactive Waste Management Act (RWMA). The AEA provides for safety regulations and licensing for construction and operation of radioactive-waste disposal facilities. The RWMA, which was announced in 2008, and enacted in March 2010, established the Korea Radioactive Waste Management Corporation (KRMC) and the Radioactive Waste Management Fund in which KHNP, the nuclear utility company, annually deposits funds for decommissioning its nuclear power plants, disposing of their LILW, and managing their spent fuel.[222]

The main administrative authorities for nuclear power in South Korea are the Ministry of Knowledge Economy, which supervises the nuclear power program, including proposing and implementing policies regarding radioactive waste management, and the Ministry of Education, Science and Technology (MEST), which is responsible for developing licensing criteria for the construction and operation of radioactive waste disposal facilities and to which the Nuclear Safety Commission is subordinated.

According to KAERI's analysis, if the repository design developed for Sweden were used, tunnels sufficient to accommodate the approximately 100,000 tons of fuel that could be discharged if South Korea's PWR capacity increased from 40 to 75 GWe between 2030 and 2100, would underlie an area of at least 20 square kilometers.[223] KAERI argues that the area could be reduced by pyroprocessing and removing and fissioning the transuranic elements.

A projection of 75 GWe nuclear generating capacity is most likely high for a country of South Korea's size.[224] But, even if the growth were as projected, the argument that South Korea could not accommodate the deep underground disposal of the resulting spent fuel is unpersuasive.

The KAERI analysis assumes that the spent fuel would be emplaced in the repository 40 years after discharge.[225] At 40 years, removal of the transuranics would reduce the heat output and hence the required repository area by about 40 percent. But cooling the spent fuel for 70 years before emplacement would do the same. Furthermore, cooling the spent fuel for 200 years, as KAERI proposes to do before emplacing the most hazardous fission products, strontium-90 and cesium-137, in the deep repository, would reduce the repository area by 75% to about 5 km^2. For comparison, each of South Korea's nuclear power plants covers an area of 3–5 km^2. If one of those sites were chosen, the fact that they are also on the coast would make it possible also to extend the repository under South Korea's shallow continental shelf.

KAERI's argument that pyroprocessing is necessary to reduce the area of a repository to a size that can be accommodated by South Korea therefore does not stand up to scrutiny. Recently, as part of the negotiations of a new U.S.-South Korea Civil Nuclear Cooperation Agreement, the United States and South Korean governments agreed to carry out a multi-year joint study on this and other issues to determine the best alternative for managing South Korea's long-term spent fuel problem.[226]

The future of South Korea's spent-fuel management policy

A major reason for South Korea's political failures in siting a central spent-fuel storage site was that its early site-selection process did not include consultation with local communities. Instead, the central government selected sites based its own assessments, met strong opposition from the proposed host region, and gave up.[227] This pattern has occurred in other countries and has been called the "Decide, Announce, Defend, and Abandon" (DADA) process in an assessment of the UK experience.[228] Conversely, adopting a consultative process with local governments, including financial incentives and a local veto has resulted in success in siting geological spent-fuel repositories in Sweden and Finland,[229] as it has in the siting of South Korea's low and intermediate-level waste repository. (It is interesting to note that, in all three cases, the site selected was in a community that already hosted a nuclear power plant.)

In April 2007, after the success in siting the LILW repository, a subcommittee of the then National Energy Commission chaired by South Korea's President established a task force to design a process to achieve a public consensus on spent fuel management. Based on the task force's report, in July 2009, the Ministry of Knowledge Economy (MKE) established a committee to manage the process. A month later, however, the process was suspended and MKE announced that a legal framework and a solicitation of expert opinion were required first. An expert group composed of members of South Korea's nuclear establishment was instructed to carry out a year-long research project during 2010 as a basis for the public consensus process.[230]

If it is to be credible, however, such a public consensus process for spent fuel management will have to be open and transparent and involve local communities and independent experts.[231] Whether or not the public consensus process will in fact be finally launched remains to be seen.

Frank von Hippel

Appendix

Current, planned and potential spent-fuel storage capacity in South Korea through 2021

South Korea's nuclear power reactors are clustered at four nuclear power plants, three for PWRs (Kori, Yonggwang and Ulchin) and one for HWRs (Wolsong). The table shows the generating capacities and actual and expected initial operating dates of South Korea's power reactors at these sites through 2021, along with the existing planned and potential capacities of their spent fuel pools and for the dry storage at Wolsong.[232]

Site	Unit	Type	Capacity (GWe)	Operation (year.month)	Pool storage capacity [a] (tons)		
					Existing	Increase	
						Planned	Potential additional
Kori PWRs	Kori-1	PWR	0.587	1978. 4	158.8		
	Kori-2	PWR	0.650	1983. 7	327.6		
	Kori-3	PWR	0.950	1985. 9	270.9	696.4	
	Kori-4	PWR	0.950	1986. 4	270.9	697.4	
	Shin-Kori-1	PWR	1.000	2010.12	428.7		1024.5
	Shin-Kori -2	PWR	1.000	2011.12	428.7		1024.5
	Shin-Kori -3 [c]	PWR	1.400	2013. 9	625.7		1480.1
	Shin-Kori -4 [c]	PWR	1.400	2014. 9	625.7		1480.1
	Shin-Kori -5 [c]	PWR	1.400	2018.12	625.7		1480.1
	Shin-Kori -6 [c]	PWR	1.400	2019.12	625.7		1480.1
Yonggwang PWRs	Yonggwang-1	PWR	0.950	1986. 8	270.9	697.4	
	Yonggwang-2	PWR	0.950	1987. 6	270.9	186.8	509.7
	Yonggwang-3	PWR	1.000	1995. 3	215.4	268.3	323.4
	Yonggwang-4	PWR	1.000	1996. 1	215.4	268.3	323.4
	Yonggwang-5	PWR	1.000	2002. 5	224.9	203.8 [b]	407.1
	Yonggwang-6	PWR	1.000	2002.12	224.9	203.8 [b]	407.1
Ulchin PWRs	Ulchin-1	PWR	0.950	1988. 9	144.9	297.7	
	Ulchin-2	PWR	0.950	1989. 9	144.9	273.7	
	Ulchin-3	PWR	1.000	1998. 8	215.4	352.6	239.1
	Ulchin-4	PWR	1.000	1999. 12	215.4	352.6	239.1
	Ulchin-5	PWR	1.000	2004. 7	224.9		610.9
	Ulchin-6	PWR	1.000	2005. 4	224.9		610.9
	Shin-Ulchin-1	PWR	1.400	2015. 12	625.7		1480.1
	Shin-Ulchin-2	PWR	1.400	2016. 12	625.7		1480.1
	Shin-Ulchin-3	PWR	1.400	2020. 6	625.7		1480.1
	Shin-Ulchin-4	PWR	1.400	2021. 6	625.7		1480.1
Wolsong CANDUs	Wolsong-1	HWR	0.679	1983. 4	842.7	6,929, dry storage as of February 2010	
	Wolsong-2	HWR	0.700	1997. 7	736.8		
	Wolsong-3	HWR	0.700	736.8	736.8		
	Wolsong-4	HWR	0.700	1999. 10	736.8		
Wolsong PWRs	Shin-Wolsong-1	PWR	1.000	2012. 3	504.8		1024.5
	Shin-Wolsong-2	PWR	1.000	2013. 1	504.8		1024.5

[a] Pool storage capacity measured in metric tons of original uranium in the fuel. Values do not include capacity reserved in case all the fuel in the current reactor core has to be unloaded quickly.

[b] Planned to be installed in 2012.

[c] Shin-Kori 3,4,5 and 6, although contiguous with Kori 1,2,3 and 4 and Shin-Kori 1 and 2, are in different jurisdictions. Moving spent fuel between jurisdictions requires permission from the latter jurisdiction.

7 Russia

Russia's spent fuel management policy is based on the assumption that, in the long run, its nuclear industry will move toward a closed fuel cycle. This will involve reprocessing of pressurized water reactor (PWR) spent fuel and using the recovered plutonium in initial cores for a fleet of fast-neutron plutonium breeder reactors. Russia already operates a small civilian reprocessing facility that extracts plutonium from the spent fuel of its first-generation PWRs and is doing research and development in preparation for building a full-scale reprocessing plant. Russia's government-owned nuclear corporation, Rosatom, is operating a prototype fast-neutron reactor and is constructing a second but has thus far only used HEU fuel.

Russia has two large central storage pools in Zheleznogorsk, Siberia for fuel from its second-generation PWRs. It is also building central dry-cask storage capacity there for additional PWR fuel and for spent fuel from Russia's graphite-moderated reactors, for which there are no reprocessing plans. Currently, Russia has no active program to site or build a geological repository for either spent fuel or high-level waste.

Spent-fuel annual discharges and stocks

Russia has the world's fourth largest nuclear generating capacity (22.7 GWe) provided by 32 power reactors at ten sites: 16 VVERs (PWRs), 11 graphite-moderated, water-cooled RBMK-1000 reactors, four graphite-moderated, water-cooled EGP-6 reactors, and the BN-600 sodium-cooled fast-neutron breeder prototype reactor (Figure 7.1).[233] These reactors produced 18 percent of Russia's electric power in 2009.[234] Seven large PWRs, a 0.8-GWe demonstration breeder reactor, and two 0.032-GWe KLT-40S units that will power a single floating power plant are currently under construction.[235]

Russia's 11 RBMK-1000 reactors, when operating at a capacity factor of 79%, discharge annually about 550 tons of spent fuel (50 tons/GWe-yr). RBMK spent fuel has a lower percentage of plutonium than PWR spent fuel and there are no plans to reprocess it. The spent fuel is stored in pools adjacent to the reactors and in separate pools on the same sites. The capacities of the RBMK on-site spent-fuel storage pools have been increased twice by installing higher density storage racks. As of the end of 2010, they held about 13,000 tons of spent fuel (Table 7.1).

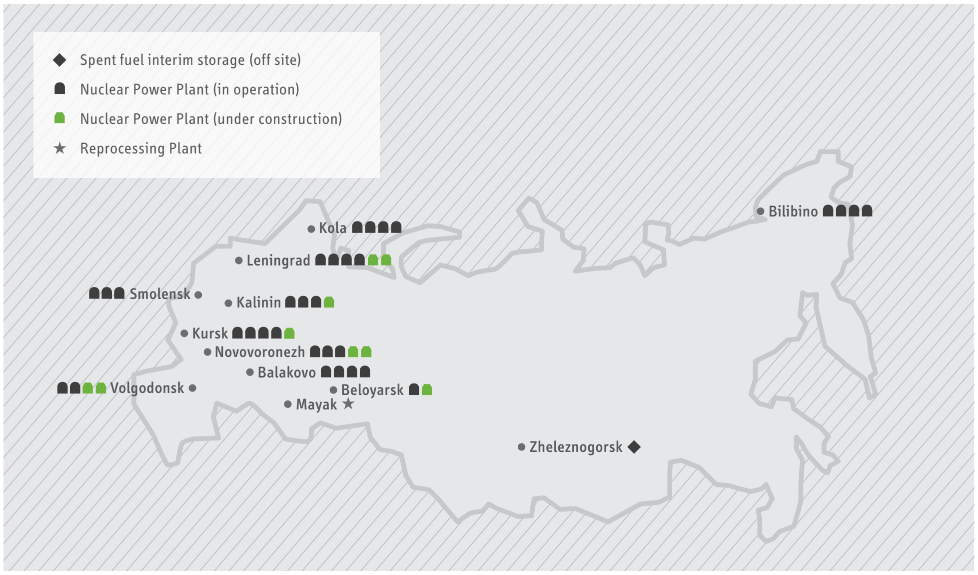

Figure 7.1: Location of Russia's nuclear power plants, spent fuel storage facilities, and reprocessing complexes.

Of the 16 VVERs, ten are VVER-1000s that discharge annually about 210 tons of spent-fuel (21 tons/GWe-yr) at a capacity factor of about 80 percent. After 3 to 5 years of storage in the cooling ponds adjacent to the reactors, the spent fuel is shipped to a central storage pool at the Mining and Chemical Combine (MCC) in Zheleznogorsk near Krasnoyarsk, Siberia (Figure 7.2). As of the end of 2009, the VVER-1000 reactors had discharged 5872 tons of spent fuel of which about 5000 tons had been transported to the MCC.

Figure 7.2: Technician looking under the cover over the huge storage pool for VVER-1000 spent fuel at the Mining and Chemical Combine in Zheleznogorsk. The pool was originally built as part of a reprocessing plant (RT-2) that was not completed. *Source: Thomas Nilsen; copyright: Bellona.*

The remaining six VVER-440 units discharge a total of about 87 tons of spent fuel annually (36 tons/GWe-yr). After cooling in the reactor storage pools for 3 to 5 years, this fuel is shipped for reprocessing in the RT-1 plant of the Production Association "Mayak" in Ozersk, near Chelyabinsk in the Urals. The VVER-440 fuel assemblies each contain only 115 kg of uranium, versus 390 kg in the VVER-1000 fuel assemblies.

The sodium-cooled BN-600 reactor is HEU-fueled and discharges 3.7 tons of spent fuel and 2.5 tons of irradiated uranium in blanket assemblies annually, containing a combined 0.36 tons of plutonium. The spent fuel is cooled at the reactor site for three years before being sent to RT-1 for reprocessing.

About 140 tons of spent fuel has been discharged over the lifetimes of four 11 MWe graphite-moderated, water-cooled EGP-6 reactors at Bilibino in far Eastern Siberia, The reactors went into operation during 1974-6. All the spent fuel is stored on site.

Finally, about 90 tons of spent research-reactor fuel is stored at Russia's nuclear research centers. This fuel has a great variety of enrichments, designs, fuel matrices and cladding materials. Some research-reactor spent fuel is reprocessed.[236] Research is currently underway on reprocessing and long-term storage options for the fuel that is not currently reprocessed.[237]

	Number of units and reactor type[a]	Generating capacity (GWe)	Start of commercial operation	Stored spent fuel (tons)
VVER sites				
Balakovo	4 VVER-1000	3.80	1986 – 1993	400.3
Kalinin	3 VVER-1000	2.85	1985 – 2006	222.1
Kola	4 VVER-440	1.64	1973 – 1984	75.4
Novovoronezh	2 VVER-440	1.77	1972 – 1973	73.9
	1 VVER-1000		1981	138.5
Rostov (Volgodonsk)	2 VVER-1000	1.90	2001	98.2
RBMK sites				
Kursk	4 RBMK-1000	3.70	1977 – 1985	4,612
Smolensk	3 RBMK-1000	2.78	1983 – 1990	2,372
Sosnovy Bor (Leningrad)	4 RBMK-1000	3.70	1974 – 1981	4,485
Other sites				
Beloyarsk	2 AMB[b]			190.9
	1 BN-600	0.56	1981	35.9
Bilibino	4 EGP-6	0.48	1974 – 1976	140.9
Central storage				
Mayak (VVER-440)				379
MCC (VVER-1000)				4,671
Total	**31**	**23.18**		**17,895.2**

Table 7.1: Stored spent fuel in Russia as of 1 January 2008.[238]

a. VVER is pressurized-water reactor; BN is sodium-cooled reactor; and RBMK, AMB and EGP are water-cooled, graphite-moderated channel-type reactors.

b. These two units have been shut down and are being decommissioned.

Central storage and reprocessing

Rosatom, Russia's Federal Atomic Energy Agency, operates two central facilities involved in spent-fuel management:

- RT-1, the reprocessing plant at Ozersk, has a design throughput of 400 metric tons per year but has never reprocessed more than 100 metric tons a year.[239] The high-level radioactive waste produced there is vitrified. An average of 500 tons of vitrified waste is produced annually.

- RT-2 at Zheleznogorsk was originally intended to be a reprocessing plant but only the spent fuel storage pool was completed before the project stalled during the 1980s. The original design capacity was 13,416 VVER-1000 fuel assemblies (6,000 tons) but has been increased to 7200 tons as a result of the installation of higher-density storage racks and an additional pool with capacity of 1200 tons has been built. As of the end of 2010, more than 6000 tons of spent fuel was stored in the pools.[240]

The pools at the RBMK nuclear power plants also are very close to full. In 2003, therefore, construction of dry spent fuel storage was begun within some of the buildings of the uncompleted RT-2 reprocessing plant. Dry storage capacity of 37,785 tons is to be built, with 26,510 tons for RBMK-1000 fuel and 11,275 tons for VVER-1000 spent fuel. The first unit, with a capacity for 5,082 tons of RBMK-1000 fuel, is to be put into operation during 2011.[241]

Foreign spent fuel

Russia continues the Soviet policy of taking spent fuel back if it is of Russian origin and irradiated in Soviet or Russian-built reactors. During Soviet times, spent fuel from VVER-440 reactors in Finland, Hungary, Bulgaria and Slovakia was shipped to Mayak for reprocessing. Today, only Bulgaria and Ukraine ship their spent fuel to Russia.

During 1989-2009, Russia received 315 tons of spent fuel from Bulgaria's four VVER-440 reactors, two of which shut down in 2002 and two in 2006, and about 240 tons of spent fuel from Bulgaria's two VVER-1000 reactors. Russia continues to receive about 37.5 tons (96 fuel assemblies) annually from Bulgaria. The contract specifies that the vitrified nuclear wastes resulting from reprocessing will be repatriated.[242]

Before 2005, Russia received annually about 220 tons of spent fuel from Ukraine.[243] Because of the rising price of Russia's reprocessing and spent-fuel storage services, however, Ukraine's nuclear-power plant operator, Energoatom, decided to construct dry storage facilities. The first Ukrainian dry-cask spent-fuel storage facility came into operation in 2004 at the Zaporozhskaya nuclear power plant with a capacity 3500 tons of spent fuel.[244] Since 2005, Ukraine has been shipping to Russia spent fuel from its other sites, however: about 150 tons a year from seven VVER-1000s and about 30 tons a year from its two VVER-440s.

Domestic and foreign spent fuel from VVER-440 reactors is reprocessed at RT-1 while that from VVER-1000 reactors is stored in the wet storage facility at RT-2.

Reprocessing policy

Rosatom views reprocessing as an essential element of its nuclear fuel cycle strategy. It therefore plans to build a new plant for reprocessing LWR spent fuel, to become operational around 2035, to recover plutonium for startup breeder reactor cores, and then begin large-scale construction of breeder reactors.[245]

In support of this strategy, and of expanding nuclear energy in general, Rosatom has initiated several governmental Federal Targeted Programs (FTPs):

- In 2008, to provide 2.084 trillion rubles (≈$69 billion) from 2009 through 2015 to increase Russia's nuclear generating capacity from about 22 GWe to 33 GWe in 2015.[246] The federal budget is to provide 605.7 billion rubles (≈$20.2 billion) and Rosatom 1.159 trillion rubles (≈$38.6 billion).

- In 2007, an FTP covering the years 2008 until 2015 with the primary objectives of constructing at MCC (Zheleznogorsk) 38,000 tons of dry spent fuel storage capacity and a center for testing, development and demonstration of advanced spent fuel reprocessing technology. The total budget is 145.4 billion rubles (≈ $4.8 billion) with 131.2 billion rubles (≈ $4.4 billion) from the federal budget.

- In 2010, an FTP focused on the development of fast-neutron-reactor and closed fuel cycle technologies.[247] In 2006, Rosatom gave high priority to completion of the semi-commercial BN-800 fast reactor, construction of which was first begun in 1987. The total budget for this FTP is 128 billion rubles (≈$4.2 billion) of which 110.4 billion rubles ($3.6 billion) is to be from the federal budget.

Rosatom also has been developing a legislative basis for dealing with nuclear waste and spent fuel. A draft federal law on "Management of Radioactive Wastes" has been introduced into the Russian parliament. The law mandates a registry of all radioactive waste storage facilities on the territory of Russian Federation, a system for classification of radioactive wastes, ownership and responsibility for radioactive waste management, determination of the financial basis for waste management activities, the regulation of the import of radioactive waste, and the national operator for final disposal. The draft had a first of two readings in January 2010 but the second reading has been delayed.[248]Another law entitled "On spent nuclear fuel management" reportedly has been prepared but not made public.[249]

Russia's policy with regard to the import of foreign spent fuel

Russia's spent nuclear fuel management policy is based on the concept that "[spent nuclear fuel] is a valuable secondary feed for producing nuclear fuel components and a number of radioactive isotopes used in medicine, agriculture, and industry."[250] Russia's plan is therefore to establish arrangements for long-term storage while developing reprocessing technology for recovering plutonium and uranium for use in nuclear fuel. The current legal basis for Russia's import of foreign spent fuel includes a number of changes that were made in 2001. These changes included the lifting of a 1991 ban on the import of radioactive material and the establishment of a mechanism to regulate the import of spent fuel.

The 1991 law explicitly prohibited bringing "radioactive waste and materials from other countries" for the purposes of storage or disposal.[251] It seriously disrupted shipments of spent fuel from power plants outside of Russia in 1992-1993, although it did not stop them completely.[252] To honor its obligations under Soviet contracts, the Russian Government made exceptions from the import ban for spent fuel from nuclear power plants built by the Soviet Union in Eastern Europe and Finland.[253] Arrangements were made for spent fuel imports from former Soviet republics as well.[254]

The Ministry of Atomic Energy (Minatom) Rosatom's predecessor agency, which considered reprocessing of foreign spent LWR fuel potentially a significant source of hard-currency income, argued that the fissile material content of spent fuel, especially plutonium, makes spent LWR fuel an energy resource and not a waste.

The issue was resolved in Minatom's favor in April 1993, when a presidential decree confirmed Russia's obligations to supply fresh fuel to and accept spent fuel back from nuclear power plants constructed by the Soviet Union.[255] The decree stated that the preferred policy is to return the reprocessing waste to the country that used the fuel, but did not make that a requirement. This was changed in a presidential decree in 1995, however, which made it Russia's policy to return the radioactive waste.[256] The decree also called for development of radioactive waste handling and storage facilities at the Mayak reprocessing plant.

According to the 1993 decree, other foreign spent fuel also could be brought to Russia for reprocessing under the condition of return of the radioactive waste. The decree specified that spent fuel from foreign-origin reactors could be accepted if it were to be processed at the RT-2 facility, which was under construction at Zheleznogorsk.[257]

Detailed guidance for the spent fuel transfer process was issued only in 1995.[258] Any spent fuel transfer and reprocessing contract had to be preceded by an international treaty with the owning country that would regulate the issues involved in transfer of radioactive materials.[259] Return of plutonium and uranium recovered during reprocessing, was conditional on the supplier country, if it was a non-weapon state, having all its nuclear activity under IAEA safeguards.[260] In an apparent attempt to facilitate development of Russia's reprocessing services market, the guidelines required that all future contracts for nuclear power plant construction abroad include fuel take-back (and reprocessing) arrangements.

Overall, the 1995 guidelines created a framework that allowed Minatom to market its reprocessing services for both Russian and foreign-origin fuel.

Foreign interest in reprocessing turned out to be much lower than expected, however. No contracts with new customers materialized other than the fuel take-back arrangement with Iran, which was required because of the proliferation concern that Iran might otherwise reprocess the spent fuel itself to recover the plutonium for nuclear weapon purposes. Most of the old reprocessing contracts were not extended.

Russia's insistence on returning the waste from reprocessing to owners of the reprocessed spent fuel was probably the major reason for lack of foreign interest in Russia's reprocessing services. In 1998, therefore, the spent fuel transfer guidelines were amended to allow the reprocessing waste to stay in Russia if the Soviet-era agreement did not specify how it should be handled.[261] But this measure had very limited applicability and did very little to attract new customers for Russia's reprocessing services.

Minatom therefore came up with a proposal to further relax the requirement of unconditional return of reprocessing waste. In 1999, a group of Duma deputies formally introduced legislation to make the changes sought by Minatom. The proposal received full support of all branches of the Russian government and, despite numerous objections of environmental NGOs, was approved by the Duma in June 2001.[262]

The first change introduced by the amendments was to allow bringing into Russia spent fuel for "temporary technological storage and/or reprocessing." A second change, as important as the first, allowed the government to decide whether or not to return reprocessing waste to fuel owners.[263] While the federal law still prohibits import of radioactive waste for permanent disposal, spent fuel and the waste generated during reprocessing are explicitly exempted by this provision.[264]

The approval procedure established by the federal law requires an international treaty to provide a legal foundation for a contract governing practical aspects of spent fuel storage or reprocessing in Russia and a thorough environmental impact assessment of all aspects of the transfer. A separate federal law that was approved as part of the package requires in addition that 75 per cent of the profit from fuel transfer contracts be spent on the rehabilitation of radioactively contaminated areas.[265] Oversight of the process is to be provided by a commission of scientists, politicians, and governmental officials.[266] A statute approved in 2003, however, gives the commission no more than an advisory role to the President.[267]

It has also been decided that spent-fuel import from the countries that currently have agreements to send spent fuel to Russia—Bulgaria, Ukraine and Iran—do not require new treaties. All are covered by earlier agreements.[268]

The changes in the law that were introduced by the Duma in July 2001 provided a basis for detailed guidelines that were approved by a government decree in 2003 for handling of foreign spent fuel and return of radioactive waste. These guidelines specify that spent fuel can be brought into Russia only for temporary storage, after which it has to be either returned to the owner or reprocessed.[269]

If fuel is imported for eventual reprocessing, an international treaty is required to establish the legal basis for a subsequent contract.[270] The guidelines make a distinction between Russian-origin fuel and foreign-origin fuel. As a rule, the radioactive waste produced by reprocessing the former can be left in Russia, while the waste from foreign fuel should be returned to the fuel owner. This provision can, however, to be circumvented by the treaty that governs fuel transfer.[271]

If the fuel is being brought for temporary storage, the guidelines require the treaty to provide guarantees of eventual fuel return to the owner. All other aspects of the deal, including the length of storage, are to be handled by the contract. No explicit limit of the length of storage is set; instead, the guidelines specify that it should not exceed a certain technological limit. The language is not specific on what this technological limit is but suggests that it would be determined by the durability of fuel and other technical considerations.[272] Once the initially-established term for temporary storage expires, the guidelines allow spent fuel to be continued to be stored or for switching to the reprocessing option. It is not clear whether a change of terms would require renegotiating the treaty that governed the initial fuel transfer or simply involve changing the terms of the contract. It would, however, require a new environmental impact assessment and probably a fresh review by the presidential commission established in July 2001.[273]

Overall, the procedure for spent fuel transfer is designed to encourage its eventual reprocessing. It is very unlikely fuel would be removed from Russia once it was brought into the country for temporary storage. Fuel owners would have to choose between extending a storage contract or giving their consent to reprocessing. The option of leaving the waste in Russia is designed to make reprocessing more attractive.

Even though the laws give it wide latitude in devising a national spent fuel management strategy, Rosatom has to take into account the very strong public opposition to the import of foreign origin fuel, whether for storage or reprocessing. Otherwise, the public does not appear to be anti-nuclear power. Public polls in Russia typically find that people are not supportive of expanding or shrinking the industry. In 2006, however, when Russia and the United States discussed the possibility of signing a nuclear cooperation agreement, a suggestion that the agreement might open a way to transfer of U.S. spent fuel to Russia generated a serious controversy that forced Rosatom to publicly announce that "Russia has not imported foreign spent fuel, is not importing and will not import it in the future."[274] Even though this was not a legally binding commitment, Rosatom has not since put forward proposals to import foreign-origin spent fuel. This self-imposed restriction, does not, however, affect Rosatom's ability to repatriate Russian-origin spent fuel.

Anatoli Diakov and Pavel Podvig

8 Sweden and Finland

Sweden, which has a modest nuclear energy program, has decided on a national plan and site for a geological repository for its spent nuclear fuel. The plan is to emplace spent fuel in copper canisters intended to withstand corrosion. The canisters in turn are to be surrounded by bentonite clay in tunnels in granite bedrock.

A license application was submitted in March 2011 for a permit to construct a repository at the site of the Forsmark nuclear power plant. Sweden's regulator and environmental court are expected to take until the end of 2012 in their reviews of whether to accept the application. If no major amendments to the application are required, the application review process is expected to take another three to four years. Sweden's Government will make the final decision, based on the recommendations from the regulator and the court. The community of Östhammar, where Forsmark is situated, can veto the decision but the Government can override the veto. Current opinion in the community is 80% in favor of the repository plan.

This chapter covers Sweden's repository planning experience in some detail. It also reviews briefly developments in Finland's nuclear waste management system, since Finland is planning to use the same method as Sweden for disposal of spent nuclear fuel and has also chosen to site its repository next to a nuclear power plant.

Nuclear power in Sweden

Sweden's interest in nuclear technology began with an interest in nuclear weapons. A combined military and civil nuclear program based on heavy-water reactors was initiated. After a long public debate in the mid-1960s, however, the decision was taken to abort the military program. The heavy-water reactor program also was stopped and orders were placed for boiling water reactors made in Sweden based on General Electric designs and for imported U.S. pressurized water reactors designed by Westinghouse. Between 1972 and 1985, twelve reactors were built and put on line at four sites (Figure 8.1). Sweden also built or acquired a number of smaller research and prototype reactors that are now all shut down.

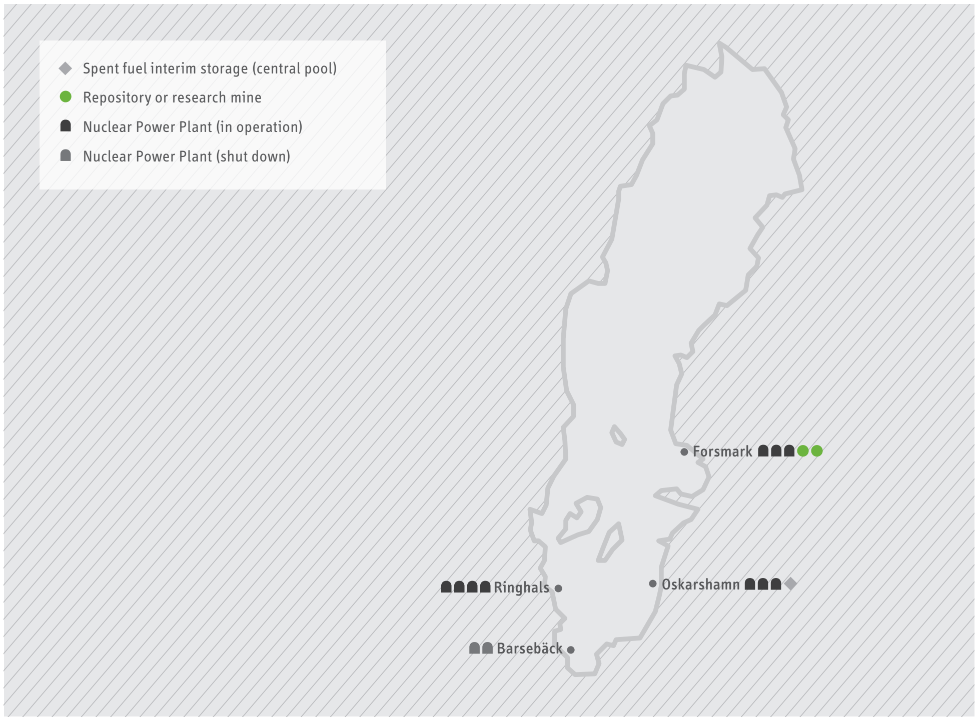

Figure 8.1: Locations of nuclear reactors, spent fuel interim storage sites, and proposed repository in Sweden. Forsmark is the site of both the centralized repository for low-level and medium-level short-lived nuclear waste and the planned final repository for spent fuel.

There was very little public debate about nuclear waste disposal in Sweden until nuclear energy as a whole became controversial in the early 1970s. At that point, the waste issue became central to the nuclear debate. The Swedish nuclear waste program that exists today was shaped by the results of that debate.

The U.S. Three Mile Island reactor accident in 1979 led to a referendum in Sweden in 1980 on the phase-out of nuclear power. The political result of the referendum was a decision that nuclear power would be phased out in Sweden by 2010.[275] This decision appeared to settle the debate and, by the mid-1980s, nuclear power was no longer an important political issue. The 1986 Chernobyl accident, which deposited considerable radioactive fallout in Sweden, revived political discussions and led to the eventual shutting down of the Barsebäck nuclear power plant. Public interest then fell to very low levels again except for the past few years when there has been limited discussion of the possibility of building new nuclear power reactors.[276]

Four factors underlie the failure to implement the plan to phase out nuclear power by 2010:

1. Strong promotion of nuclear power by the large Swedish electric utilities and the fact that all the major newspapers are pro-nuclear.

2. A lack of replacement power due to low investment in renewables. (Swedish wind power capacity is, however, now growing rapidly.)

3. Little interest in Sweden's major political parties and coalitions in discussing nuclear issues, as it risks internal conflicts between pro-nuclear and anti-nuclear factions.

4. High levels of trust in the state, its institutions and other large entities such as the state-owned power company Vattenfall.[277] It has therefore been difficult to mobilize public opinion in the face of a general perception that the policy and decision-making process are basically rational and sound.

Nuclear waste in Sweden

Since 1985, a centralized interim storage facility for spent nuclear fuel, CLAB, has been in operation next to the Oskarshamn nuclear power plant and, since 1988, a centralized final repository for low-level and medium-level short-lived nuclear waste, SFR, has been in operation next to the Forsmark nuclear power plant.

The responsibility for management of nuclear waste in Sweden is placed clearly in the hands of the nuclear industry. A Nuclear Waste Fund has been established by law to guarantee the polluter-pays principle and the industry has established a company, SKB, to propose a site and design for a spent nuclear fuel repository. There are also plans for a repository for medium-level long-lived waste in the future.

Both Sweden and Finland are planning to use the KBS method, which was developed in Sweden since the early 1970s, for their final repositories for spent nuclear fuel. (KBS in Swedish is kärnbränslesäkerhet, translated as nuclear fuel safety.) The method also has been adopted for the nuclear management systems in Canada and the United Kingdom.[278] As a result, there has been collaboration in research and development between the four countries but the KBS method is primarily a Swedish system. The recent repository license application submitted by the nuclear waste company SKB and the review of that application will be significant for all of these countries in the coming years.

From reprocessing to direct disposal of spent fuel

Sweden's early combined nuclear power and nuclear weapons program was based on domestic uranium, an indigenous heavy-water reactor and a planned reprocessing plant. Even though the reprocessing plant was never built, small-scale reprocessing was carried out within the military program during the 1950s and 1960s. The quantity of plutonium separated was probably less than a kilogram and the waste from this period is stored at the Studsvik nuclear research site.

As in other countries with nuclear energy programs in that period, commercial reprocessing of spent fuel was part of Sweden's nuclear policy through the 1970s. In the mid-1970s, Sweden's nuclear utilities signed reprocessing contracts with France and the United Kingdom. In the early 1980s, however, Sweden followed the lead of the United States and decided to forego reprocessing.[279] All high-level nuclear waste to be disposed of in Sweden will be in the form of spent nuclear fuel.

Interim storage

Operations at Sweden's central interim storage site for spent fuel, CLAB, started in 1985. Spent fuel is transported to the facility by sea from the nuclear power plants. Storage is in a pool about 50 meters underground in granite bedrock. The facility has been expanded with a second pool put into service in 2008. At present the spent fuel inventory in CLAB is about 7,000 tons. The projection for the total amount of Swedish spent nuclear fuel to be produced is 12,000 tons. The amount is based on an assumed 50 to 60 year operational lifetime of the remaining 10 nuclear reactors and no new-build. The nuclear industry claims that, if necessary, the spent fuel can be stored safely in the pools for at least one hundred years.

Development of a repository system for spent fuel (the KBS method)

As the nuclear debate developed in Sweden in the early 1970s it became clear that the nuclear waste issue had to be taken more seriously. The Government set up the AKA Commission to study the question in 1972, the same year that the first Swedish nuclear power reactor went into operation. The Commission's report in 1976 recommended that high-level reprocessing waste be encapsulated and disposed of in granite bedrock at a depth of several hundred meters.[280] The commission stated that it was important that the bedrock be free from fissures that could transport water loaded with contaminants from the repository.

When the AKA Commission report was published, the Swedish political scene was in turmoil. The Social Democrats had lost power in the 1976 elections for the first time in forty years. The Center Party, that led the winning center/right coalition, had gained substantial support for its anti-nuclear agenda. Once in power, the party enacted the Stipulation Act, which required a solution for final disposal of high-level nuclear waste as a prerequisite for licenses to start new nuclear reactors.

The Stipulation Act forced the nuclear industry to act quickly and it launched the KBS project to develop a repository concept for high-level reprocessing waste or spent nuclear fuel. The project was developed in close collaboration with the Swedish Nuclear Fuel Supply Company (SKBF), which the nuclear utilities had created in 1972 to coordinate Swedish nuclear fuel supply.[281]

The 1977 KBS-1 report described how vitrified high-level nuclear waste from reprocessing, the industry policy at this time, could be disposed.[282] It was approved in a controversial decision by a minority government after the Center Party government fell, and enabled the launch of additional nuclear power reactors.

The Stipulation Act also allowed for direct disposal of spent nuclear fuel without reprocessing. The 1978 KBS-2 report therefore provided a prescription for the direct disposal of spent nuclear fuel, similar to that for vitrified reprocessing waste.[283]

The KBS concept relies on man-made barriers to hinder the migration of radionuclides from the high-level waste. To do this, the waste form, either vitrified reprocessing waste or spent nuclear fuel, is put in a canister made out of a material that can withstand corrosion. The KBS-1 report suggested a canister made of titanium and lead. The KBS-2 report, however, proposed copper, which has been the material of choice ever since. The copper canister presented in the KBS-2 report was to be 20 cm thick. The KBS-2 report also proposed the use of a buffer around the canister made of bentonite clay. In both reports the canister was to be placed vertically in holes in the floor of deposition tunnels 500 meters down in Sweden's granite bedrock (Figure 8.2).

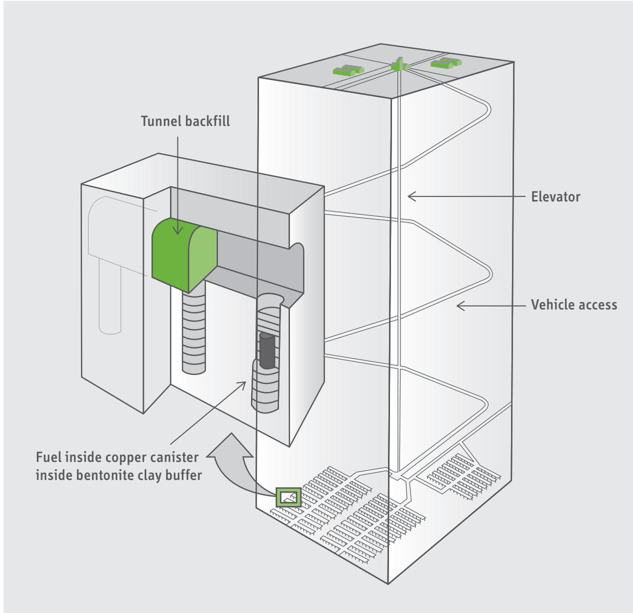

Figure 8.2: The KBS concept for a deep geological repository for spent fuel. The repository depth is at about 500 meters.
Source: Adapted from SKB.

SKB continued to develop the KBS concept.[284] After Sweden decided to abandon reprocessing, the focus was put on further developing a repository for spent nuclear fuel. In 1983, the KBS-3 report was produced as part of the licensing process for the last two Swedish nuclear reactors, Oskarshamn-3 and Forsmark-3, started in 1984. The KBS-3 report had a more developed discussion of long-term safety and relied on results from the geologic studies done to date.

The 1983 KBS-3 report also looked in more detail at the theoretical understanding of corrosion processes and the required thickness of the copper cask.[285] Although no recommendation for the thickness of the copper was given, a decision was taken later that a 5 cm thickness for the cask would be sufficient. This is still the assumption today. The KBS-3 report was the last report in this series and the proposed disposal method is sometimes called the KBS-3 method. Here, it will be called simply the KBS method or KBS concept.

The KBS concept envisages a copper canister that is 5 meters high and has a diameter of 1 meter. In early versions of the concept, the fuel rods would be held in place in the canister by pouring lead or copper into the space between the rods. In the early 1990s this changed to an insert made of steel and later to cast iron designed to reinforce the canister against crushing from the extra weight of an ice cap such as was present over Scandinavia during the ice ages. The cast iron insert is made in two different versions to accommodate fuel from pressurized water and boiling water reactors.

During emplacement, the copper canister would be taken down into the repository deposition tunnels and put into a hole bored into the tunnel floor. The hole would be lined with rings of bentonite clay and the canister would be inserted into the central hole. There would be a 1-cm space between the copper canister surface and the clay.

The importance of the copper and clay barriers

Central to the KBS case for the long-term safety of this spent fuel disposal method is that copper will not corrode in the repository environment. In environments where there is oxygen, as in air, copper corrodes to form copper oxides. The corrosion speed is slow enough so that copper is used for durable roofing on buildings, but the longevity of even a thick copper canister would be insufficient to contain plutonium and other long-lived isotopes for hundreds of thousands of years until they decayed away,

It is well understood that there is no free oxygen in the ancient groundwater in the bedrock at a depth of 500 meters because the oxygen has reacted with elements in the rock. This so-called anoxic condition is essential to the safety case for the KBS method. In the late 1970s and the early 1980s, several studies bearing on the behavior of copper in anoxic conditions were conducted, and by 1983 when the KBS-3 report was published, the case for using copper was thought to be solid.[286] Later reviews carried out by SKB have continued to make this case, even though some problems were perceived due to possible corrosion by sulphides from bacterial activity in the repository.[287]

Thus, the copper was not to expected corrode significantly in the repository environment and the 5 cm of copper was believed to give a good margin in a worst-case scenario over hundreds of thousands of years. It was understood also that, if ground-water flow past the canister could be limited, then the transport of corrosive substances to the canister and of corrosion products from the canister could be prevented and any corrosion that did occur would be very limited. The main purpose of the second barrier of bentonite clay therefore was to protect the copper, but it could also delay leakage from a compromised canister.[288]

Bentonite clay has the important property that it swells when absorbing water. This means that, after the deposition hole is closed groundwater seepage into the hole from the surrounding bedrock would swell the clay so that it first fills up the deposition hole and then becomes relatively impermeable to the passage of water and chemicals.

Once the man-made barriers of copper and clay are gone, the bedrock is expected to delay dissolved radioactive materials from reaching the surface. But this delay is much less significant for the KBS safety case than the copper canister and bentonite.

The safety case

The safety issues for the KBS method therefore focus to a large extent on whether the man-made barriers of copper and clay can withstand long-term stresses including several glaciations, and how radionuclides that leak through these barriers could be transported to the surface and harm humans and nature.

Four major safety analyses of the KBS concept have been carried out, *SKB 92*, *SR-97*, *SR-Can* and *SR-Site*.[289]

SR-Site is the safety analysis for the current licensing application. In a safety analysis the first task is to identify the relevant features, events and processes that would challenge the integrity of the barrier system. This includes glaciation. After a compilation of input data, a reference case for the evolution of the repository is simulated and analyzed along with a number of scenarios in which its safety functions are not maintained. This provides the opportunity to simulate release scenarios. Conclusions then can be drawn by comparing the results of the analysis with the regulatory safety criteria that have been set for the repository. A summary of the results from the latest *SR-Site* for the Forsmark site is presented in Figure 8.3.

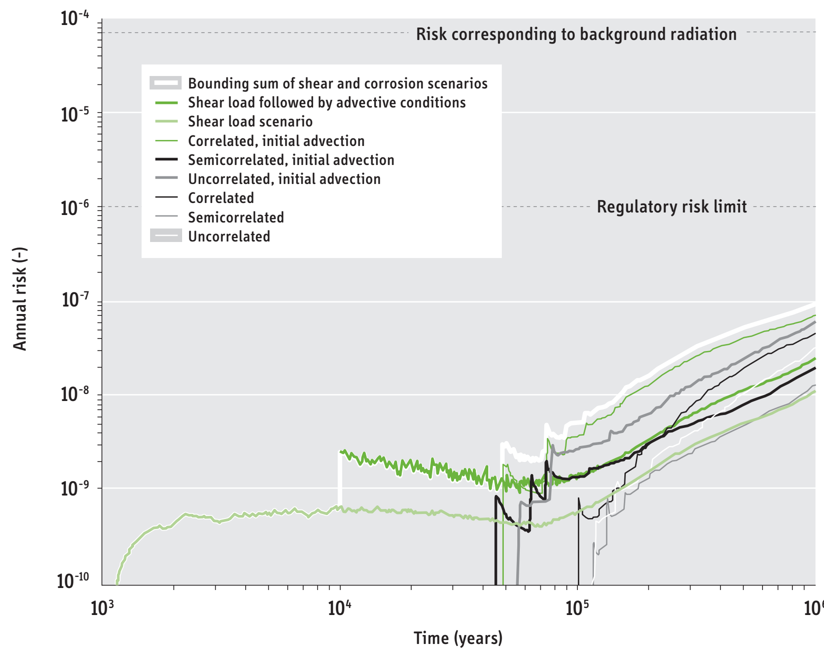

Figure 8.3: Estimated risks for the highest calculated doses from the safety analysis SR-Site, expressed as annual individual risk of serious harm from exposure to radioactivity from the spent fuel repository compared to the risk from natural background radiation, which is assumed to be about 0.01 percent per year. Several alternatives for the corrosion scenario are shown, and two for the shear load scenario, in which some canisters are sheared by movement of rock along fractures that intersect their emplacement holes. Advection refers to loss of the water retardation function of the bentonite. *Source: SR-Site.*[290]

Sweden's regulatory criteria for long-term radiological safety of a repository for spent nuclear fuel were developed by Sweden's Radiation Protection Agency in the late 1990s. The criteria are set so that individuals in the group exposed to the greatest doses from the repository should not have an added risk of harmful effects (lethal and non-lethal cancer and hereditary effects) of more than one chance in a million per year. Regulations also were formulated by Sweden's Nuclear Power Inspectorate for how the safety analysis should be carried out. When the two regulators were combined into the Swedish Nuclear Safety Authority in 2008, the regulations were transferred to the new authority but remain as separate requirements.[291]

Safety

The nuclear waste company SKB has spent large resources on developing the KBS design and on research on its safety. A research and development program, called the Fud program, has been presented and reviewed every three years since 1986. Fud program reports are reviewed by the regulators, comments are sought from academics, NGOs and others and the Government then gives the go-ahead to the program.[292]

A major part of the SKB effort has been mathematical modeling for the safety analysis, including trying to determine the factors that influence the analysis. An important consideration is the long-term risk from stress on the repository by multiple glaciation cycles (ice ages), including the effects of the associated earthquakes and permafrost. Models of the behavior of the clay buffer and the copper canister in such changing environments have been developed and tested to a limited extent in laboratory studies. A second focus has been on how to build and operate a repository. Two special research facilities for studies of the canister and the bentonite behaviors have been built. These have been used to explore how a canister could be produced, welded shut after being filled, emplaced within its clay buffer, and the deposition tunnels filled.

For understanding how the clay and copper barriers would behave in real repository conditions, the most important part of the research program has been the construction of the Äspö underground Hard Rock Laboratory close to the Oskarshamn nuclear power plant.[293] A number of experimental projects have been carried out there that have given a better understanding of the bedrock and groundwater characteristics at depth. There are also a number of on-going projects for studying how copper and clay behave in a realistic repository environment. Of major importance are microbial studies that have shown that a major concern for copper corrosion may be sulphide production by bacteria.

At Äspö, a Prototype Repository project has six heated full-scale copper canisters emplaced in deposition holes since 2001. The first canisters were to be retrieved in 2011. Another important experiment is the LOT project where, at the turn of the century, long heated copper rods were emplaced in holes filled with clay. The plan has been to have two packages, one normal and one stressed at a higher temperature, deposited for one, five and ten years. So far packages have been retrieved after one year (normal and stressed) and after five years (stressed only). There is no plan to retrieve any more packages at this time, but it is possible that retrieval of the normal five-year package may be necessary during the present licensing review. A third project is the MiniCan project where corrosion of copper and cast iron is studied. The first package from the MiniCan Project is to be retrieved in 2011.

In the last few years there has been some controversy regarding the results obtained in the LOT and MiniCan projects. Reports from the MiniCan project may have misrepresented some of its results.[294] There has been some speculation that this has occurred because the results have not been in agreement with those expected by SKB. Copper corrosion rates have been unexpectedly high in the Äspö laboratory experiments and the clay has not behaved as predicted in the models.

The controversy over copper corrosion

The controversy concerning the results for copper corrosion in the Äspö Hard Rock Laboratory feeds into the larger on-going dispute about the risks for copper corrosion in the repository environment. This debate started in the late 1980s but it surfaced in full force in the autumn of 2007 with the publication of a scientific paper by researchers at the Royal Institute of Technology (KTH) claiming that experimental results showed that copper corrodes in pure anoxic water.[295] As this goes against claims by SKB that the metal is close to immune to corrosion in the absence of oxygen the result could influence assessments of the long-term safety of a KBS repository.

The KTH paper was heavily criticized by a broad array of Swedish and international scientists. Many of them were working for SKB, but criticism also came from scientists working as experts for the regulator and for the Government's scientific advisory board, the Swedish Council for Nuclear Waste. The KTH researchers followed up with subsequent publications in 2008 and 2009, making it clear that the issue remained unresolved.[296] An international scientific workshop was organized in November 2009 by the Swedish Council for Nuclear Waste in an effort to try and unravel the controversy.[297] The conclusions of the expert panel invited to comment on the issues raised were not categorical, however, leading the Council to state that "mechanisms of copper corrosion in oxygen-free water must be investigated experimentally to determine whether corrosion of copper by hydrogen evolution can take place in pure, deionized, oxygen-free water and in groundwater with bentonite."[298]

This led SKB to set up a project where researchers at Uppsala University will attempt to replicate the experimental results of corrosion in pure water that the researchers from KTH obtained. Despite the evident need for further experiments on copper corrosion also in a simulated deoxygenated repository environment, SKB has not started such work. There is in fact no experimental evidence that corrosion stops in a repository-like environment after oxygen is consumed, except in cases where the system has been too isolated to properly represent real-life conditions.[299]

Apart from experimental results, much of the copper corrosion controversy has focused on the issue of whether there is any theoretical possibility that copper can corrode in anoxic water. Initially, it was strongly believed that theoretical thermodynamics shows that copper is immune to corrosion in water in the absence of oxygen. With time, however, there appears to be less and less certainty on this issue. The results of a project commissioned by Sweden's Radiation Safety Authority recently opened up the theoretical issue, arguing that:[300]

> "The assumption that copper is unequivocally immune in pure water under anoxic conditions is strictly untenable, and it is even more so in the presence of activating species, such as sulfide. Thus, it appears that two conditions must be met in order to explain the existence of the native deposits of copper that occur in granitic formations: (1) A suitably high hydrogen fugacity (partial pressure) and; (2) A suitably high cuprous ion activity, as shown in this report. Accordingly, the success of the KBS-3 program must rely upon the multiple barriers being sufficiently impervious to the transport of activating species and corrosion products that the corrosion rate is reduced to an acceptable level."

In this context, it is interesting to note that the researchers at the Royal Institute of Technology who have been critical of SKB's copper corrosion work, have been raising the issue of what will happen in the repository with regard to corrosion during the first thousand years. In the relatively dry bedrock in Forsmark, it will in many cases take up to over a thousand years for the bentonite clay to swell and become tight. This is also the time period when the copper canisters are hot, some water is present, and the radiation is high. One interesting issue to examine in the upcoming license review issue, therefore, will be whether the safety case can hold up over the first thousand years of the repository.

In the license application and the associated license safety analysis, SKB is relying solely on the models for copper corrosion established at the beginning of the project, as well as on mass balance calculations, to show that only a few millimeters of copper will corrode in a million years. It remains to be seen whether the regulator will be satisfied with these calculations or whether there will have to be amendments to the application requiring experimental results supporting this theoretical case.

The siting of a repository

Sweden's legal framework puts all the responsibility for finding a site on the nuclear industry. There is already a Swedish repository for low and intermediate-level short-lived waste, SFR, at the site of the Forsmark nuclear power plant. The siting of that repository was relatively straightforward since the community of Östhammar already hosts the Forsmark nuclear power plant and is very dependent on nuclear jobs. The siting of the intermediate storage site, CLAB, at the Oskarshamn nuclear power plant was similarly not a major problem. In contrast, the siting process of the spent fuel repository has been long and problematic.

The first trial drillings at a number of sites started in 1977. They led to an initial choice of Sternö on the south-eastern coast as the site for a KBS-type repository in order to satisfy the political requirement for proceeding with the licensing of new reactors but the results did not, in fact, meet the criteria set for the hydro-geology of the bedrock.[301]

A number of drilling projects were carried out at other sites owned by the national government, mainly in national forests. The Three Mile Island nuclear accident in 1979 and the resulting public consultation and referendum on nuclear power in Sweden in 1980 led, however, to public protests wherever the industry wanted to drill. Some drilling projects were stopped by demonstrations and civil disobedience. At others, the drilling campaign was carried through, but only with police intervention and protection. The protests led to a national network of local opposition groups, The Waste Network (Avfallskedjan).[302]

During the winter of 1985 – 1986, SKB was to start a drilling campaign in Almunge, east of the city of Uppsala, just north of Stockholm but protests at this site became a major national media event. On the national evening TV news, viewers saw demonstrators being carried away by police with police dogs. The Government told SKB that it wanted no repetition of such scenes. This made it impossible for SKB to carry through its plan for 10 to 15 site investigations during the 1980s to be followed by more detailed investigations at three sites between 1992 and 1998. The decision therefore was taken to try to find a few sites for investigation in a more voluntary process.

At this point, SKB devalued its own standards for the needed characteristics of the bedrock. In the company's safety analysis, SKB-91, the claim was made that SKB analyses showed that a repository deep down in Sweden's bedrock with technical barriers that are stable in the long term could, with a good margin, meet the criteria proposed by the regulators. SKB stated furthermore that "the safety of a carefully designed repository is only affected to a small extent by the ability of the rock to retain the escaping radionuclides" and that "the primary role of the rock is to provide a stable mechanical and chemical environment in the repository over a long period of time so that the function of the engineered barriers is not jeopardized."[303]

In the research and development program for 1992 (Fud-92) SKB followed up with the announcement of a significant change in the criteria for siting.[304] The bedrock was dismissed as a "decisive siting factor." The barrier system was to be the main factor in the safety analysis and "almost any rock would do." This allowed the siting process to continue with unspecified geological criteria.

SKB had already decided to start a process with voluntarism as a basic strategy. In October 1992, a letter was sent to almost all Swedish local communities with an invitation to cooperate with SKB in the site-selection project. Many communities felt the letter lacked seriousness and did not respond. A number of communities in the north of Sweden did respond, however, with a hope of getting new jobs and other resources from a nuclear waste venture. In the communities of Storuman and Malå the interest was mutual and pre-studies were performed. Further work was not continued, however, after local referenda were held that rejected the effort.

After these setbacks in northern Sweden the strategy was changed again. The choice of site was now foremost a question of public opinion. The hope was that it would be easier to obtain the support of local opinion in communities that already had nuclear facilities. Four of these communities were among those that had responded to the letter suggesting cooperation and they were now chosen as possible candidates:

- Östhammar north of Stockholm, where the Forsmark nuclear power plant and the repository for low and short-lived medium-level waste are situated;

- Nyköping on the coast south of Stockholm, where there was a nuclear research facility with research reactors;

- Oskarshamn, on the south-east coast where the Oskarshamn nuclear power plant and the centralized storage facility for spent nuclear fuel, CLAB, are situated; and

- Varberg on the west coast, where the Ringhals nuclear power plant is situated.

In addition, the communities of Älvkarleby and Tierp, adjacent to Östhammar, and the community of Hultsfred, inland from Oskarshamn, were included.

While the issue was under discussion in Varberg, there was a minor earthquake that tipped the decision to "no." Nyköping also later said "no." In Tierp and Älvkarleby, there were political decisions not to move forward.

These developments led SKB in 2002 to choose Oskarshamn and Forsmark for complete site investigations. SKB decided to investigate the bedrock just adjacent to the nuclear power plants and worked to promote public support for the repository project in each of the two communities.[305] In 2009, SKB offered the two communities 2 billion SEK ($300 million) as compensation for their willingness to host a repository. Given the expected employment benefits that would come with the repository, 25% would go to the community that was chosen and 75% to the other.

With willing hosts having been identified, SKB set a schedule for the final choice of site and for the submission of a license application. The plan was to gather sufficient data from each of the two sites to have a preliminary safety case report (*SR Can*) ready by 2006.[306] This report was then to be used by the nuclear waste company to make the final choice of site after being reviewed by the regulators. A final safety case *SR Site* was to be ready by 2009 when the application for a repository was to be submitted.

In the published *SR-Can* safety analysis, the Forsmark site met the regulatory standards by a large margin while the Oskarshamn site, at least after preliminary analysis, only just met them.[307]

After finally concluding both site investigations, SKB in June 2009 decided to choose Forsmark. The siting process is now to be reviewed by the regulator and the Environmental Court in the licensing process.

The main reason for choosing Forsmark appears to be that its bedrock has few fissures. Therefore, the engineered barrier systems have become less critical to the safety analysis. It is as if the much sought after "crack-free" bedrock of the 1980s has finally been found. It is perhaps a little ironic that, while the bedrock now shows promise, the engineered barriers are facing criticism. It remains to be seen if the net effect of the dry rock in Forsmark is positive or negative in a revised safety analysis. With the rock so dry, the bentonite clay will absorb moisture and swell and become tight only slowly, possibly allowing corrosion to proceed at higher rates for the first thousands of years.

Legal, regulatory and financial framework

The Radiation Safety Authority and the Environmental Court will engage in two parallel reviews of the spent fuel repository application. The processes are interconnected, as the Environmental Court will rely heavily on the input from the regulator when deciding on the long-term safety of the repository. It is expected that the Environmental Court will focus less on technical issues and more on public concerns, such as retrievability of the spent fuel from the repository and risks of unintentional intrusion.[308]

The Swedish Council for Nuclear Waste will provide advisory input into the review. The views of the Council will be sought especially if and when the regulator and the court advise the Government to give the final go-ahead to the repository.

Sweden's funding system for nuclear waste management is set up around a Nuclear Waste Fund under the Financial Act. The fund has been built up with fees taken from the nuclear power operators. The regulator recommends a fee to the Government based on SKB projections of costs.[309] The present fee is about 0.01 SEK ($0.0015) per nuclear kWh and the fund contains on the order of 45 billion SEK ($7 billion).[310] Future costs for waste management and disposal, and for decommissioning of Sweden's nuclear facilities is estimated at 90 billion SEK ($14 billion). Thus far, a little more than 20 billion SEK ($3 billion) has been spent, about half on the development of the spent nuclear fuel repository. There is also a separate system with fees for financing the management and final disposal of nuclear waste that has not been produced in the nuclear power plants. This waste comes from the civil research facilities as well as the discontinued military research program. The fee is also to cover decommissioning of the involved facilities.

Controversies in the licensing process

The license review marks a shift in the role of the Radiation Safety Authority. For the first time, it will be possible for the regulator to decide issues and make demands on SKB. The Environmental Court also will decide on issues. In the legal deliberations during the upcoming years, the following issues will have to be decided:

- The integrity of the engineered barrier systems in the first millennium;

- The integrity of the engineered barrier systems in the very long term;

- The alternative of deep boreholes;
- The choice of site; and
- Long-term safeguard requirements.

Integrity of the engineered barrier systems in the first millennium. The risk of serious damage to the copper canisters during the first thousand years before the bentonite becomes tight has already been discussed. The controversy is partly scientific but also involves issues of access to research results in reports that SKB has said are internal and have not been made available during the pre-licensing public consultation process.

Integrity of the engineered barrier systems in the very long term. If the controversy surrounding the integrity of the engineered barrier systems in the short term is decided favorably for SKB, there remain a number of issues regarding the long-term behavior of the barriers. These include: risks of copper corrosion and clay erosion during glaciation when groundwater chemistry could change considerably, risks that permafrost damages the clay in the repository, and risks that earthquakes caused by the burden of the ice sheet damage the repository.

The alternative of deep boreholes. The legislation governing the licensing of a repository requires that alternative disposal methods be examined. In the case of a KBS repository, it is generally agreed that the appropriate alternative is disposal in 3-5 km deep boreholes. Since the late 1980s, SKB has undertaken several studies of deep borehole disposal. Questions have been raised, however, as to whether these investigations have been serious or whether the company's main goal has been to remove the borehole alternative from the agenda. During the last five years, there been indications that the regulator is not yet satisfied with SKB's work on deep boreholes.

The choice of site. One controversial issue is that Forsmark is situated on a tectonic fault zone. Although SKB claims that the fault is now inactive, there is controversy over how a glaciation will affect the fault zone. Another issue is whether an inland site for a KBS-type repository might be safer than a repository at the coast. If the repository were sited in a so-called inland recharge area, a leak might take much longer to reach the surface. This is contested by SKB, but there are studies that show the time difference could be longer than 50,000 years.[311]

Long-term safeguard requirements. As the plutonium in the spent fuel in the repository has a half-life of tens of thousands of years and is weapons-usable, there may be a need for international surveillance for these long time scales. If other methods for disposal, for example deep boreholes, could make the waste less retrievable it would lessen this burden.

Finland's plan for a spent nuclear fuel repository

Finland has many similarities to Sweden when it comes to nuclear waste management, as well as some important differences. The most important similarity is that Finland plans to use the Swedish KBS method for a repository and has chosen a site.

Historically, Finland did not pursue nuclear weapons as Sweden did. In the 1970s, Finland decided to start a commercial nuclear power program and imported two pressurized water reactors from the Soviet Union and two boiling water reactors from Sweden.

The reactors were brought on line between 1977 and 1980 and are located at Olkiluoto and Loviisa. Finland is presently constructing a fifth nuclear reactor at Olkiluoto, designed by the French company, Areva.

The spent nuclear fuel from the two Soviet reactors was initially returned to the Soviet Union for reprocessing as per the original contract for the reactors. The spent fuel from the two reactors imported from Sweden was stored on-site. The first nuclear waste legislation was introduced in 1987, patterned on Sweden's legislation from the early 1980s. The responsibility for waste management was put in the hands of the nuclear industry and direct disposal of spent fuel was considered an option. A nuclear waste fund for financing repositories and decommissioning was also set up.

With the collapse of the Soviet Union, it became clear that the way the Russians managed their nuclear facilities would not be acceptable to the Finnish public. In 1994, therefore, Finland promulgated new nuclear legislation that stopped spent fuel export for reprocessing. Since there will not be any high-level reprocessing waste returned to Finland from Russia, Finland will only dispose of spent nuclear fuel.

Following the abandoning of reprocessing, Finland's two utilities, Fortum that owns the Loviisa plant and TVO that owns the Olkiluoto plant, decided to work together and follow the Swedish approach to final disposal of spent fuel. In 1995 the nuclear waste company Posiva was created to implement the KBS method in Finland.

Finland's site selection process has been much less complicated than Sweden's. Site screening was started in the early 1980s and by the early 1990s TVO was proceeding with site characterization studies at five sites, two of which were at the nuclear power plants. By the time Posiva was created, three sites remained and a fourth was added by the company before the final site evaluations were made.[312]

In 1999, Posiva decided to select a site beside the Olkiluoto nuclear power plant in Eurajoki. The decision was then taken to start building a hard rock laboratory, Onkalo, at a depth of 400 meters at the Olkiluoto site. The laboratory is to be used for site characterization and eventually expanded to create the repository. Finland's government has confirmed this strategy in what is called a "decision in principle."

Finland's decision-making process differs from that of Sweden and the proposed license for Finland's repository would be subject to a different, and perhaps less thorough, review. Posiva has indicated that it is planning to submit a license application for a Finnish repository in Olkilouto in 2012. Given the slower licensing review process in Sweden, there has been some speculation that Finland could start to build a KBS repository before Sweden.

Johan Swahn

9 United Kingdom

Over the course of fifty years, UK radioactive waste policy change has been coupled with institutional change without much progress towards the ultimate goal of safe, long-term stewardship of wastes.[313]

There has been enormous institutional change, with perhaps the most important stemming from the failed attempt to privatize the whole of the civil nuclear industry. A primary cause of this failure was the escalating costs associated with decommissioning and waste management.[314] As of 1 April 2011, the discounted cost of decommissioning the UK legacy nuclear sites was an estimated £44 billion ($70 billion).[315] Of this, the reprocessing site at Sellafield accounted for half.[316] As the ultimate result of this very large legacy, the national nuclear assets were split up.

The UK's newest reactors: fourteen uranium-oxide fuelled, graphite-moderated Advanced Gas-cooled Reactors (AGRs), with a total generating capacity of 7.5 GWe, and one 1.2-GWe pressurized water reactor (PWR) were sold to British Energy, now a subsidiary of Électricité de France. The reprocessing site and 30 older power reactors—mostly first-generation uranium-metal-fuelled Magnox gas-cooled reactors—and other legacy facilities were eventually turned over to a Nuclear Decommissioning Authority (NDA) established by the Energy Act of 2004 (Figure 9.1). All of the NDA's reactors are now shut down, except for four Magnox reactors with a total generating capacity of 1.4 GWe that are to be shut down in 2011/12.[317]

Location	Fuel type	Quantity (tons heavy metal)
UKAEA Dounreay breeder reactor R&D	Various (including 0.7 tons foreign)	14
Magnox power stations	Magnox fuel	180
Sellafield	Magnox fuel	1200
	Advanced Gas Reactor (AGR) fuel	2800
	Foreign light water reactor (LWR) fuel	750
	Other	470
British Energy reactor sites	AGR and PWR	440
France (Cadarache)	Zero Energy Breeder Reactor	about 8

Table 9.1: United Kingdom spent fuel inventory as of 31 March 2008.[318]

The UK had, as of 31 March 2008, about 6000 tons of stored spent fuel (Table 9.1). The Magnox fuel is all to be reprocessed in the dedicated B-205 reprocessing plant at Sellafield by 2016. About 2,500 tons of AGR spent fuel are contracted to be reprocessed in the Thermal Oxide Reprocessing Plant (THORP), also at the Sellafield site, along with about 600 tons of foreign light-water reactor (LWR) spent fuel remaining from about 5,000 tons of foreign reprocessing contracts.[319] No new foreign contracts are expected. For the moment, there are no contracts to reprocess the fuel of the British Energy's lone LWR. The NDA has contracted to take to Sellafield the spent fuel that is to be discharged by British Energy's AGRs in the future but has the option of storing that fuel for direct disposal in a geological repository if it decides to shut down the THORP plant, as currently planned, in 2020.[320]

Figure 9.1: UK nuclear reactors, reprocessing complex, and other sites controlled by the Nuclear Decommissioning Authority. These do not comprise all the nuclear reactors in the UK Fifteen power reactors are owned by Électricité de France. *Source: Nuclear Decommissioning Authority.*[321]

As of 1 April 2010, the United Kingdom had in storage, 850 m^3 of liquid and 766 m^3 of vitrified (glassified) high-level waste (HLW), 94,000 m^3 of intermediate-level waste (ILW), 66,000 m^3 of low-level waste (LLW) in storage and about 1 million m^3 LLW already disposed of in a near-surface facility near the village of Drigg close to Sellafield. The total volume of the HLW is expected to decline as the liquid HLW is vitrified and HLW is returned to countries that had their fuel reprocessed in the UK, but the volumes of ILW and LLW are expected to increase to 192,000 and 4.4 million m^3—primarily as a result of the decommissioning of the reprocessing plants at Sellafield (Figure 9.2).[322] The UK plans to store its high-level, intermediate-level and long-lived low-level waste in a common deep geological repository.[323]

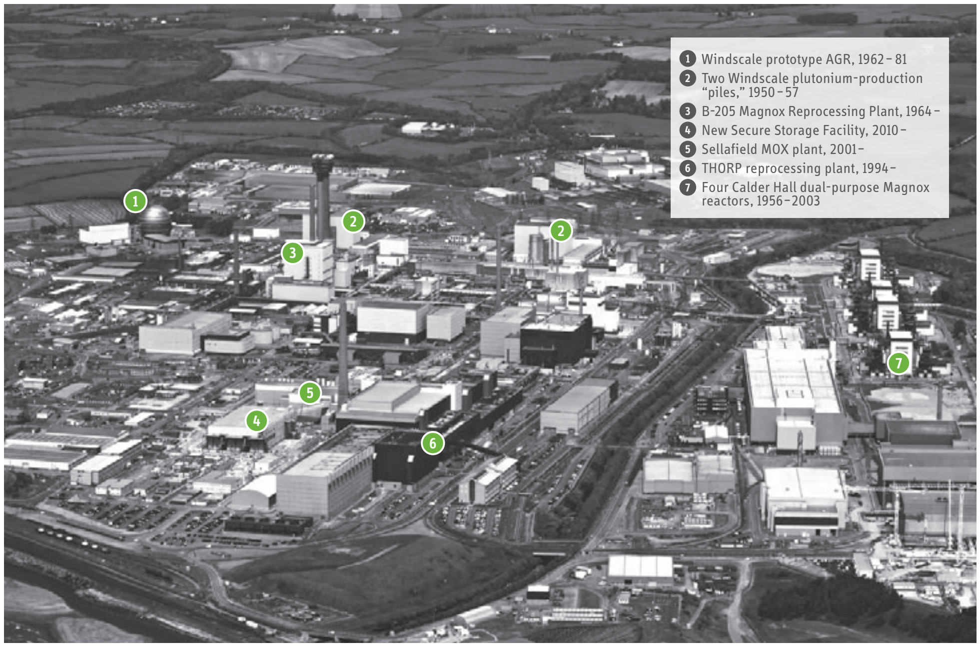

Figure 9.2: The Sellafield site in 2008. The decision to close the Sellafield MOX plant at the "earliest practical opportunity" was announced in August 2011.[324] *Source: Sellafield Ltd.*

As of the end of 2009, the UK also was storing 84.4 tons of its own separated civilian plutonium and 27.7 tons separated for other countries.[325] The size of the UK stockpile of separated civilian plutonium is enormous in weapon equivalents—approximately equal to the stockpile of plutonium that the U.S. produced for weapons during the Cold War.[326] The UK Government has launched a public consultation on options for disposing of it, with an expressed preliminary preference for placing the plutonium into MOX fuel and then managing the spent MOX fuel.[327]

In parallel with the process of establishing the Nuclear Decommissioning Authority, in 2003 the UK Government established the Committee on Radioactive Waste Management (CoRWM), an independent but publicly-funded group with an initial remit to develop a new and explicitly more legitimate policy process. This remit was amended in 2007 by creating a 'Mark 2' CoRWM with a more limited role of mainly scientific scrutiny of the policies developed by the first incarnation of CoRWM.

The changes in the ownership and management of the nuclear industry have been matched by a proliferation of regulatory and advisory agencies, with emphasis shifting to the need to demonstrate their independence not only from the nuclear industry, but also increasingly from government itself.

Against this background, the debate over UK radioactive waste policy has moved from a focus on claims about the 'facts' concerning radioactive waste, its hazards and disposal to an increasing emphasis on the processes by which decisions are made concerning these questions. The central task has become achieving broad social and political legitimacy for programs and policies that aim at management of radioactive waste.

Establishing an industry (1946 to 1976)

As in most other countries with civilian nuclear power, the UK has found it difficult to make any progress in implementing coherent policies for radioactive waste management, especially for higher activity wastes (intermediate level as well as high level—heat-generating—wastes). Policy has been piecemeal, relying on varying notions of scientifically best advice, and heavily conditioned, until very recent years, by a perceived need to protect spent fuel reprocessing.[328]

In the first 30 years of nuclear power development, from 1946 to 1976, government was in a constant hurry to develop nuclear technology. At first this was because of military imperatives. By the later 1950s, however, this had given way to a political desire to establish world leadership in civilian nuclear technology.[329] And, by the early 1970s, the issue had become the need to escape from dependence on oil, now apparently controlled by the OPEC cartel. In all this time, the strategic issue of the 'back end' of the nuclear fuel cycle—how to manage the processes of nuclear-facility decommissioning and waste management as a whole—was given limited attention, even though the political imperative to reprocess spent fuel was substantially complicating the technical challenge. There was some progress on management and disposal of radioactive wastes: sea dumping of solid wastes started in the 1950s and the shallow land burial site at Drigg was opened for low-level wastes. But decisions on high level, heat-generating waste from reprocessing were not made, though the Atomic Energy Authority (AEA) conducted major experiments on vitrification in the late 1950s and 1960s.[330]

In this early period, the dominant institution was the government-owned AEA, which controlled both military and civilian research programs. The AEA was essentially self-regulating. The Radioactive Substances Act in 1963 developed some formal criteria against which to judge radioactive waste management policy but the institutional dominance of the AEA was unchecked and remained outside parliamentary and departmental oversight. In 1965, the Nuclear Installations Inspectorate (NII) was established as the regulator of safety and health issues on all nuclear sites.

By 1971, as the UK civilian nuclear program faltered and the political strength of the AEA began to ebb, the military responsibilities of the AEA were taken from it and given to the Ministry of Defence, while a new publicly-owned company, British Nuclear Fuels (BNFL), was formed to carry out the AEA's "commercial" activities, principally fuel reprocessing at Sellafield. Government took limited strategic interest in radioactive waste management, preferring to leave it in the hands of the "industry"—primarily BNFL and the AEA, but with increasing influence from the state-owned electric utility, the Central Electricity Generating Board (or CEGB).

Politicization (1976 to 1997)

The 1970s saw a major change of context and the rapid politicization of nuclear power issues in the UK. First, the government and the CEGB announced ambitious plans to build at least 18 large new power reactors as a response to the first oil shock of 1973/74.[331] This generated a community opposed to nuclear power. By 1976, waste policy was caught up in the newly politicized process.

That year, the Royal Commission on Environmental Pollution published an eloquent and influential report on nuclear power and the environment.[332] For the first time, an official body had examined the radioactive waste issue thoroughly and with attention to the politics as well as the technical issues. This so-called "Flowers report", named after the Chair, Sir Brian Flowers, a distinguished member of the nuclear science community, made a large number of recommendations, the most significant being that government should not embark on a large program of nuclear power until it had established that there could be safe containment for high-activity wastes for the indefinite future. One important effect of the Flowers report was that government for the first time began to assume—in principle at least—strategic responsibility for radioactive waste management, and this responsibility was given to the relatively new Department of the Environment, where it has remained ever since. In addition, the government appointed an independent Radioactive Waste Management Advisory Committee (RWMAC) to advise ministers on radioactive waste policy.[333]

In 1977, a large public inquiry began on the proposal by BNFL to build a large new reprocessing plant at Windscale (as Sellafield was then known), mainly to cater to overseas demand, especially from Japan. The context of this proposal was a conviction on the part of BNFL—shared by government—that, in the wake of the 1973 oil crisis, there would be a burgeoning need for nuclear power worldwide. The related belief was that this would require a shift before long to fast breeder reactors, requiring plutonium-based fuel. As a number of countries likely to expand their nuclear capacity were not expected to build their own national reprocessing facilities, at least initially, the possibility of profiting from the UK's reprocessing capabilities was too tempting to forego. Under the terms of the reprocessing contracts to be signed with foreign utilities, the separated plutonium and uranium, as well as all wastes arising from reprocessing, would be returned to the country of origin. However, these contracts left open whether wastes would be returned in the relatively large volumes in which they would directly emerge from the process, or rather in much smaller volumes of high level waste containing the same amount of radioactivity as the original wastes. The latter "substitution" policy, committing the UK to permanently managing large volumes of relatively low level wastes of foreign origin, was finally endorsed by the government in 2004.

By 1978 the reprocessing plant (THORP) was approved, despite a large campaign that unsuccessfully tried to block it. The ringing endorsement given to reprocessing by the judge at the Windscale inquiry[334] was clearly at odds with much of the substantive evidence heard and resulted in a deep-seated public mistrust of the radioactive waste policy-making process.

In the late 1970s, the AEA began a drilling program to look for potential sites for high level wastes. Following intense local resistance at the chosen sites, the program was ended abruptly in 1981.[335] This led that same year to a decision, following advice from RWMAC, to shelve the question of a high-level waste repository formally for 50 years. The rationale was to allow the wastes to cool so that handling them would be easier and the costs lower. Attention then turned instead to finding new sites for low-level and intermediate-level wastes. A new industry-owned agency, Nirex, was created with a remit to search for potential LLW and ILW sites. Nirex pursued several different repository search programs in the 1980s, all of them abandoned in the face of local opposition—frequently just ahead of national general elections. A more measured program, started after 1987, led to the development of a proposal to site an ILW repository close to Sellafield.

Policy up to 1997 was often described as "decide, announce, defend" (DAD), meaning that the government, the nuclear industry and selected scientists would develop policy in a closed environment, then announce it and finally seek to defend it against the local and national opposition that ensued. Given the UK government's unwillingness to force radioactive waste management sites on resistant local populations, however, the word "abandon" had to be added. DADA was a fair representation of two decades of policy failure. Policy was developed more or less exclusively by a small group of nuclear industry insiders, with contributions from a limited part of the scientific/academic community, principally earth scientists on RWMAC.

In 1989, the government's plan to privatize nuclear power along with the rest of the electricity supply industry came unstuck.[336] First the Magnox reactors, and then the Advanced Gas-Cooled Reactors (AGR) and the prospective Pressurized Water Reactor (PWR) at Sizewell, had to be removed from privatization and kept in public ownership. Nuclear power was evidently substantially more expensive than fossil-based power and the expected costs of decommissioning and waste management in particular were expected to be high with major risks of serious future cost escalation. This episode deepened public mistrust of government and industry information and plans. It also threw the nuclear industry into long-lasting disarray. A formal moratorium on new nuclear plants until 1994 was followed by a decade in which nuclear new build was completely off the political and business agenda.

In 1993, a new Radioactive Substances Act became law, updating the 1960s legislation. But a 1995 White Paper on radioactive waste management proposed very little change to the status quo.[337] The Nuclear Installations Inspectorate, now a division of the Health and Safety Executive, continued to have responsibility for the safety licensing of all nuclear sites, including research and waste installations. Regulation of the environmental impact of nuclear sites was placed in the Environment Agency, a semi-autonomous government-sponsored regulatory agency, from which all nuclear sites had to gain approval for radioactive discharges. This division of responsibility did not always work well, and led to the NII and the EA signing a memorandum of understanding that more clearly spelled out the division of their responsibilities and provided a better basis for co-ordination between them.[338]

The central government also had divided responsibilities for nuclear power, even though the environment ministry, now re-named the Department of Environment, Food and Rural Affairs (DEFRA), remained the official lead for radioactive waste management issues. The Department of Trade and Industry (DTI) had responsibility for "commercial" aspects of nuclear power, including policy on nuclear electricity generation and oversight of BNFL, which had clean-up responsibilities, as well as reprocessing and fuel fabrication activities. This division worked reasonably well as long as nuclear new-build was off the agenda. However by 2005 new-build started to become prominent again and tensions emerged between the two Departments. DTI wanted a rapid "solution" to the radioactive waste management issue as a probable impediment to the approval of new build. DEFRA favored a less hurried approach.

Collapse of the old order (1997 to 2003)

Nirex's site selection process for a deep intermediate-level waste repository began in the early 1990s to concentrate on two nuclear sites, Sellafield[339] and Dounreay[340], with most attention concentrated on Sellafield. It was evident to the public and many stakeholders that the primary reason for this choice was the likely political acceptability of a repository in areas that were used to, and heavily dependent on, the nuclear industry. But, when a public inquiry was held in 1995/96 into the Nirex proposal to make Sellafield the national ILW disposal site, it faced formidable opponents in the shape of the Cumbria County Council and Friends of the Earth, both of which employed a wide range of credible expertise. The Inspector turned down the proposal on multiple grounds: process; scientific evidence; and economics and, in 1997, the UK government endorsed the Inquiry Inspector's crushing verdict.[341] The credibility of Nirex was so seriously damaged by the failure that it had little impact subsequently.

In 1999, the Science and Technology Committee of the House of Lords published a major new report on radioactive waste management,[342] recommending the establishment of a new Commission to oversee policy. Perhaps most importantly, the Committee argued that policy could only be made effectively if the public and stakeholders were engaged in the process from the start, and not just in seeking approval after the fact. That same year, a non-governmental but well-publicized "consensus conference" featuring a citizens' jury met to deliberate on the right way forward for radioactive waste strategy.[343]

DEFRA began to think of radically different policy-making processes. In this it was influenced by the growing tendency in other areas of policy involving science and technology to engage the unaligned public and relevant stakeholders in policy formation, as well as by the advice of RWMAC. This led, after substantial delay, to a consultation paper in 2001, *Managing Radioactive Waste Safely*,[344] which offered a fresh approach. It acknowledged the depth of public mistrust in the earlier policy processes and proposed the setting up of a new advisory body, the Committee on Radioactive Waste Management (CoRWM), to recommend, starting from a "blank sheet of paper," the right way forward for radioactive waste management policy.

Influenced by rapidly rising estimates of the costs of decommissioning and waste management and by the post-Thatcher neo-liberal consensus, the government also was keen to introduce mechanisms of competition into back-end management. This led to a White Paper in 2002 from the DTI, *Managing the Nuclear Legacy*.[345] The main overt purpose of this White Paper was to harmonize and rationalize back-end policy by creating a new public agency, eventually called the Nuclear Decommissioning Authority (NDA), to manage all public sector nuclear liabilities (military, civil and research), and to introduce a new system of long-term planning and international competitive bidding for decommissioning work. A less overt—but strongly pursued—objective was the privatization (and subsequently also the breaking up) of BNFL, which was now perceived by the government as an obstacle to efficient management of back-end activities.

Seeking public confidence (2003 to 2008)

When the government set up CoRWM in 2003 to consider long-term waste strategy,[346] it included spent fuel, uranium and plutonium, on the grounds that they also might be classified as waste in the future.[347] Other novel features of the CoRWM process were:[348]

- Its terms of reference gave equal weight to the objectives "to inspire public confidence" and to "protect people and the environment." The Committee was also enjoined to undertake wide-ranging public engagement.

- CoRWM was asked to start *without* pre-conceptions about the best long-term technological route for managing long-term radioactive waste. This became known as the "blank sheet of paper" approach and was criticized by some members of the scientific community on the grounds that international research had long since established that the best long-term management route was deep geological disposal and that it was therefore a waste of time (as well as a risk) to re-open an apparently settled question.

- CoRWM members were appointed from diverse backgrounds, including a founder member of Greenpeace UK, a lifelong scientific employee of the nuclear industry, the Chair of the Equal Opportunities Commission, and a citizen member of the 1999 consensus conference mentioned above. It also included academic social scientists.

CoRWM decided early on that, while good science mattered, the critical missing ingredient from previous policy had been public confidence. It therefore put most of its early effort into establishing an open dialogue with both the public (i.e., those without prior interests or commitments) and stakeholders.[349] CoRWM effectively extended the idea of the "blank sheet of paper" to its process, which was seen as vital to the development of legitimacy.

Much of CoRWM's work in its first year was devoted to deciding on a detailed program of public and stakeholder engagement. It took advice from the academic community and from specialists in engagement, and learned lessons from previous and largely unsuccessful attempts at engagement by the government, notably the *GM Nation*? debate.[350] In particular it developed the view that engagement must be as deliberative as possible, incorporating Ortwin Renn's notion of a "co-operative discourse"[351] in which the inputs of experts, public and stakeholders could be combined and synthesized.

The Committee used a wide range of broadly deliberative approaches, including Citizens Panels, discussion groups, a national stakeholder forum, nuclear-site stakeholder round tables, a web-based program and a large school project.[352] One external review commented that the CoRWM engagement program was the "the most elaborate and extensive to have been carried out in this kind of policy issue" and that CoRWM had "attempted to adopt a highly reflective approach to its task, scrutinizing its own assumptions to an extent that contrasts markedly with the technocratic approach taken in the past."[353] Listening was an integral part of the process.

This early concentration on engagement at the apparent expense of "sound science" created much political controversy. Both the Royal Society and the House of Lords' Science and Technology Committee criticized CoRWM in quite severe terms for its apparent pandering to public and stakeholder opinion at the expense of a rigorous scientific evaluation of the options. There also was internal dissent, with two members of CoRWM (both of whom eventually left the Committee) accusing the Committee of pursuing a dangerous post-modern and relativist view of the world (and of science in particular).[354] Although CoRWM did employ much scientific expertise, including "counter expertise," after it had narrowed its long list of disposal options down to a short list,[355] its technical work largely consisted of a review of existing scientific evidence, not the commissioning of new work.

CoRWM made its main recommendations to the UK government in July 2006.[356] Within the overall package of recommendations, three "pillars" stand out:[357]

1. Geological disposal as the end-point for all legacy HLW and ILW;

2. Robust interim storage, possibly for 100 years or more, as an integral part of policy (as well as acting as a fallback should disposal fail); and

3. For siting of major new facilities, a voluntarism and partnership approach between government/industry and the affected communities, including allowing communities to withdraw from negotiations up to a pre-determined point.

By mid-2006 the views of the House of Lords and other earlier critics had changed radically, and they supported the Committee's recommendations.[358] This gave a quite different and much more broadly-accepted and legitimate meaning to the disposal recommendations. Even those groups (for example Greenpeace) who remained strongly opposed to an early commitment to geological disposal of all wastes, including "legacy wastes,"[359] gave public support to the CoRWM process.[360]

The government welcomed the CoRWM recommendations and, in a statement in October 2006, accepted all its main recommendations, including the ideas of voluntarism and partnership.[361] Nirex was wound up and the government-owned Nuclear Decommissioning Authority was given responsibility for the long-term management of all UK radioactive wastes. NDA therefore now has executive responsibility for all "back end" activities, from initial decommissioning to final disposal of wastes. A new committee, retaining the name of CoRWM, but with new membership and new terms of reference, was established to provide advice to the government on implementation of the new strategy. It initiated a new round of official consultation that ended with a government policy statement in June 2008.[362]

A next generation of nuclear reactors (2007/10)

A potential threat to the ability of the government to pursue the new policy effectively is the re-emergence of the issue of nuclear new build. When CoRWM started work in November 2003, new nuclear power stations appeared to be off the political agenda for the indefinite future. An energy White Paper earlier that year had been lukewarm at best about nuclear power and explicitly stated that the government was not recommending new nuclear development. This meant that, in its early work, CoRWM could concentrate almost exclusively on the issue of legacy waste This was politically relatively uncontroversial as all parties recognized that a "least bad" solution had to be found for radioactive material that had to be managed as a result of past decisions. But, in late 2005, the political climate around nuclear power changed rapidly and it became clear that the Government had developed an enthusiasm for nuclear new-build. This led stakeholders opposed to new-build to become less co-operative in the process of finding ways forward for waste management.

CoRWM's response was to draw a clear distinction between the issues of legacy waste and new-build waste. Technically, there was no distinction. Both could be accommodated in the same stores and disposal sites. But creating new-build wastes was a choice, and there were alternatives. The political, social and ethical issues surrounding the deliberate creation of new wastes were therefore quite different from those arising from the inevitable need to manage the legacy.[363] CoRWM argued that the waste implications of any new build proposals would need their own assessment process.

Some parts of the government chose to ignore this message. In particular, in 2006, the Department of Trade and Industry represented CoRWM's views purely in terms of its endorsement of the technical similarity of legacy and new-build waste management solutions.[364] Greenpeace instigated a judicial review of the government's consultation process on the subject of nuclear power and a High Court judge found that the government's presentation had been "seriously misleading" precisely on the issue of legacy versus new-build waste.[365] One result of this judgment was that the government had to undertake a further consultation on nuclear power before finally announcing its new pro-new-build stance in January 2008.

The habit of conflation has persisted. In its June 2008 policy statement on radioactive waste management,[366] the government drew no distinction between legacy and new-build wastes. This has probably made the implementation of CoRWM's proposals with regard to the management of legacy wastes less straightforward. Given the open-ended nature of the government's commitment to building more nuclear power, it will be impossible to know exactly over what time period a potential site would need to receive wastes and in what volume. The process of finding a 'volunteer' community to negotiate with NDA and the government on an agreement to host a geological repository has been going slowly. One group of local authorities, those—not surprisingly—in the Sellafield area adjoining the UK's reprocessing complex, have come forward, however, to see if they can find a basis to start negotiations.

Conclusions

The UK experience with radioactive waste management policies suggests legitimacy has to be secured across at least four domains of policy—each influencing the legitimacy of the other. These domains are:

1. *The generation of radioactive wastes:* Radioactive wastes are an inevitable consequence of operating nuclear facilities. There is a range of principled objections that are made to the generation of all types of radioactive wastes.

2. *Storage versus disposal of radioactive wastes:* One of the fundamental choices facing radioactive waste management is about how long to maintain institutional stewardship over the materials. Storage as a policy option assumes continuity of institutional oversight over very long periods of time, while disposal removes the option that new knowledge and technology can be applied to the management of wastes in the future, and reduces active oversight over wastes.[367]

3. *Standards of protection:* Radiological protection standards have been formalized internationally since the 1960s, with national regulators interpreting recommendations developed by the International Commission on Radiological Protection. The validity of the science underlying recommendations on dose limits, as well as the practical implementation of such standards in specific places, has come under sustained critique. More broadly, there remain factual and normative questions about the application of such standards over the long-term future.[368]

4. *The safety of radioactive waste management:* Many conventional radioactive wastes have very long lifetimes, up to hundreds of thousands of years. By adopting the principle of containment, the management philosophy is to achieve near total control over these materials, so that they pose minimal risks to people in the future. Demonstrating the future safety of radioactive waste repositories has proven to be extremely problematic. A crucial issue relates to the kinds of actors who will be able to judge the validity of hypothetical safety assessments. Should these be experts alone, or a broader range of societal actors? And if the latter, do they need to be representative, and who would they represent—current or future generations of people?

The long and tortuous story of UK radioactive waste policy demonstrates that achieving legitimacy around the management of these wastes is a social process with long time horizons. After 50 years of policies, institutional change and debate, extraordinarily little has been achieved in securing the long-term disposition of wastes. This is in large part due to a failure to generate legitimacy around proposals. At least until the period of CoRWM, the fundamental conditions for open and reasoned discourse about the options did not exist. But the construction of legitimacy by demonstrating open and reasoned debate that appeared to have been secured under CoRWM may again be under threat. The UK government's new enthusiasm for a rapid and "streamlined" (read "more closed" and less deliberative) decision-making process for building new reactors creates the risk that the newly created conditions for legitimacy will now be undermined.

Gordon MacKerron and Frans Berkhout

10 United States

The United States operated its first nuclear reactors during World War II to produce plutonium for weapons. In 1955, the first naval propulsion reactor went into operation and, in 1957, the first reactor for generating electrical power. Today, more than 95% of the fission products stored in the U.S. are in spent power-reactor fuel.

Since 1970, the U.S. Government has been attempting to site a geological repository for spent fuel and the high-level waste (HLW) from reprocessing. Thus far, except for plutonium waste from weapons production, which is being disposed in the deep underground repository called the Waste Isolation Pilot Project, these efforts have failed for political or technical reasons or both. The most recent failure was of the $15 billion attempt by the U.S. Department of Energy (DOE) to establish a repository under Yucca Mountain in Nevada. That attempt was aborted as a result of sustained political opposition from the state of Nevada. In early 2010, the Obama Administration established a "Blue Ribbon Commission" to recommend a new approach.[369]

U.S. high-level waste (HLW) and spent fuel are currently in interim storage:

- The HLW waste from plutonium production is still at the production sites, where it is being mixed into glass and then stored awaiting deep underground disposal.
- Spent naval reactor fuel and HLW from the reprocessing of some naval fuel are being stored at the Idaho National Laboratory, also awaiting a deep disposal site.[370] By agreement with the state of Idaho, this radioactive waste is to be removed by 2035.[371]
- Almost all U.S. spent power reactor fuel is in cooling pools or dry cask storage at the power plant sites where it was produced, also awaiting a deep disposal site.

Given the lack of success in siting a permanent repository, there have been various attempts to establish large interim storage sites for U.S. power-reactor spent fuel. The U.S. Nuclear Regulatory Commission (NRC) has licensed one site in Utah to hold up to 40,000 tons of power-reactor fuel in air-cooled casks but its use has been blocked to date by political opposition from the state.

The situation is far from desperate, however. Interim storage can be prolonged. The NRC has concluded that spent power reactor fuel can be stored safely and with minimal environmental contamination on site for at least 60 years after the power plant that produced it has been shut down.

Origins

Plutonium production. The U.S. first generated high-level waste on a large scale in connection with its production of weapon-grade plutonium at the DOE's Hanford site on the Columbia River in Washington state (1944-87) and later at its Savannah River Site in South Carolina (1953-88). Approximately 100 tons of plutonium were produced at the two sites combined.[372] The associated HLW, containing somewhat more than one ton of fission products per ton of plutonium produced and about 1 percent of the plutonium, was stored in huge tanks for later disposal. Cleaning up the production sites, including immobilization of the HLW in glass ("vitrification") has been under way for more than two decades at the Savannah River Site and preparations for a similar vitrification project are underway at the Hanford Site. The associated spending rate is about $1 billion per year at each site.[373] A smaller amount of liquid HLW from a commercial spent-fuel reprocessing plant that operated from 1967 to 1972 is being vitrified in West Valley, New York.[374]

Naval nuclear propulsion. The propulsion reactors of U.S. nuclear-powered submarines and aircraft carriers have generated about 100 tons of fission products in spent fuel since the first U.S. nuclear submarine, *Nautilus,* went to sea in 1955.[375] Until 1992, the spent fuel was reprocessed at the Idaho Chemical Processing Plant. The reprocessing plant shut but the navy continues to send its spent fuel to the Idaho National Laboratory for interim storage.

Electric-power production. As of the end of 2010, U.S. nuclear power plants had generated about 64,500 tons of spent fuel.[376] This contains about 700 tons of plutonium and other transuranics and about 3000 tons of fission products. All but 2,800 tons of this spent fuel is stored at the sites of operating power plants.[377] An additional 2,000 tons of spent fuel are being discharged each year.

Disposal policy

U.S. high-level-waste disposal policy has gone through many changes of course in the past 50 years. Until 1976, it was assumed in the United States, as in other countries with nuclear power plants, that spent fuel would be reprocessed and the recovered plutonium used to provide startup fuel for plutonium breeder reactors. After India's 1974 nuclear test, which used plutonium nominally separated for its breeder reactor program, the Ford and Carter Administrations reviewed the economic case for reprocessing and breeder reactors and concluded that nuclear power would be both less costly and more proliferation resistant if spent fuel were not reprocessed.[378] U.S. nuclear utilities came to agree—at least with regard to the economics—and, in 1982, Congress passed the Nuclear Waste Policy Act (NWPA) instructing the Department of Energy to establish a geological waste repository that would accommodate power-reactor spent fuel as well as defense high-level waste and DOE spent fuel. The legislation required that the utilities pay $0.001 per nuclear kilowatt-hour generated toward the construction and operation of the facility.[379] This disposal fee has not changed since. As of early 2011, the unspent balance of the resulting Nuclear Waste Fund was approximately $25 billion and the annual revenues were about $0.75 billion.[380]

The 1982 NWPA instructed DOE to come up with three candidate repository sites. In 1987, Congress amended the NWPA to instruct DOE to focus its siting study on Yucca Mountain, Nevada, 160 kilometers northwest of Las Vegas.[381] Twenty-three years later, in March 2010, however, Secretary of Energy Steven Chu carried out a campaign commitment that President Obama had made to the state of Nevada and requested that the Nuclear Regulatory Commission (NRC) end the licensing process for the repository.[382] The NRC's Atomic Safety and Licensing Board initially rejected the Administration's request to withdraw the license application because

> "the NWPA does not give the Secretary the discretion to substitute his policy for the one established by Congress in the NWPA that, at this point, mandates progress toward a merits decision by the Nuclear Regulatory Commission on the construction permit."[383]

In October 2010, however, the chairman of the NRC instructed the NRC staff to stop working on the license, because Congress had not provided funding for continuing that work.[384] As of mid-2011, the five Commissioners had been unable to make a collective decision on the licensing issue. The States of Washington and South Carolina, joined by the National Association of Regulatory Utility Commissioners and a number of other interested organizations, have challenged the Obama Administration's action in court.

Interim on-site storage

Currently, almost all U.S. spent power-reactor fuel is still at the nuclear power plants. As the spent-fuel cooling pools at the plants have filled up, a process of transferring the oldest spent fuel to on-site air-cooled storage casks has begun to make space for newly discharged spent fuel. The casks come in a variety of designs: thick-walled cast iron casks and thin-walled steel canisters placed vertically or horizontally within thick reinforced concrete radiation shields with vents that allow outside air to cool the canister surfaces. A typical dry cask holds 10 to 15 tons of spent fuel.[385]

As of the end of 2010, 15,350 tons of spent power reactor fuel about quarter of the U.S. inventory, was stored in dry casks.[386] As of early 2011, all but eleven of the sixty five U.S. sites with operating nuclear-power reactors had either built or were seeking licenses to build dry storage facilities (Figure 10.1).[387] There were an additional ten storage facilities at sites where reactors are no longer operating and one independent storage pool in Morris, Illinois at a reprocessing plant that never operated because of a fatal design flaw.[388] In 2004, the U.S. Nuclear Regulatory Commission began to extend the initial 20-year operating licenses for dry-cask storage facilities to 60 years.[389]

The Department of Energy was obligated by the Nuclear Waste Policy Act of 1982 to begin taking spent fuel to a national repository by 1998. Its failure to do so has resulted in it having to pay the utilities the costs for expanding their on-site storage capacity. The Department of Energy projects that these payments will rise to $ 0.5 billion per year after 2020 if it does not take custody of the fuel.[390] This still amounts to only about $ 250 per kg spent fuel discharged per year—much less than the more than $ 1000/kg cost of reprocessing spent fuel.

Figure 10.1: Dry cask storage in the United States. Forty one casks contain 412 tons of spent fuel, the lifetime discharges from the Connecticut Yankee Nuclear Power Plant (0.62 GWe, 1968-1996, decommissioned 1998-2007) *Source: Connecticut Yankee Atomic Power Company.*[391]

On-site-dry cask storage requires a relatively small area and is inexpensive to maintain. This is true especially on sites with operating power reactors because guards are already present.

U.S. citizens groups concerned about the hazards of nuclear power have indicated that they prefer on-site storage to reprocessing of spent fuel and, in most cases, to central storage, which involves transport and is seen by many as a step toward reprocessing. They have called for spent fuel to be placed in on-site dry casks after at most five years of cooling in spent-fuel pools and for "hardening" the dry cask storage, including shielding the casks from attacks by, for example, placing them inside thick-walled buildings as is done in Germany and Japan.[392]

In 2010, the Nuclear Regulatory Commission updated its 1990 assessment of how long spent fuel could be stored on the power-reactor sites and concluded that on-site storage could continue safely for up to 60 years after the reactor that discharged the fuel was shut down.[393] Given that most U.S. reactors are expected to have their licenses extended to allow 60 years of operation, this means that the oldest spent fuel could be stored on site for 120 years.

Interim centralized storage

U.S. nuclear utilities are eager to demonstrate that the spent fuel will not stay on-site indefinitely. Thus far, however, all efforts to establish central interim storage facilities have been unsuccessful.[394]

The Oak Ridge Retrievable Surface Storage Facility. In 1971, after its first failed attempt to site a high-level-waste repository (see below), DOE's predecessor agency, the U.S. Atomic Energy Commission, decided to establish a long-term surface storage facility for vitrified high-level reprocessing waste. This led to a number of designs for surface storage, including air-cooled dry casks for solidified reprocessing waste quite similar to the casks that were later designed for storage of spent fuel. The proposal went no further, however.[395]

The 1982 Nuclear Waste Policy Act (NWPA) required DOE to come up with a proposal for one or more Monitored Retrievable Storage (MRS) facilities.[396] In 1985, the DOE proposed to build an MRS for spent fuel on a site in Oak Ridge, Tennessee that had originally been purchased for the cancelled Clinch River plutonium breeder reactor demonstration project. The community of Oak Ridge conditionally supported the proposal but the state of Tennessee, fearing that interim storage could become permanent, opposed it. The NWPA provided for the possibility of a Congressional override of state opposition. Instead, however, in 1987, Congress amended the 1982 Nuclear Waste Policy Act to block construction of a federal interim spent-fuel storage facility until after a construction license had been issued for a geological repository under Yucca Mountain.[397]

The NWPA also established a Commission to report to Congress on the need for interim storage and an Office of Nuclear Waste Negotiator to try to find communities that would be willing to host interim storage. In 1989, the Commission reported that centralized storage would be slightly more expensive than on-site storage at operating power plants and recommended only two small storage facilities:[398]

- A federal emergency storage facility with a 2000 ton capacity; and

- A utility-owned central storage facility with a capacity of 5,000 tons for spent fuel from shutdown nuclear power plants and from the few nuclear power plants that were having difficulty obtaining state permission to build on-site dry-cask storage capacity.

Despite some initial interest from Native American tribes in hosting interim storage, Congress cancelled the Office of Nuclear Waste Negotiator in 1993.

Private Fuel Storage. In 2005, the Nuclear Regulatory Commission granted a 20-year license with the possibility of renewal to Private Fuel Storage, a company owned by a consortium of U.S. utilities, to establish a central dry cask storage facility, with a capacity for up to 40,000 tons of spent fuel (Figure 10.2). The host was the Skull Valley Band of the Goshute tribe one of the groups of Native Americans that had volunteered to the Office of Nuclear Waste Negotiator. Its reservation is about 100 km from the Utah state capitol building in Salt Lake City. Only about two dozen of the 118 members adults and children in the Skull Valley Band of the Ghoshute tribe, including children, live on the 70 km^2 reservation and they were deeply divided over the project, even though it could yield them fees speculated to be as much as $100 million.[399]

Utah state officials strongly opposed the facility and, in 2006, under pressure from Utah's Congressional delegation, the U.S. Department of the Interior's (DOI) Bureau of Indian Affairs reversed itself and rejected the lease agreement for the site, and the DOI's Bureau of Land Management refused to permit transport of the fuel across the lands that it controls around the reservation. Four years later, in September 2010, however, a federal judge found these actions to be “arbitrary and capricious” and ordered the DOI to reconsider. The DOI decided not to appeal this ruling.[400] As of mid-2011, however, it had not taken any action.

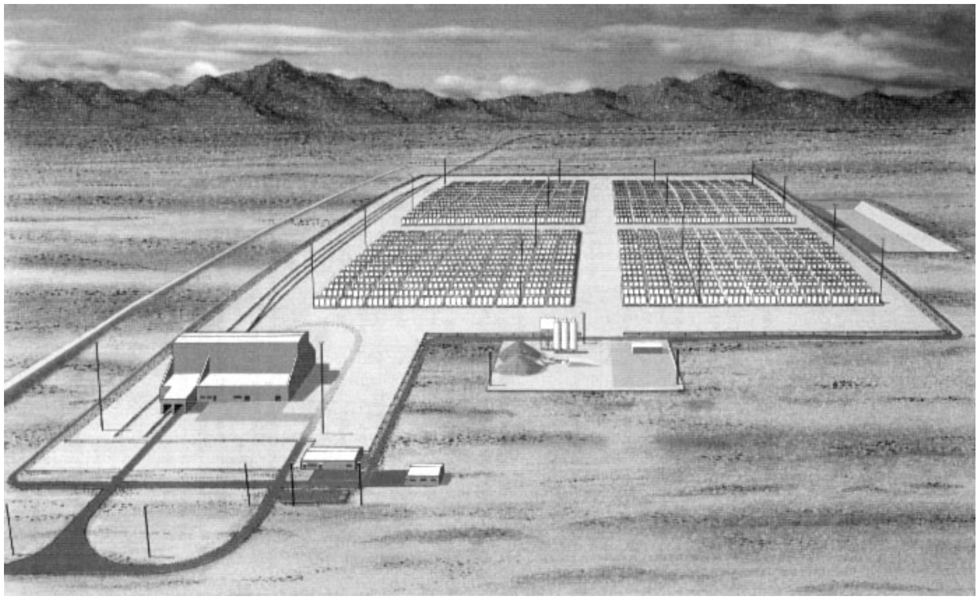

Figure 10.2: Artist’s conception of an interim storage facility in Utah licensed by the U.S. Nuclear Regulatory Commission in 2005 to store up to 40,000 tons of spent fuel in dry casks. The fenced area would only be 0.4 km^2. The U.S. Department of the Interior blocked construction in 2006, but, in response to a federal judge’s order, agreed in 2010 to reconsider.[401] *Source: Private Fuel Storage*

Ultimate disposal

U.S. Government efforts to establish a high-level waste repository have been marked for four decades by heavy handedness on the part of the federal government and political uprisings in a succession of states where it proposed to site repositories.

Lyons, Kansas Salt Mine. In 1957, in response to a request by the U.S. Atomic Energy Commission, the U.S. National Academies published a report on options for the disposal of the liquid high-level wastes generated by reprocessing.[402] The report recommended bedded salt as an ideal disposal medium because, at depth, salt flows and seals holes and cracks.

In 1970, the AEC announced the selection of an abandoned salt mine near Lyons Kansas as a national repository. The head of the Kansas Geological Survey urged that the integrity of the geology around the mine be investigated first. The AEC agreed but continued preparatory work, raising suspicions that it had prejudged the outcome. This stimulated opposition among concerned Kansas citizens and politicians. In 1971, the AEC was forced to abandon the site after a company that was using solution mining to recover salt nearby, disclosed that, several years earlier, it had lost 640 metric tons of water in the formation.[403]

The Waste Isolation Pilot Project. Community leaders in Carlsbad, New Mexico, where the major employer, U.S. Potash, had just closed its mine, heard of the failure of the AEC's effort in Kansas and offered its bedded salt deposit for consideration. Thus was born the Waste Isolation Pilot Plant (WIPP) project.[404]

Initially, the AEC proposed using WIPP for the disposition of the plutonium waste being generated by its Rocky Flats plant in the adjoining state of Colorado, where the AEC produced plutonium "pits" for U.S. nuclear weapons from 1952 till 1992. In 1977, however, the DOE announced that it was considering also using WIPP as a national repository for defense reprocessing wastes and spent fuel. New Mexico's political leadership reacted negatively and a state lawsuit ultimately resulted in:

- Congress legislatively limiting the scope of WIPP to defense-related wastes;

- The establishment of a quasi-independent Environmental Evaluation Group to provide reliable information to the state and local citizens; and

- Oversight of the repository design by the Environmental Protection Agency (EPA) under the Resource Conservation and Recovery Act, because the wastes included hazardous chemicals as well as plutonium.

In 1988, the DOE decided to accelerate the opening of WIPP after Idaho Governor Cecil Andrus used the state police to block shipments of plutonium waste from Rocky Flats to the Idaho National Laboratory for interim storage. Andrus announced that he would not allow further shipments until WIPP opened. In 1991, however, New Mexico sued again, this time to block the DOE from opening WIPP without EPA or state concurrence. This time, the state persuaded Congress to pass a law that:[405]

- Bans the use of WIPP for high-level waste,

- Limits the volume of wastes that can be buried there to 6.2 million cubic feet (176,000 m^3) and the total radioactivity to 5.1 million;[406] and

- Provided New Mexico with compensation of $20 million per year for 14 years.

In 1998, the EPA approved WIPP and it went into operation in 1999, the world's first geological repository containing ton quantities of plutonium.

The Yucca Mountain Repository. The 1982 Nuclear Waste Policy Act (NWPA) mandated that the DOE select three candidate sites for a geological repository for U.S. spent fuel and high-level waste.[407] In 1986, the DOE nominated sites in Texas (salt), Washington state (basalt) and in Nevada's Yucca Mountain (volcanic tuff).[408]

At the time, two of the most politically powerful members of Congress, the Speaker of the House and the House Majority Leader, represented Texas and Washington state respectively. They opposed siting the repository in their states. By comparison, the delegation from Nevada was politically relatively weak and so Yucca Mountain became the focus of attention.

Yucca Mountain was attractive as a repository site because it was in a desert area owned by the federal government[409] and the DOE had ranked it high with regard to containing radionuclides.[410] Yucca Mountain also borders the huge Nevada Test Site where 928 nuclear explosive tests were conducted between 1951 and 1992, one hundred of them above ground.[411] A considerable quantity of transuranics and fission products therefore already had been deposited on the site, both underground and on the surface.

In 1987, therefore, Congress amended the Nuclear Waste Policy Act to direct that Yucca Mountain would be the only site to be examined for suitability for the first U.S. geological repository.[412]

The 1982 NWPA had mandated that the second repository be in crystalline rock, i.e., in the eastern half of the country, where most of the country's power reactors are located. However, the 1987 amendments also instructed the DOE to "phase out in an orderly manner funding for all research programs … designed to evaluate the suitability of crystalline rock as a potential repository host medium."[413]

To reassure Nevada that other states would ultimately share the burden of hosting the nation's radioactive waste, Congress also set a legal limit on the amount of radioactive waste that could be emplaced in Yucca Mountain "until such time as a second repository is in operation." The limit was established as "a quantity of spent fuel containing in excess of 70,000 metric tons of heavy metal or a quantity of solidified high level radioactive waste resulting from the reprocessing of such a quantity of spent fuel."[414] This was approximately the cumulative amount of spent fuel and high-level waste projected for 2010.

The amendments therefore also required that the Secretary of Energy to report before 2010 on the need for a second national repository.[415] Secretary of Energy Bodman submitted the mandated report in 2008. It recommended that Congress remove the 70,000-ton limit on Yucca Mountain.[416] In fact, a year earlier, a report commissioned by the utility-owned Electric Power Research Institute had concluded that Yucca Mountain could physically accommodate 260,000 to 570,000 tons of spent fuel.[417]

The G.W. Bush Administration also launched a program to reprocess U.S. spent fuel and build fast-neutron reactors that would fission the long-lived transuranic elements. It was argued that if, in addition, the 30-year half-life isotopes, cesium-137 and strontium-90 were stored on the surface for hundreds of year to decay, the heat output of the waste would be so reduced that it would be possible to increase one hundred-fold the amount of spent fuel whose residual wastes could be deposited in Yucca Mountain.[418] One could well ask why not store the unreprocessed spent fuel above ground in interim storage for hundreds of years at one tenth the cost?[419] In any case, key members of Congress became skeptical about the cost of the Bush Administration proposal and also became concerned that it might undermine U.S. policy to discourage the spread of spent fuel reprocessing to additional countries. As a result, the Bush Administration failed to contract for the construction of a reprocessing plant before it left office. The Obama Administration decided to scrap the initiative but has continued with a broad R&D program on "advanced fuel-cycle technologies."[420] It appears likely that the Blue Ribbon Commission will encourage a continuation of this policy.[421]

Not surprisingly, the 1987 amendments to the Nuclear Waste Policy Act were seen as illegitimate in Nevada. The state government and its Congressional delegation therefore united in an effort to kill the Yucca Mountain repository.[422]

This effort was provided ammunition by a number of disturbing findings from the DOE's underground exploration of Yucca Mountain. One was that rainwater was seeping down to the repository level much more quickly than had been assumed. The spent-fuel canisters therefore could be exposed to dripping water carrying salts leached out of the rock above. The DOE therefore proposed to add costly titanium drip shields to protect the canisters—but only just before closure of the repository, at least a hundred years after it was opened, with remotely operated machines, since the tunnels would be too hot and radioactive for humans. This proposal was greeted with some skepticism.[423]

A second issue that was raised was that there have been numerous volcanic eruptions in the immediate neighborhood of Yucca Mountain, the most recent less than 100,000 years ago.

The DOE spent more than $15 billion (2010 $) trying to establish the suitability of Yucca Mountain.[424] This included building a 7.6-meter-diameter, 8-kilometer-long U-shaped tunnel into and along the length of the proposed repository level (Figure 10.3). The tunnel was sized on the assumption that it would become the main tunnel in the repository. A second smaller tunnel was built across the repository and hundreds of vertical boreholes were drilled down through it from the surface.[425] The resulting data provided the basis for the DOE's "Viability Assessment."[426] According to the official peer review panel for the DOE's Total System Performance Assessment, however, all this effort only succeeded in establishing the complexity of the site's geology and the resulting uncertainties in its performance.[427]

Figure 10.3: Workers carried in an open rail car enter the main tunnel under Yucca Mountain. The white tube above their heads carries ventilation air.[428] *Source: Las Vegas Sun.*

In 2002, the Secretary of Energy, with President Bush's support, certified that the Yucca Mountain site was suitable. Nevada objected, but Congress quickly overrode its veto, as allowed by the NWPA.

The state of Nevada mounted numerous challenges in federal court to the quality of the work underlying the Bush Administration's finding of suitability. Most of these challenges were rejected, but one was upheld. In 1985, the Environmental Protection Administration had limited the performance requirement for the repository to 10,000 years. In 1992, however, Congress included in the Energy Policy Act of 1992 the requirement that the EPA's performance requirements be guided by the findings of a panel selected by the National Academy of Sciences (NAS).

In 1995, the NAS National Research Council panel recommended that the performance requirements extend out to the period of projected peak doses to the public "tens to hundreds of thousands of years or even farther into the future."[429] These peak doses would occur after the canisters and fuel had corroded through and the long-lived transuranics and fission products had migrated to and then through the aquifer and reached the water supply of the nearest down-stream population. In 2004, the U.S. Court of Appeals for the District of Columbia Circuit found that, since the 10,000-year standard was not in conformity with the findings of the National Research Council study, the EPA should reconsider the standard. The EPA did so and, in 2008, issued limits on radiation doses to the most exposed individual out to a million years.

The individual dose limits were set at 0.15 milliSieverts per year out to 10,000 years and 1 mSv/yr from then to 1 million years after disposal and were to be calculated from the average of the uncertainty range in the projections.[430] These dose rates would today bring with them an estimated additional risk of cancer death on the order of about 0.1 and 0.5 percent respectively as a result of 70 years exposure.[431]

In 2006, Nevada Senator Reid became Senate Majority leader and was able to cut the funding for the Yucca Mountain repository project. Then, in 2008, both of the leading Democratic presidential candidates, while campaigning against each other in Nevada, committed that, if elected, they would end the Yucca Mountain project. Barak Obama delivered on his commitment in 2010.

The Blue Ribbon Commission. In January 2010, as a first step toward establishing a new U.S. spent-fuel policy, the Obama Administration launched a Blue Ribbon Commission on America's Nuclear Future "to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle and to provide recommendations for developing a safe, long-term solution to managing the Nation's used nuclear fuel and nuclear waste."[432] The Commission issued an interim report in July 2011 that recommended that as the basis for new policies for managing spent fuel and radioactive waste, the United States:[433]

- Adopt an "adaptive, staged, and consent-based" approach to siting future nuclear waste management facilities, with a "heavy emphasis on consultation and cooperation" and based on "encouraging communities to volunteer to be considered to host a new nuclear waste management facility … [and] allowing for the waste management organization to approach communities that it believes can meet the siting requirements;"

- Establish a new government body to administer the waste management program, including responsibility to "site, license, build, and operate facilities for the consolidated interim storage and final disposal of civilian and defense spent fuel and high-level nuclear waste" as well as "safe transport of waste and spent fuel to or between storage and disposal facilities, and for undertaking [related] research, development, and demonstration (RD&D) activities;"

- Move promptly to develop one or more centralized interim storage facilities and one or more geologic disposal facilities; and

- Support R&D on nuclear reactor and fuel cycle technologies that recognize the importance of "all elements of the fuel cycle," including "waste transportation, interim storage, and disposal" and "safety, security, and non-proliferation."

The Blue Ribbon Commission is expected to issue a final report in January 2012.

Frank von Hippel

11 Multinational Repositories

There has been sustained interest in the possibility of multinational spent fuel storage facilities or geological repositories. Thus far, however, there has been only very limited progress in proceeding towards implementation. A few proposals have failed, leading many to conclude that there would have to be one or more *national* repositories or at least centralized storage facilities before multinational facilities can be seriously considered. At the same time, many of the countries contemplating multinational facilities have invested in interim dry storage at their reactor sites that can be expanded to suffice for many decades. They therefore see little urgency in figuring out what exactly to do ultimately with their spent fuel. The lack of any urgency is of course still more the case for countries only now beginning to consider starting nuclear power programs.

There are many arguments in favor of the development of shared facilities in a few countries to which other countries could send their spent fuel for long-term interim storage and/or eventual disposition. Such facilities could take advantage of economies of scale, provide more time for countries to decide on fuel cycle strategies, and strengthen the nonproliferation regime.

Shared spent fuel facilities could be an option both for interim storage and for final disposal. They could be add-on facilities where a country storing or disposing of its own spent fuel is willing to accept spent fuel from other countries; or facilities constructed and managed through a partnering approach by several countries, which could be regional, international, or multinational. The remainder of this chapter reviews briefly:

- The history of past attempts to study and promote shared spent fuel facilities;
- The cases of some of the countries which might be most interested in shared facilities;
- The potential advantages and disadvantages of shared facilities; and
- Some current initiatives.

Past attempts

The idea of shared spent fuel facilities is not new. In 1975, in the wake of India's nuclear test using plutonium separated in a national reprocessing plant, the IAEA undertook a study examining a multinational approach to nuclear fuel cycle facilities, and although the study identified several advantages, no steps were taken to develop the concept further.[434] The study envisaged facilities for "spent fuel storage, fuel reprocessing, plutonium fuel fabrication and waste disposal" as a combined package, either in the same location or in different locations.[435] In the late 1970s and early 1980s, the International Fuel Cycle Evaluation (INFCE) study of the IAEA further investigated possible international arrangements for spent fuel storage, but concluded that in the short term, no demand existed.[436]

In 1987, the OECD's Nuclear Energy Agency published a study on possible international approaches to spent fuel disposal. It noted that "there were two basic approaches to international waste repositories: an international project from the very beginning, or the extension of a national project, on a commercial basis, to accept additional material from other countries. The creation of an international repository through the commercial extension of national programmes was judged to be a more credible route than the formation of an international project."[437]

Although the study committee concluded that there were no insurmountable technical or institutional obstacles to international approaches, but that, "because of slow progress in the development of national repositories [it] did not believe that the time was right in 1987 to embark on a comprehensive generic study."[438] As the other chapters in this report show, more than two decades later, progress in the development of national repositories is still slow and, in some countries, includes a ban on the import of foreign spent fuel.

Three failed projects from the 1990s, exemplify the difficulties of finding sites for multinational spent fuel facilities:

- In 1995, the President of the Marshall Islands proposed hosting a storage and disposal facility, but the idea ran into strong opposition from other Pacific states and the United States. There was also fierce local opposition.[439] The idea was dropped when the government changed.

- Also in the mid 1990s, a U.S. based group, U.S. Fuel and Security, with support from the Russian Ministry of Atomic Energy,[440] initiated a scheme involving fuel storage on a Pacific Island—initially Wake Island and then later Palmyra Island. The scheme was met with strong opposition from the U.S. Administration, and was not pursued further. The Pacific Islands Forum, formerly the South Pacific Forum, a political grouping of sixteen independent and self-governing states in the Pacific, condemned the idea of using Palmyra as a "dumping ground for nuclear waste."[441] All six members of Hawaii's Congressional delegation signed a June 1996 letter to U.S. President Bill Clinton urging him to resist the project.

- A third project was initiated by organizations in several countries, including Pangea Resources, a British-based company, to develop an international repository in West Australia. Political opposition in Australia stopped further progress on the scheme.[442]

Around 2000, attention turned to the Russian Federation, with its nuclear expertise and need for foreign investment, as a potential international host for spent fuel. Russia's Ministry of Atomic Energy (Minatom) was interested but the U.S. Government had prior consent rights over most of the spent fuel in potential customer states such as South Korea and Taiwan. Also, the U.S. did not have an agreement for nuclear cooperation with Russia at the time. Such an agreement would be required before spent fuel subject to U.S. consent rights could be exported to Russia or reprocessed there as Minatom preferred.

A group of entrepreneurs organized the U.S. based Non-proliferation Trust to try to obtain the agreement of cooperation in exchange for a share of the proceeds and control over the disbursement of a larger share for various worthy causes in Russia. But Minatom was unwilling to cede so much control to a foreign entity and the U.S.-Russia agreement of cooperation was delayed by a decade by U.S. concerns over Russia's technical assistance to Iran's nuclear program.[443] Nevertheless, as discussed further below and in the chapter on Russian spent fuel policies, Russia today is one of the few countries willing to accept foreign spent fuel—although currently only fuel that it has supplied and with the presumption that the spent fuel will be reprocessed to recover its contained plutonium.[444]

As a result of the confrontation over Iran's enrichment program, there has been a new round of interest in multinational fuel-cycle facilities, including spent-fuel facilities. In 2004, an IAEA expert study group published an analysis of such facilities, with a focus on repositories.[445] In 2005, the IAEA published an overview of the issues associated with multinational facilities, including spent-fuel repositories and storage facilities.[446] The 2004 study concluded that "the global advantages of multinational repositories are clear and the benefits can be significant for all parties, if they are equitably shared," and suggested further studies.[447] The 2005 report concluded that, for countries "with smaller nuclear programmes, a dual track approach [to repositories] is needed in which both national and international solutions are pursued. Small countries should keep options open (national, regional, or international), be it only to maintain a minimum national technical competence necessary to act in an international context."[448] The report also advocated that "countries with state-of-the-art storage facilities in operation should step forward and accept spent fuel from others for interim storage."[449]

Countries with small nuclear power programs

Today, there are 30 countries with civilian nuclear power programs (including Taiwan, Figure 11.1). Many of the 17 countries with 5 or more reactors deployed appear to have accepted the principle of national responsibility for their spent fuel—that is that there will be no export of spent fuel except under certain specified conditions, and, for the most part, no import either. For example, the principles for disposal proposed by Germany's AKend Committee (see chapter on Germany) were: safety first, geological disposal as the only sustainable option; national responsibility—no export from or import to country, and responsibility of today's generation.[450] The OECD countries and the EU have agreed to ban exports to non-OECD countries of nuclear wastes intended for final disposal.

As Finland appears to be demonstrating, a country with a small nuclear program can design, site and build an affordable spent-fuel repository. Indeed, the estimated cost per ton of Finland's repository is comparable to the estimated cost for countries with much larger nuclear programs.[451] (Finland currently has a nuclear capacity of 2.7 GWe.) Nevertheless, the greatest interest in shared facilities so far has been coming from countries with small nuclear programs, such as those involved in the SAPIERR initiative, discussed later. Thirteen of the 30 countries at present have fewer than 5 reactors (Figure 11.1).[452]

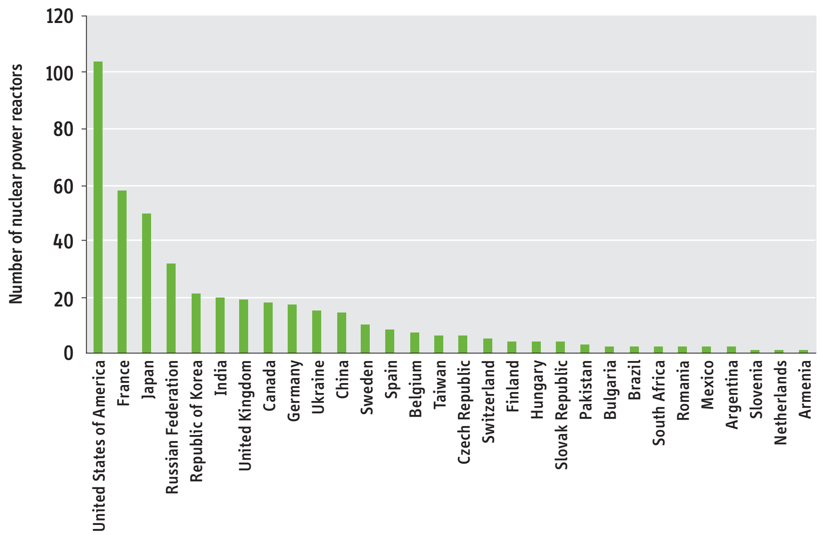

Figure 11.1: Number of operational reactors per country. *Source: International Atomic Energy Agency.*[453]

In addition to the countries that already have nuclear power, more than 30 other countries have indicated an interest in acquiring nuclear power plants. These include some of the smaller countries in Europe, several countries in the Middle East and North Africa, a few other countries in Africa, several countries in Asia, and three countries in Latin America.[454]

For most countries, thinking about the development of geological repositories is at an early stage. Even in the few countries that are developing repositories, operational targets are in almost all cases beyond 2025. As the IAEA has noted, the small programs "started later than countries with more advanced nuclear power programs. Therefore the need for geological disposal appeared later."[455] Elsewhere, the IAEA has noted that, "given the small quantities of radioactive waste arisen in these countries [with small nuclear programs], it may be even more difficult to convincingly present the need for a national disposal program. Consequently, time schedules for their implementation are shifted far into the future."[456]

Dry-cask storage allows a country many decades to make a final decision on long-term geological disposal. Indeed, the IAEA has recently pointed out that some un-named countries are already contemplating "storage periods of 100 years and even beyond."[457] More specifically, the IAEA notes that "some countries, like Hungary, Bulgaria, Argentina, or Lithuania, have chosen to postpone a decision on long-term spent fuel management. Other countries such as Slovenia and Romania, have taken strategic decisions on geological disposal but have kept open other options such as the development of multinational repository or the export of spent fuel."[458]

Hungary, for example, reported to the Nuclear Energy Agency (NEA) in 2009 that "due to the interim storage of the spent fuel, there is no immediate need to establish a deep geological repository before the middle of the century. … However, as site selection process for such a deep geological repository requires a very long period of time, some preliminary exploratory works were done in a promising clay-stone formation."[459] Norway (which at present has only a research reactor) provides another illustration, reporting in 2009 that it had decided "to construct an engineered surface-storage facility with sufficient capacity for all the radioactive wastes generated in a period of at least 100 years." However, Norway had done preliminary exploratory studies and concluded that "there are no safety-related factors that would prevent the deep underground disposal of radioactive waste in salt."[460] Spain is following a similar path, in this case undertaking to increase the storage capacity of reactor pools by means of re-racking, and constructing dry-cask storage facilities, while studying non site-specific designs for repositories in granite, clay and salt.[461]

Advantages, challenges and disadvantages

According to the IAEA: "Several studies have identified the potential benefits, in terms of possible economic, nonproliferation, safety and security advantages, of multinational disposal as well as the institutional and political issues standing in the way."[462] The claimed potential advantages are several:

Economies of scale: Theoretically, one would expect that a larger repository would be less costly per ton of spent fuel disposed. For example, a study by SAPIERR based on cost models developed by projects in Sweden, Finland, and Switzerland found savings of 5 to 10 percent from building one repository instead of two, each with half the capacity. SAPIERR projects much greater savings for the case of 14 small nuclear countries sharing a single European repository.[463] The significance of this result is not clear, however, since, siting politics may contribute more than such savings to the cost. Indeed the estimated cost per ton of the Yucca Mountain repository, the largest proposed thus far, was larger than that for the smallest, Finland's repository.[464]

Safety and security: Increasing the number of sites increases the risk that some will contain inadequate safety provisions to prevent leaking of radioactive wastes and inadequate security to protect against penetration by sub-national groups to obtain plutonium.

Suitable geology: Although the studies that have so far been carried out suggest that repository concepts can probably be elaborated and adopted to many different types of host media, some countries may not have geology optimal for deep disposal.

Nonproliferation: Finally, there would be nonproliferation benefits to limiting the number of long-term storage sites and repositories. More than a hundred years after discharge from the reactor, the gamma radiation field around the spent fuel will no longer be sufficient to make the fuel self-protecting and the extraction of plutonium will require substantially less shielding (see chapter 1). Also, sending spent fuel out of the country for long-term storage and/or eventual disposal would undercut domestic political support for reprocessing. Russia has required that Iran ship the spent fuel from the Russia-supplied Bushehr plant back to Russia in response to international concern that Iran might reprocess the fuel.

One challenge to any shared facility is the international transportation of spent fuel that would be required. To our knowledge, there has not been a thorough analysis of this issue. The IAEA study on multilateral approaches does emphasize the obligation of countries to ensure that any transport will be done safely. There is, of course, a considerable history of international transport of both spent fuel and high-level reprocessing waste due to France, Russia and the UK providing reprocessing services to other countries.

A second challenge would be the complexity of the arrangements that would have to be worked out for multinational facilities. Such arrangements would have to address:

how the host facility would be funded and managed; the rights of the host country to terminate foreign use of the facility and to return the spent fuel; the rights of foreign users to withdraw their spent fuel before it is finally disposed; and the coverage of IAEA safeguards if the facility is shared by weapon states and non-weapon states.

The principal obstacle to either an add-on or multinational repository, however, would be the difficulty of finding a country willing to accept spent fuel from another—at least on a permanent basis. This unwillingness derives from a general reluctance of communities to host repositories for radioactive waste even for wastes arising within a country.

There are two normative problems with shared repositories. The first problem stems from the ethical argument that those enjoying the benefits of nuclear power should also incur the costs.[465] There is already a general agreement that countries should not export their hazardous waste.[466] Proponents of shared repositories counter this argument, however, by asserting that the host country would be paid very generously to accept the spent fuel. This leads to the second problem that any transfer of spent fuel from one country to another in exchange for monetary payment does not engender adequate responsibility.[467] This goes against the principles of environmental justice; it is considered wrong to inflict environmental harm on a poorer country (or community) even it is willing to accept payment for the harm.

Possible paths forward

Foreign spent fuel in national facilities. One general possibility would be for one or more of the advanced nuclear countries planning to construct their own long-term storage sites or repositories to accept spent fuel from other countries—the "add-on approach." So far, no country has offered to do this except under limited conditions.[468] Both the United States and Russia, for example, are currently importing spent research reactor fuel to support the objective of the Global Threat Reduction Initiative to convert research reactors from HEU to LEU fuel.[469]

One option that is open to countries is to send spent fuel to France for reprocessing.[470] Doing so does not, however, solve a country's radioactive waste problem. Although at one time France (and also the UK) accepted spent fuel from Japan and European countries without demanding that the high-level waste from reprocessing be returned to the country of origin, France now insists that it be returned. Partly because of this stipulation and also the high costs charged for reprocessing, almost all the countries which in the past have sent their spent fuel to France and the UK for reprocessing have decided to handle their spent fuel domestically.[471]

Russia too is willing to accept foreign spent fuel for eventual reprocessing but has a more ambiguous policy than France concerning the return of the high-level waste. When Russia changed its laws to allow the import of foreign-origin spent fuel, national opinion polls showed that 90 percent of all Russians were against importing spent fuel.[472] Environmental NGO efforts to collect the necessary number of signatures to force a referendum on the new law were stymied, however, by President Vladimir Putin's electoral commission which (arbitrarily) threw out a large number of signatures. The petition drive in Krasnoyarsk, the nearest city to Zheleznogorsk, was nullified by the Supreme Court. Thus, "the local target population—like the larger Russian public—was denied a voice in making this important decision."[473] But, thus far, this public opposition has resulted in Rosatom limiting its spent fuel imports to Russian-origin fuel, i.e., originally exported from Russia.[474]

In the case of Russian-origin spent fuel, Rosatom is willing to import the fuel for either reprocessing or long-term storage. The charge for storage and/or reprocessing is of the order of $700 per kg of spent fuel.[475] If the fuel is accepted for storage, at the end of the contracted period the fuel owner would have to choose between taking back the spent fuel, extending the storage, or giving consent to reprocessing. Currently, Russia's only customers for these services are Bulgaria and Ukraine.

Though it would be attractive on nonproliferation grounds for countries with large nuclear programs to accept foreign spent fuel without reprocessing, this does not look likely at present. For example, in essays published in 2010 by the American Academy of Arts and Sciences, the contributors from both Japan and the United States strongly advocated that the latter be willing to accept spent fuel from countries with smaller nuclear programs. In this same collection of essays, however, Ellen Tauscher, U.S. Undersecretary of State, while agreeing that it could be in the U.S. and global interest to do so, pointed out that Congressional opposition to such imports was likely.[476]

The United States and Japan have reportedly been discussing with Mongolia the prospect of that country accepting spent fuel.[477] This would allow Japanese and U.S. reactor vendors, in combination with Mongolia, to offer to their foreign customers the same complete package of a reactor plus fuel-cycle services that Russia offers. Transporting spent fuel to Mongolia would involve the use of the Trans-Siberian railway (Figure 11.2).

These discussions became public two months after the Fukushima accident.[478] This led the Mongolian authorities to issue a statement denying plans to bring nuclear waste to the country and pointing out that "Article 4.1 of Mongolia's law on exporting and banning import and trans-border shipments of dangerous waste unequivocally bans import of dangerous waste for the purpose of exploiting, storing, or depositing."[479]

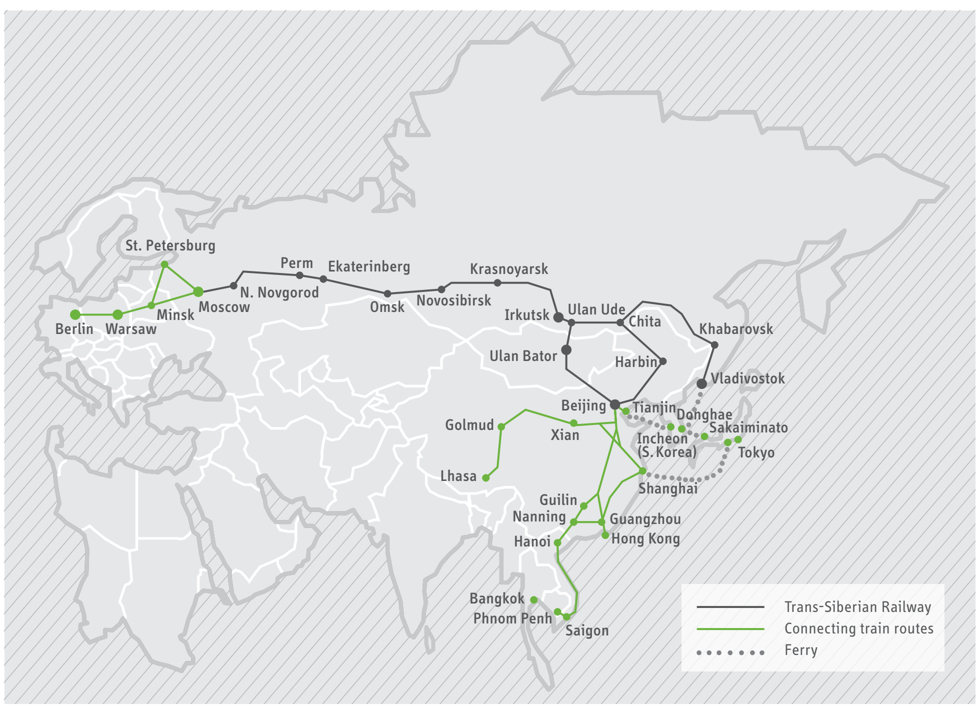

Figure 11.2: Trans-Siberian railroad and links to it that could allow spent fuel to be transported to Mongolia from Western Europe and East Asia. *Source: Adapted from "The Man in Seat 61" website.*[480]

Multinational spent fuel facilities. An alternative to a single nation constructing a spent-fuel storage facility or repository and offering its use to other countries would be for several small countries to band together to construct a multinational facility. As described by Charles McCombie, a champion of this approach, siting of the multinational repository would proceed under a series of guidelines, including: that the countries should establish agreed upon technical criteria for siting, and that potential host sites must self-identify with voluntary expressions of interest at the local level.[481]

The most advanced effort to explore such multinational arrangements is the Strategic Action Plan for Implementing European Regional Repositories (SAPIERR II) funded by the European Commission. This effort has led to the establishment by the European Union of a working group on a European Repository Development Organization (ERDO).[482]

In July 2011, the European Commission adopted a directive for disposing of spent fuel, including radioactive wastes from nuclear power plants and from medical and research facilities. It sets compulsory and legally enforceable standards for all European Union member states. It does not specify specific disposal strategies, but it does permit two or more member states to share a disposal facility and also allows exports of spent fuel and radioactive waste—but not to African, Caribbean, or Pacific countries.[483]

Conclusion

The establishment of add-on or multinational spent fuel storage facilities and repositories, where countries with small nuclear programs could send their spent fuel has some potential attractions, especially if a host of new countries deploy nuclear reactors. So far, however, only Russia has been willing to accept foreign spent fuel—and that only if it is Russian origin. Given the general difficulty in locating geological repositories and centralized storage facilities even for exclusively national radioactive waste, this is not surprising. The difficulty with siting a repository means that there is an incentive for countries to seek external solutions independent of other considerations, but that also offers little incentive for a country to complicate its siting politics further by adding the issue of foreign wastes.

The lack of a shared or multinational spent fuel facility is not yet a show-stopper for efforts to prevent the accumulation of spent fuel in every country with a nuclear power plant. The alternative of dry-cask storage allows a grace period of decades before a final decision will have to be made on long-term disposal.

There could be one real benefit, however, if an arrangement could be made in the near term for countries to send their spent fuel out of country for storage. This would be if such an alternative prevented a new generation of countries from pursuing the existing out-of-country option: sending their spent fuel to France or Russia or perhaps elsewhere for reprocessing.

Despite the interest in many countries in exporting their spent-fuel problem and to the international community in general of consolidating long-term spent-fuel storage and disposition, thus far, no country appears ready to host a multinational spent fuel facility or to accept spent fuel from other countries except for reprocessing.

Harold Feiveson, M.V. Ramana, and Frank von Hippel

Technical Background

12 Interim Storage and Transport

The fission products and transuranic elements in spent fuel generate heat and penetrating radiation that decline with time as the shorter half-life isotopes decay away. Arrangements for storage and transport therefore require robust radiation shielding and cooling. During the first years after discharge, both are provided by a deep pool of water next to the reactor. After several years, air cooling is sufficient but a thick-walled cask is required for radiation protection.

During the first few years, while water cooling is required, loss of coolant could result in an overheating accident. The temperatures reached could be high enough so that the zirconium metal cladding of the fuel could ignite in air and lose its integrity resulting in a release of volatile fission products—most importantly, 30-year half-life cesium-137, the primary source of the long-term land contamination by the Chernobyl accident. Spent fuel pools are very robust and a complete loss-of-coolant accident has never happened. The potential vulnerability of some spent-fuel pools to an airplane crash or terrorist attack remains a contentious issue, however.

For older spent fuel in air-cooled storage or transport casks, the concern is a loss of integrity of the cask as a result of a transport accident or a terrorist attack with an anti-tank weapon. Here the potential release of radioactivity would be relatively small, unless the spent fuel was subsequently heated by a fire.

The first years: pool storage

When spent fuel is discharged from a reactor, it is conveyed immediately into a deep cooling pond adjacent to the reactor. Refueling typically occurs every 1 to 1.5 years for a light-water reactor. For an average fuel burnup of about 50 GW-days (thermal) per ton of heavy metal (GWd/tHM), the annual discharge of fuel would be about 20 tons of heavy metal per GWe of generating capacity. For natural-uranium-fueled heavy water reactors, the rate of spent-fuel discharge is about seven times higher because the burnup is lower. The water and gas-cooled graphite-moderated reactors deployed by Russia and the UK respectively are intermediate cases.

Cooling ponds typically were originally designed to hold only a few years' discharges. This is because, in the 1960s and 1970s, when most of today's reactors were designed, the expectation was that, within a few years, the spent fuel would be shipped to a reprocessing plant. For many light water reactors (LWRs), this expectation was not realized. Their operators responded first by increasing the storage density of the spent fuel in the pools by a factor of five—to almost the density in the core. In such dense-packed pools, each fuel assembly is enclosed in a box lined with neutron-absorbing boron plates to assure that the fuel doesn't go critical.

As of 1997, in the United States, where spent fuel is not reprocessed, LWR pools associated with operating reactors had a capacity of about 600 tons per GWe, i.e., 30 years storage, while pools in France, where spent fuel is reprocessed, had an average capacity of 200 tons/GWe at the reactor and 260 tons/GWe at the reprocessing plant.[484]

Spent fuel pools at heavy water reactors in Canada are designed with about ten years of storage. Since spent fuel discharged by heavy-water reactors will not go critical in ordinary water, the spent fuel assemblies are therefore simply stacked up in the pools.[485]

Safety. One week after discharge a ton of spent fuel generates about 100 kilowatts of heat. Using the parameters of Japan's Fukushima Daiichi Unit #4, whose spent fuel pool was a special focus of concern after the 11 March 2011 accident, for a near worst-case scenario, a full core (90 tons) of spent fuel loaded into a pool would generate 9 MWt, which could evaporate 344 tons of water per day,[486] a 3-meter layer for the pool that has an area of 120 square meters.[487] Since the depth of water above the fuel in a spent-fuel pool is typically about 7 meters, it would take only a little more than two days of loss of cooling and no water replacement for the water level in a pool to fall to the top of the spent fuel.

Spent fuel pools are typically located at the same level as the power-reactor core. For boiling-water reactors, this level is some distance above ground (Figure 12.1). Even for pools that are on or in the ground, in many cases, drainage could occur if the massive pool wall or floor were ruptured by a dropped cask or a terrorist-caused explosion or penetrated by the spindle of a jet engine from a crashing aircraft.

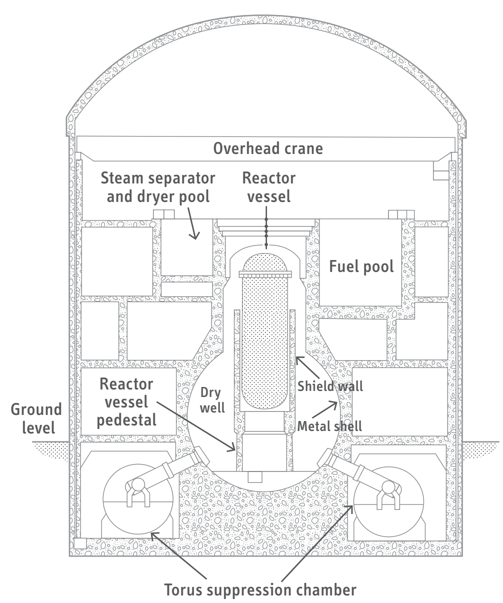

Figure 12.1: Schematic section through a G.E. Mark 1 boiling water reactor plant, such as Fukushima Daiichi unit #1, shows that the spent fuel pool is well above ground level.
Source: U.S. National Academy of Sciences.[488]

In 2003, a controversy erupted in the United States as a result of an article about the possibility of a spent-fuel fire resulting if a pool lost enough of its water so that some or all of the spent fuel were exposed to the air.[489] The damages from a spent-fuel fire could be hundreds of billions in losses due to long-term evacuation of contaminated areas.[490] Special concern was expressed about "dense-packed" pools because the boxes surrounding the individual fuel assemblies could prevent air circulation—especially if the holes in the bottoms of the racks were blocked by residual water. The authors of the article urged that the pools be returned to their original storage density by moving spent fuel more than five years past discharge into dry-cask storage.[491] This would cost several billion dollars, however, an expense that the U.S. Nuclear Regulatory Commission did not believe to be required given the unknown but probably low probability of successful terrorist attack against a spent-fuel pool.[492]

As a result of this controversy, the U.S. Congress requested the National Research Council, the research arm of the National Academies, to conduct a review. The review concluded that:[493]

> "under some conditions, a terrorist attack that partially or completely drained a spent fuel pool could lead to a propagating zirconium cladding fire and the release of large quantities of radioactive materials to the environment."

The NRC has acknowledged that a pool fire could occur but still argues that the risk is too small to justify moving away from dense-packed pools.[494] It is unfortunate that the NRC has chosen to keep secret the analytical basis for its optimistic judgment.[495] Prior to 11 September 2001, the NRC published much less optimistic detailed reports on the risks to spent-fuel pools and of spent fuel fires in drained spent-fuel.[496]

The 11 March 2011 Fukushima Daiichi accident focused attention on the spent fuel pool for unit #4—especially after the hydrogen explosion there, four days after the accident began. This convinced many—including the U.S. NRC—that a spent fuel pool fire may have occurred.[497] Three months later, after having seen the undamaged fuel in the pool on video, however, the NRC withdrew this conclusion.[498] It is thought now that the hydrogen that produced the explosion in unit #4 had come from unit #3 via a shared vent line.[499]

Dry storage

For LWRs, after 30 years or so, even with dense packing, no more spent fuel can be placed into the pools and additional storage capacity must be built. Typically, this is dry air-cooled storage for the older, cooler spent fuel. Compared to spent fuel pools, casks being completely passive, require much less attention and are relatively cheap, costing $100–200 per kilogram of uranium in the fuel (0.025–0.05 cents per kWh of electricity generated).[500]

Spent fuel will have to be packed in canisters for eventual transport in any case. In fact, the designs for this storage evolved initially from transport casks, designed to take spent fuel from the reactor sites to reprocessing plants. The first dry-storage casks were thick-walled cast iron and could be used for either storage or rail transport.[501] Later, however, less costly dry storage was built by using a relatively thin steel canister to hold the spent fuel, and surrounding it at the storage site with a heavy shell of reinforced concrete for protection and radiation shielding (Figure 12.2). The concrete shell contains vents in the outer shield to allow air to flow into the space between the canister and shield and out at the top. When the air between the cask and the shield is warmed, it expands, becomes less dense than the surrounding air, and therefore becomes buoyant and flows out of the top vent, drawing in replacement air through the bottom vent. A second more compact design, not shown, has the canisters inserted horizontally or vertically into a concrete monolith sized to hold six or more canisters with channels for convective air cooling.

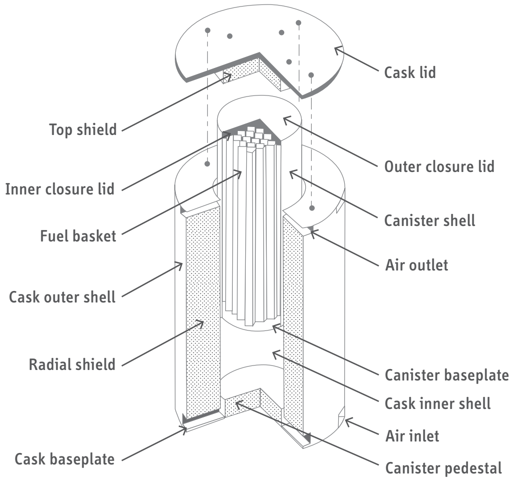

Figure 12.2: A spent-fuel-storage cask sized to hold about 12 tons of spent fuel. The fuel basket in the inner canister holds the spent fuel in position. The thick reinforced concrete outer shell provides protection and radiation shielding. Cooling is provided by air flowing convectively through the air inlets at the bottom and out of the air outlets at the top. *Source: U.S. Nuclear Regulatory Commission.*[502]

The area density of dry storage is about 0.1 ton per square meter.[503] The lifetime output of a 1 GWe LWR, about 1200 tons of spent fuel discharged during a 60-year lifetime, therefore could be stored on a hectare. Such an area is easily available within the exclusion zone associated with most nuclear power plants.

In the United States, dry storage is in the open. In Germany, Japan and other countries, a thick-walled building provides an extra layer of protection against attack and also additional radiation shielding for passers by if the storage area is near a road (Figure 12.3). The intense gamma radiation emitted by spent fuel means casks have to be filled under water or remotely behind shielding. In order to avoid repacking again into disposal casks at a geological repository, the U.S. Department of Energy has proposed a system in which the spent fuel canister would have different overpacks for storage, transport and disposal.[504]

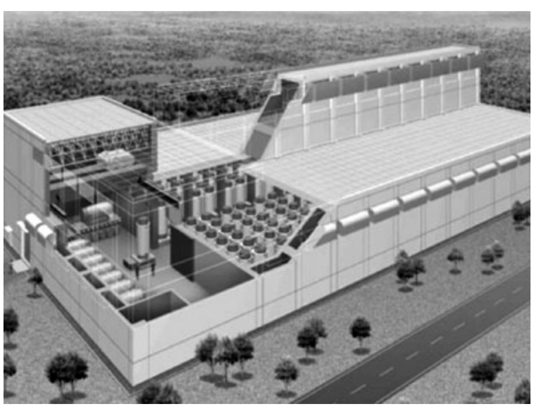

Figure 12.3: Artist's conception of a 3,000-ton-capacity interim dry-cask storage facility under construction in Mutsu in Aomori Prefecture, Japan near Japan's Rokkasho reprocessing plant. The outer walls provide additional radiation shielding and protection against projectiles. The purpose of the high structure running down the middle of the building is to increase the convective flow of warm air out of the building through the "chimney effect."[505] *Source: Hitachi-GE Nuclear Energy Ltd.*

Safety. Convectively air-cooled storage could suffer accidental or deliberate blockage of cooling ducts. The resulting temperature increase of the fuel would be modest because of the relatively low heat output of older spent fuel and the relatively large surface areas of the storage casks would result in a radiative cooling equilibrium being established with a temperature that would be small in comparison with that which would cause fuel damage.[506]

The casks could be penetrated by anti-tank missile or explosively shaped charges. A U.S. National Academy of Sciences review concluded that:[507]

> "Radioactive material releases from a breach in a dry cask would occur through mechanical dispersion. Such releases would be relatively small."

They did suggest, however, additional protective measures such as berms and "visual barriers" to make it impossible to target the casks from the ground outside the barriers. As already noted, in some countries casks are placed inside thick-walled buildings to provide an additional layer of protection against attack. In the United States, a large coalition of non-governmental organization has called for the "hardening" of dry cask storage.[508]

The National Academy report also reviewed analyses of the impact of aircraft crashes, including the resulting jet-fuel fires, on dry-cask storage. These analyses concluded that large releases would not result.

Central storage

In countries that do not reprocess, most spent fuel storage is at the reactor sites. Reprocessing plants have large storage pools, however:

- In France, the storage capacity at the La Hague reprocessing plants is 17,600 tons.[509] This is equivalent to about thirteen years' discharges by France's reactors.[510]

- Spent mixed-oxide fuel is being stored indefinitely in these pools. In the U.S., the storage pool of the Morris, Illinois reprocessing plant, built in the 1970s but never operated, is used for long-term storage of 772 ton of spent fuel.[511]

- In Russia, the 8,400-ton-capacity storage pools at an uncompleted reprocessing plant near Krasnoyarsk is used for central storage of light-water reactor (VVER) fuel and a huge dry cask storage facility is being built nearby with a planned capacity of 26,510 tons for spent fuel from Russia's graphite-moderated RBMK reactors and 11,275 tons from Russian and foreign VVER light-water reactors.[512]

- Japan's utilities are currently building a centralized interim dry-cask storage facility for 3,000 tons of spent fuel near the Rokkasho Reprocessing Plant (Figure 12.3) with the anticipation that an additional unit with a capacity of 2,000 tons will be built later on the same site and that the equivalent of at least an additional six 5,000-ton units would have to be built during the next 40 years.[513]

- In the U.S. central dry-cask storage facilities have been proposed but not built because of opposition in the host states due to concern that interim storage might become permanent.[514]

There is little economic incentive to remove spent fuel stored on site in dry casks to central storage until after all the reactors at a site have been shut down. As long as reactors are operating on site, nuclear power plant personnel can provide security and maintenance for on-site dry cask storage. In some localities, however, local governments have the power to block the expansion of on-site storage and are doing so.

Interim storage for how long?

Modern LWR fuel is remarkably durable in either pool or dry storage. In the reactor, about one in seven thousand rods develops a leak.[515] The conditions in dry cask storage can be stressing, however, because the temperature of the fuel in the center of the canister can be hotter than the water temperature in a PWR and the internal gas pressure of the rods is not offset by the higher water pressure in an operating reactor. Also, LWR fuel is being pushed to higher burnups, which is associated with more radiolytic hydrogen embrittlement of the zirconium cladding. Nevertheless, the temperature and internal pressure decline with time in dry cask storage and the fact that failures have not been observed during the first decades provides the basis for a good prognosis for the future.[516] The Nuclear Regulatory Commission has observed that:[517]

> "Degradation rates of spent fuel in storage … are slow enough that it is hard to distinguish by degradation alone between spent fuel in storage for less than a decade and spent fuel stored for several decades."

The oldest nuclear power plants operating in the U.S. were connected to the grid in 1969 but there is spent fuel in on-site interim storage from U.S. power plants that came into operation in 1960, more than 50 years ago.[518] Samples of stored spent fuel are checked periodically to verify that there are no surprises. To date, no significant degradation has been reported. The thick steel canisters and their concrete overpacks are also very durable.

The U.S. Nuclear Regulatory Commission (NRC) has steadily extended the period of its declarations of confidence in the feasibility of on-site storage of spent fuel as the availability of a U.S. geological repository has receded. In December 2010, the NRC expressed its confidence that spent fuel can be stored in either pools or dry casks for up to 60 years beyond the operating lifetime of the reactors that produced it.[519] Since many U.S. reactors are having their licenses extended to 60 years, the NRC finding means that the first fuel that they discharged could be stored on site for about 120 years. The NRC has already extended licenses for a few dry storage facilities to 60 years.

Transport

Eventually, spent fuel has to be transported off site. France, Russia and the United Kingdom have a considerable amount of experience because they have been shipping large quantities of spent-fuel to their reprocessing plants for decades. Sea transport is used from Japan to Europe and from the continent to the UK. Most of the transport within continental Europe and Russia is by train. Smaller casks, containing 0.5–2 tons of spent fuel, are transported by truck.

Transport casks typically are thick-walled metal casks, incorporating an inner layer of lead for gamma-ray absorption and an outer layer that includes both hydrogen in plastic to slow neutrons and boron to absorb the slowed neutrons (Figure 12.4).

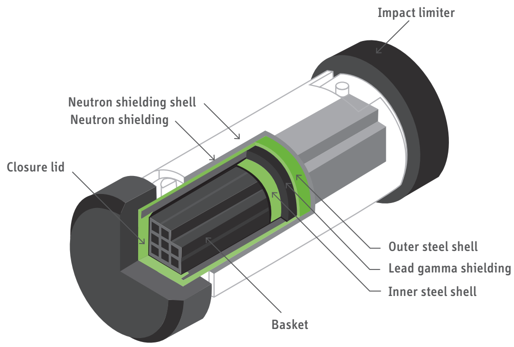

Figure 12.4: A rail cask for transport of spent-fuel. Such casks typically hold 10–18 tons of spent fuel and weigh 150 tons or more when loaded. The ends are capped with "impact limiters" to protect against crashes. *Source: U.S. Nuclear Regulatory Commission.*[520]

Transport casks are subject to specific tests against accidents, including:[521]

- Drop tests from a height of nine meters onto an unyielding surface;
- Puncture tests, involving a one-meter drop onto a vertical 15-cm diameter steel "pin";
- A thermal test equivalent to immersion in an 800 °C oil fire for 30 minutes; and
- Immersion tests in water at pressures equivalent to a depth of 15 meters for eight hours and a depth of 200 meters for an hour.

As with storage casks, terrorists could breach a transport cask with anti-tank missiles or shaped charges. The difference is that storage casks are located in exclusion areas outside cities. Railroads generally go through the hearts of cities.

A U.S. National Academy of Sciences committee examined the risks of spent fuel transport accidents, including reviewing analyses of spent fuel casks hypothetically exposed to a number of extreme historical accidents and concluded that, in the absence of a prolonged (multiple-hour-long) fires, the risk of large releases from accidents was small. It added, however, that:[522]

> "Malevolent acts against spent fuel and high-level waste shipments are a major technical and societal concern, but the committee was unable to perform an in-depth examination of transportation security because of information constraints. The committee recommends that an independent examination of the security of spent fuel and high-level waste transportation be carried out prior to the commencement of large-quantity shipments to a federal repository or to interim storage."

Later in the report, the committee emphasized that the examination it was recommending:[523]

> "should be carried out by a technically knowledgeable group that is independent of the government and free from institutional and financial conflicts of interest. This group should be given full access to the necessary classified documents and safeguards

> information to carry out this task. The findings and recommendations of this examination should be made available to the public to the fullest extent possible."

As of late 2010, the recommended study had not been commissioned.[524]

Despite the robustness of the containers, the transport of spent fuel and high-level waste has inspired considerable controversy. Internationally, there have been protests against shipments between Europe and Japan.[525] In Germany, there have been huge protests associated with shipments of spent fuel and high-level waste to a central interim surface storage site in Gorleben, Germany. Twenty thousand German police were deployed in response to a November 2010 protest.[526] In the United States, opponents to the Yucca Mountain repository made the issue a national one by describing the transport of spent-fuel and high-level waste to the repository site as "Mobile Chernobyls"[527] and the state of Nevada published maps showing potential routes for rail, truck and barge shipments of spent fuel from U.S. reactors to Yucca Mountain passing through all but a few states.[528]

Conclusion

Increasing quantities of spent fuel are in interim storage pending the availability of geological repositories. There are good safety reasons to limit the density of storage in pools but moving fuel to dry casks provides a relatively safe and economic interim storage option that can be relied on for several decades or more.

Frank von Hippel

13 Geological Disposal

Spent nuclear fuel or the high-level wastes generated by reprocessing will have to be disposed and isolated from the biosphere for at least hundreds of thousand years.[529] In countries exploring such disposal, most technical experts agree that this could be accomplished by burying the spent fuel or HLW in a mined repository some hundreds of meters underground.

Disposal of plutonium from the dismantling of nuclear weapons is a related challenge. The United States and Russia have agreed to each dispose of 34 tons of excess weapons plutonium.[530] The United States also expects to dispose of most of an additional 20 tons of other separated plutonium that has been declared excess for military purposes.[531] The UK is currently discussing how to dispose of approximately 100 tons of separated civilian plutonium.[532]

Disposal in boreholes four to five kilometers deep could be an alternative for the direct disposal of already-separated plutonium. The volumes of plutonium are relatively small and could be incorporated in a very durable waste form, and the geochemical and hydrologic conditions at great depth would limit the mobility of any plutonium that went into solution. Once the plutonium has been disposed of in a deep borehole, retrieval would not be easy and any effort would become evident.

The radioisotopes in nuclear spent fuel include a wide array of fission products, some very long-lived, uranium and plutonium isotopes, and the "minor actinides"—the transuranic elements neptunium, americium, and curium (Figure 13.1). In light water reactors, the plutonium and the minor transuranic elements comprise typically about 1 percent of the heavy metal in the spent fuel.[533] Today, high-level waste (HLW) includes the fission products, typically the minor transuranics, and some residual quantities of uranium and plutonium isotopes.

After about 100 years, plutonium and americium dominate the ingestion toxicity of spent fuel.[534] Transuranics do not pose much of an external risk because the alpha-particles that carry almost all of their decay energy have ranges of only tens of microns in tissue, but they do pose a health risk if ingested or inhaled. Their radioactivity also has very specific impacts on the strategy for geological disposal. For this reason, the geochemistry of these long-lived actinides in a geological medium, discussed in the appendix, is critical to the science of geological disposal and is the focus of this chapter.
For a geological repository to successfully contain the long-lived transuranics, the geologic conditions should minimize release from the waste form, geochemical and hydrologic conditions in the repository should ensure that any water should have limited free oxygen that would promote the dissolution of the spent fuel and increase the solubility

of the contained radioactive materials, and finally, the backfill and mineralogy of the geologic formation should promote sorption of radionuclides onto mineral surfaces. Repository programs in Sweden and Finland in granite, and in France in clay provide examples of how these principles may be applied.

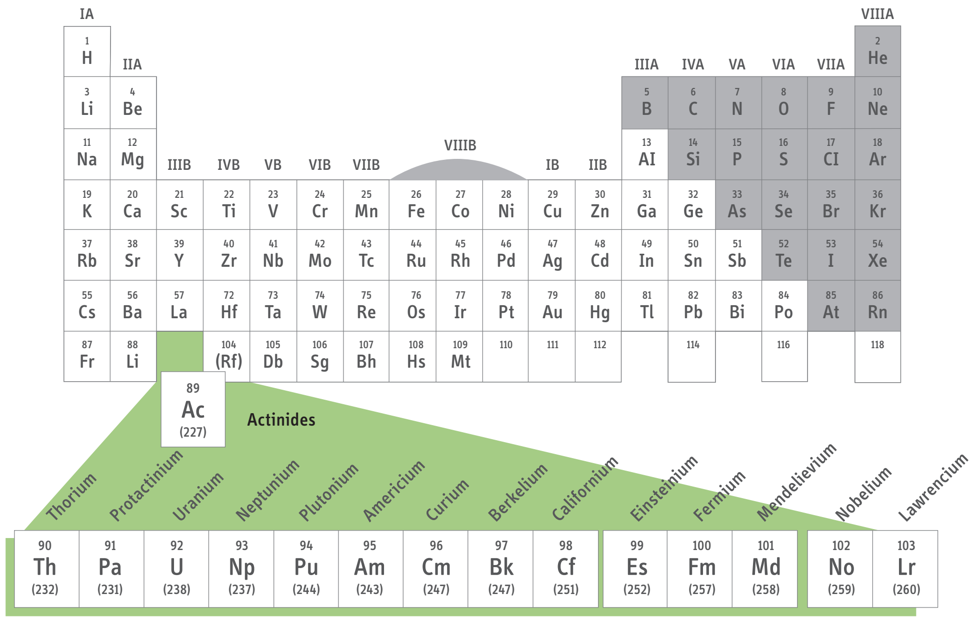

Figure 13.1: Periodic table of elements showing the actinides. In this chapter, all of the heavy elements in spent fuel, including uranium, plutonium, neptunium, americium and curium, are referred to as actinides when their chemical properties are discussed. Although they have very different nuclear properties, they all belong to a series of elements in the periodic table that can have a variety of oxidation states. The lightest member of this series is actinium. Those actinides beyond uranium in the periodic chart are the transuranic elements.[535]

The geochemistry of disposal

Each repository and disposal strategy will be characterized by a set of unique geochemical and hydrologic interactions that will evolve over time. The behavior of transuranic elements in a geological repository depends on:[536]

1. The properties of the waste form that control the corrosion and release of the radionuclides;

2. The solubility of the transuranics, which to a first approximation, is determined by their oxidation state; and

3. The long-term chemical conditions that will prevail in the geological repository.

If and when water breaches a cask in a repository, the immediate geochemical environment of the waste form will be controlled by the materials in the fuel and the engineered barriers, especially uranium in the fuel and the iron in the cask. The evolution of the near-field chemistry is complex (Figure 13.2) and is influenced by numerous processes, such as corrosion, which releases hydrogen from water, microbial activity and radiolysis. Radiolysis is the disassociation of water in contact with the radioactive fuel or other waste form by the high-levels of radiation—especially α-radiation. This can result in high concentrations of oxidants, such as oxygen and hydrogen peroxide (H_2O_2), resulting in an increase in the solubility of the actinides.[537]

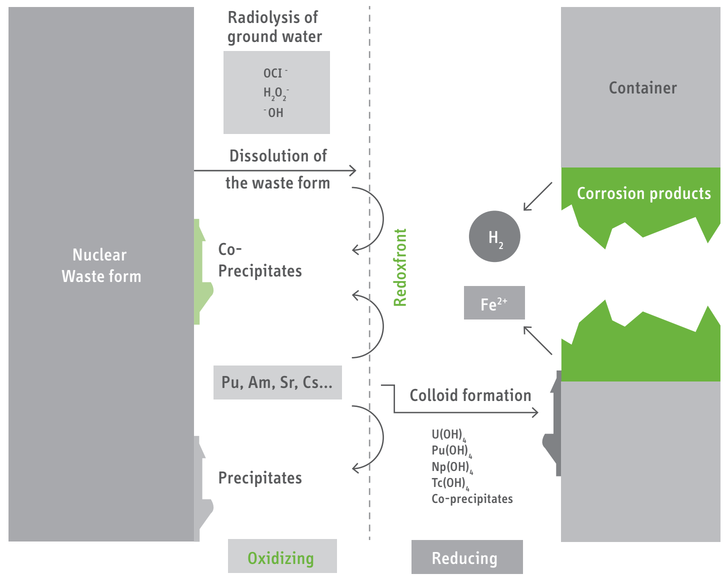

Figure 13.2: Some of the major processes that determine radionuclide release as a waste form dissolves inside its container. Transuranic elements in spent fuel are generally released by the matrix dissolution of the UO_2. Because of their multiple oxidation states, the transuranics are very sensitive to the redox (oxidation-reduction) conditions. Due to radiolysis of water, oxidizing conditions are expected near the surface of the fuel. Dissolved transuranics may precipitate as secondary corrosion products or be sorbed onto corrosion products from the waste package, such as iron oxyhydroxide colloids. The processes are highly coupled, however. For example, hydrogen created by the corrosion of the metal waste package may suppress the formation of oxidants such as H_2O_2, which result from the radiolytic decomposition of water near the surface of the fuel. *Source: Horst Geckeis.*[538]

Close to the fuel, if radiolysis makes the chemistry oxidizing, the transuranics may dissolve and then be sorbed onto the surfaces of mineral grains or colloids. Colloids are particles less than a micron in diameter that could be carried along by any water flow and carry the transuranics with them. One of the purposes of the bentonite clay buffer around the waste canister in Sweden's repository design is to filter out any transuranic-carrying particles and keep them from escaping into the ground water beyond.

Beyond the buffer, the geochemistry that transuranics are exposed to will be determined by the chemistry of the ambient groundwater, which has reacted with the large volumes of rock surrounding the repository. Here, the mobility of any transuranics depends, in large part, on the oxidation/reduction or "redox" conditions of the geochemical environment, their form in solution and the extent to which they are sorbed onto the surfaces of mineral grains or colloids. These factors are discussed in more detail in the Appendix. However, the risk of long-distance transport will be minimized, if the groundwater chemistry is reducing. This will result in lower concentrations of dissolved transuranics and lower sorption onto mineral colloids, which are ubiquitous in natural groundwater.

The ambient geochemistry differs in the major rock types being considered for repositories: granite, clay, volcanic tuff and salt.

Granite. In granite, if the water in the cracks has been exposed to the rock for centuries or millennia, its oxygen will have been depleted by reactions with the rock. The actinides will have low geochemical mobility because of their lower solubility and sorption onto mineral grain surfaces and trapping of radionuclides in the microscopic pores of the rock.[539]

Clay. The slow movement of water through clay, the absence of oxygen in the water, the high sorptive capacity of the clay and its capability to filter colloids out of the water, mean that actinides are expected have limited mobility in a clay repository, such as those being designed by France and Belgium. Actinides are expected to move only a few centimeters to meters before they decay.[540]

Volcanic tuff. Actinides would be mobile under the oxidizing conditions of volcanic tuff where the repository is located above the water table. This is evident in the performance assessments of the proposed repository at Yucca Mountain.[541]

Salt. The redox conditions in salt depend on the minor minerals embedded in salt. Salt also is a problematic medium for heat-generating wastes such as spent fuel because the brine trapped in the salt migrates toward the heat source. Finally, there have been problems with water intrusion in efforts to convert existing salt mines to radioactive-waste repositories.[542]

Deep borehole disposal

During the past decade, there has been renewed interest in disposal of radioactive waste in very deep boreholes reaching depths of up to five kilometers.[543] This is the result of a number of factors including:

- Technological advances in deep drilling techniques;
- The prevalence of dense brine in deep rock that is unlikely to rise to mix with the lighter fresh water in the aquifers above;
- The possibility of a wide range of possible locations with suitable geology; and
- The promise of strengthened proliferation resistance of deep disposal.

Proposals for borehole disposal have expanded well beyond simple emplacement in deep vertical holes to include variants with *in situ* melting of the surrounding rock using the heat from the radioactive waste and deep self-burial as dense waste moves to greater depths through melted rock or even down a borehole filled with sulfur.[544]

Concerns about borehole disposal of spent fuel include the corrosive nature of saline brines at depth; the possibility of unexpected movement of pressurized water upward due to the failure of shaft seals; and radiation exposure to workers during insertion of spent fuel into the borehole. There are also the potential difficulties and radiation dangers associated with attempts to extract a spent fuel assembly in its container if it became lodged in a borehole part way down.

Sweden's repository company, SKB, carried out the first systematic comparison of a mined geological repository to the deep borehole option in its 1992 report, *Project on Alternative Systems Studies*,[545] which compared SKB's KBS-3 concept for a geological repository to three other disposal concepts, including "very deep holes." In 2000 and 2010, SKB was required again by Sweden's regulators to compare borehole disposal with mined geological repositories.[546] SKB concluded that borehole disposal did not compare well to geological disposal because of cost and technology development needs. It cited as a key problem that the ability of deep boreholes to isolate spent fuel depended on only one barrier, the overlying rock mass, because it would be difficult to emplace a canister that had the necessary thickness and other properties to resist long-term corrosion by deep, hot brine.

In 2004, Nirex Limited in the UK completed an extensive review of the concept of deep borehole disposal and came to essentially the same conclusion as SKB, "the deep borehole concept will require significant R&D expenditure on the engineering aspects."[547]

More recently, the U.S. Sandia National Laboratories reviewed the deep borehole disposal concept. A preliminary performance assessment indicated that there was no expectation that contaminated brine could reach freshwater aquifers above. Significantly, this evaluation took no credit for the waste form or waste package. The authors recommended additional study and analysis of the scientific basis for the concept, as well as its technological feasibility and cost.[548]

The focus of all these studies has been primarily on the disposal of spent nuclear fuel or high-level vitrified nuclear waste. There have also been brief discussions, however, of using deep boreholes for the disposal of excess weapons plutonium, including by the U.S. Department of Energy (DOE) in its survey of options for disposition of plutonium.[549]

Deep bore hole disposal of transuranic elements may be an attractive possibility because the volumes of material are relatively small; the radioactivity releases mostly α-particles, which would not penetrate the waste-form container and therefore represent much less of a radiation hazard to workers; and the waste form can be designed to serve as an engineered barrier in addition to the geological barrier of the overlying mass of rock.

Plutonium waste forms

The DOE study on plutonium disposition considered direct emplacement of plutonium as either a metal or oxide. There has also been interest in the development of special materials for the incorporation and disposal of excess weapons plutonium.[550] Waste forms in which the plutonium would be mixed into glass have the advantage of having been produced on an industrial scale for the vitrification of high-level reprocessing waste, but new glass compositions would have to be developed in order to increase the concentration of plutonium in the glass. Because of the long half-life of plutonium-239, efforts also have been focused on developing chemically durable and radiation-resistant crystalline, ceramic waste forms, such as zircon ($ZrSiO_4$) and pyrochlore ($Gd_2Ti_2O_7$).[551] This work grew out of earlier work on crystalline ceramics, such as Synroc[552] for the immobilization of high-level reprocessing waste. Recent reviews of the developments in waste form research summarize over twenty years of effort.[553]

Zircon is a very durable mineral that occurs in granites and is often used in radioactive age dating because it contains low concentrations of uranium and thorium, which are members of the actinide chemical group along with plutonium. In fact, the oldest dated mineral is a zircon. Preliminary calculations suggest that, if 50 metric tons of plutonium were disposed of in 450 tons of zircon, the total release of plutonium over 500,000 years would be on the order of 100 grams.[554] There are a number of other possible waste forms, particularly the radiation-resistant forms of pyrochlore.[555]

For all of the actinide waste forms, radiation damage is a concern because it could increase the release of radionuclides. The damage accumulation process is temperature dependent, however, and materials could be designed that use the naturally higher temperatures at depth to cause thermal annealing of the radiation damage to the waste form.

Rodney C. Ewing

Appendix

Mobility of actinides in the geosphere

There have been a number of recent and extensive summaries of the behavior of actinides in the environment.[556] Actinide mobility depends on their chemical properties in the context of the specific geochemical and hydrologic conditions of a particular geological repository.

Solubility of spent fuel. The solubility of spent fuel is critical to the fate of the transuranics that it contains. This brief summary discusses only the compounds of uranium that are of most interest to the disposal of power-reactor spent nuclear fuel based on UO_2, in which uranium is in a 4+ state, i.e., two electrons have transferred to each of the oxygen atoms. In solids, uranium most commonly exists in its two principal oxidation states, 4+ and 6+.[557] The most common U^{4+} minerals are uraninite (UO_{2+x}) and coffinite ($USiO_4$). The first has the same structure and properties as the UO_2 in nuclear fuels[558] and the second is a common alteration product of UO_2 in the presence of silicate-rich ground waters under reducing conditions, i.e., in the absence of dissolved oxygen.[559] These are the primary phases for U^{4+} underground and, as long as reducing conditions are maintained, these low solubility phases limit the mobility of uranium in the geosphere.

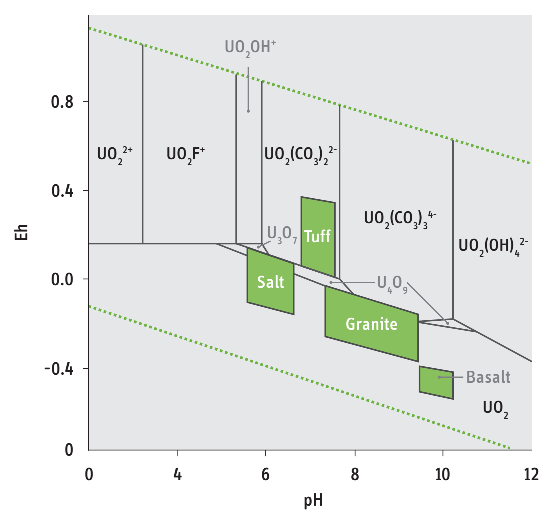

Figure 13.3: Stability diagram for UO_2 in ground water at 25°C, showing the pH-Eh stability fields for aqueous uranium species. pH refers to acidity or alkalinity, and Eh refers to oxidation potential. The upper and lower dashed lines represent the upper and lower stability limits of water, hence the limiting-boundaries for aqueous reactions. Higher Eh values indicate oxidizing conditions, and lower Eh values indicate reducing conditions. Hence, the relatively insoluble reduced form, U^{4+}, is stable in UO_2 in the lower half of the diagram. As the conditions become more oxidizing, the more soluble U^{6+} is stable and forms carbonate complexes in solution. The Eh-pH conditions for groundwaters in tuff (Yucca Mountain, Nevada), basalt (Hanford, Washington), granite (Stripa, Sweden), and salt (Permian brine groundwater) are represented by the shaded areas. Note that basaltic and granitic ground waters are reducing and do not dissolve UO_2; whereas, tuffaceous ground waters are oxidizing. Conditions in shale (not shown) are usually reducing, depending on its content of organic material, but pH will depend on rock composition and geological setting. *Source: U.S. National Academy of Sciences.*[560]

The effect of the redox conditions and chemistry of solutions in contact with the actinide-bearing material is clearly evident in a plot of dominant types of uranium compounds on an Eh-pH diagram (Figure 13.3). Under the reducing conditions present in salt, granite and basalt repositories, the dominant uranium species is solid UO_2, reflecting its low solubility under these conditions. Moving upward into the conditions of a tuff repository, i.e., Yucca Mountain, conditions become more oxidizing and the U^{6+} compounds exist in solution mainly as carbonates; thus, increasing the mobility of uranium.[561] For granites below the water table or in deep boreholes located in a granitic shield, conditions are reducing, due to the presence of sulfides. The redox state of sedimentary rocks (not shown in Figure 13.3), such as shale consisting mainly of clay, is likely to be a bit lower than for crystalline rocks, because of the presence of organic matter.

Under oxidizing conditions, however, the structural diversity of uranium phases increases dramatically.[562] In contrast to the limited number of U^{4+} minerals, there are several hundred known U^{6+} structures that may form under oxidizing conditions, depending on the temperature and ground water composition. An important issue in evaluating the release of transuranics from UO_2 fuels under oxidizing conditions is whether radionuclides, such as neptunium-237, which was found to be an important contributor to modeled radiation doses to populations using water from the aquifer that runs under Yucca Mountain, can be incorporated into the structures of U^{6+} compounds and hence have reduced mobility.[563]

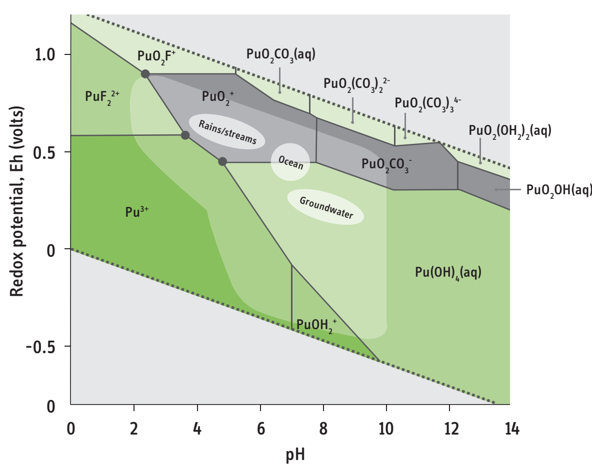

Figure 13.4: Chemical forms of plutonium in the geosphere as a function of redox potential (Eh) and acidity/alkalinity (pH). This diagram is calculated for plutonium in a typical groundwater that contains hydroxide, carbonate and fluoride ions (in concentrations typical of a water, J13, at Yucca Mountain). The geochemical system becomes more oxidizing as one moves up the vertical axis. More oxidized forms (e.g., with U^{6+} and Pu^{5+}) are orders of magnitude more soluble in typical groundwater. *Source: Wolfgang Runde.*[564]

Actinides in solution. The type of chemical species of actinides in solution depends mainly on their oxidation state and the composition of the groundwater. Plutonium can exist in four oxidation states from 3+ to 6+ in natural waters. In natural waters, hydroxide and carbonate and bicarbonate are the most common complexes.[565] Plutonium speciation is particularly sensitive to minor changes in redox conditions and pH (see Figure 13.4). In addition to hydroxide and carbonate complexes, organic molecules form complexing species in solution and can increase the mobility of actinides in the environment. The variety of oxidation states and strong tendency to form complexes, particularly with carbonates, provide a variety of mechanisms for the transport of actinides in solution. In general, Np^{5+}, Pu^{4+}, Am^{3+} and Cm^{3+} are the prevalent oxidation states of transuranics in most oceans or groundwaters. Aerobic waters or brines can create oxidizing conditions that oxidize Am^{3+} to Am^{5+} and Pu^{4+} to Pu^{6+}. In contrast, reducing, anaerobic or organic-rich waters stabilize the reduced oxidation states Np^{4+}, and Pu^{3+}, which are less soluble.

Actinides on surfaces and colloid-facilitated transport. Actinide species in solution can sorb onto mineral surfaces during transport through the geosphere. The charge and geometry of the molecular species and the structure of the exposed surface, as well as geochemical conditions, control the efficiency of the sorption process.[566] Clay minerals and iron oxyhydroxides are common minerals that have been shown to effectively adsorb actinides. In some cases, there is preferred sorption onto manganese oxides, also a common component of rocks and soils.[567]

Although sorption onto fixed mineral surfaces can result in a reduction in the mobility of actinides, sorption onto colloids can facilitate actinide mobility. Particles in the size range of 1 nanometer to 1 micron are defined as colloids. Colloids can be organic molecules or just small fragments of mineral material. Recent studies have demonstrated transport over distances of kilometers for actinides sorbed onto colloids.[568]

14 International Monitoring

Under the Nonproliferation Treaty, non-nuclear weapon states parties are obligated to submit all nuclear materials to International Atomic Energy Agency (IAEA) safeguards and the IAEA applies safeguards to verify their peaceful use. This chapter lays out how the IAEA verifies spent fuel at reactors and at away-from reactor stores, and outlines how it expects to verify spent fuel or high level nuclear waste from reprocessed spent fuel in geological repositories.

Most power reactors are fueled with pellets of low enriched uranium (LEU) or natural uranium. In a few states, plutonium recovered through spent fuel reprocessing is used as a substitute for U-235 in mixed oxide (depleted uranium and plutonium oxide) fuel, also known as MOX. The fuel pellets are stacked inside cylindrical zirconium alloy tubes, with the resulting fuel rods bound together into fuel assemblies. The IAEA assumes that the integrity of the fuel assemblies remains intact, or that any modifications would be declared. Fuel assemblies are therefore considered as "items" and the safeguards measures are applied to track the items and assure that they remain intact.[569]

The IAEA assumes that the fresh fuel enrichment and the spent fuel burnup are whatever the reactor operators declare them to be. Some rough measurements are possible, however, as described in this chapter.

In planning and evaluating inspections, the IAEA considers the quantities of nuclear material involved in relation to the amount that could give a state its first nuclear weapon. Nuclear-weapon states first recommended values for such "significant quantities" to the United Nations in 1968, and those values have remained unchanged since (Table 14.1).[570]

Material	IAEA significant quantity
Plutonium	8 kg
Highly enriched uranium (HEU)	25 kg of contained uranium-235
Low-enriched uranium	75 kg of contained uranium-235
Natural uranium	10 tons
Depleted uranium	20 tons
Thorium	20 tons

Table 14.1: IAEA significant quantities for safeguards purposes. The IAEA treats all isotopic mixtures of plutonium the same, except for heat-source plutonium containing more than 80% plutonium-238, which can be exempted from safeguards. In the case of low-enriched, natural and depleted uranium, and thorium, which are not direct-use materials, the quantities are derived from scenarios in which the uranium is either enriched to make HEU or the uranium or thorium are irradiated in a reactor to produce plutonium (from uranium) or U-233 (from thorium) and then separated in a reprocessing plant.

Similarly, the IAEA has estimated the time a state would need to convert a significant quantity of nuclear material into its first nuclear weapon, taking into account the chemical and metallurgical steps required. The resulting "conversion times" are:

- Plutonium or HEU metal, seven to ten days;
- Pure compounds of plutonium and HEU (e.g. plutonium oxide), one month;
- Irradiated forms and unirradiated LEU, three months.

Light water reactor fuel

Eighty-two percent of all operating nuclear power reactors are light water reactors (LWRs), which operate with fuel assemblies installed vertically in specific core positions. Refueling takes place with the reactor shut down and the reactor pressure vessel head removed to allow access to the fuel. All fuel assemblies are identified with unique alphanumeric identification markings engraved on the structural hardware of the fuel assemblies. This ID can be read when the fuel assembly is in the reactor core or in a spent fuel pond by means of binoculars or closed circuit television.[571]

Fuel assemblies normally remain in the reactor for three successive periods of one to two years duration. Fresh fuel assemblies are loaded into outer core locations where their high reactivity is used to flatten power production across the reactor core. After one cycle, the fuel assemblies are moved from the outer positions to intermediate locations and the assemblies displaced from the intermediate locations are moved to the inner locations for their final burn. Assemblies removed from the inner zone are discharged to the spent fuel pond.

Although, IAEA safeguards assume that the fuel assemblies remain intact from manufacture until final discharge, most of today's fuel assembly designs allow defective fuel rods to be replaced at the reactor, typically within a single work shift.[572]

Proliferation possibilities involving LWR spent fuel

For LEU irradiated fuel in the reactor and spent fuel, IAEA safeguards are currently designed to:

- Detect diversions of full assemblies without substitution;
- Attempt to detect diversions of individual fuel rods removed from assemblies, with or without substitution — a concern that is prompting renewed interest in alternative methods that might be employed to detect such diversions;[573] and
- Assure that undeclared fertile material is not placed within the core.

The reactor is examined to locate physical routes through which fuel might be moved out of the reactor core, transfer ponds or spent fuel pond. During this "design information verification," specific containment and surveillance equipment are identified, installed and commissioned for inspector use.

The IAEA will typically apply a metal cap seal on the reactor cover bolt when it is in place for reactor operations to assure that it remains closed. However, seals are sometimes broken or removed for various reasons.

The IAEA also installs surveillance systems to maintain uninterrupted views of the fuel transfer gates between the reactor and the spent fuel storage pool, the pool, and the cask loading area. It also normally installs temporary surveillance over the reactor during refueling to confirm that all transfers are taking place only through the declared routes. After they have returned to IAEA Headquarters (in Vienna, Austria), inspectors normally use automated reviewing software to examine the stored images and select situations warranting closer review.

Physical inventory verification (PIV) inspections are carried out on spent fuel at the reactor sites once each calendar year. Normally this coincides with a refueling. During a PIV, reactor operations and all reported transfers of nuclear fuel are reviewed and all fresh fuel, in-core, and spent fuel assemblies at the site are verified by item counting, some item identification on a random selection basis, and some other measures using methods described below.

Between PIV inspections, interim inventory inspections are carried out at three-month intervals to verify on a random basis that spent fuel remains accounted for and to service the surveillance systems.

For spent fuel and in-core fuel (if accessible), the inspection activities include use of a Cherenkov viewing device (CVD) to confirm that the spent fuel shows the distinctive characteristic glow of irradiated fuel (Figure 14.1). The Cherenkov glow, due to electrons from radioactive decays in the fuel traveling at high speed through the water, fades with time as the fission products decay. Using modern CVDs, the glow can be seen for at least 40 years following discharge.

A CVD provides a means to detect an irregularity that might then prompt further examination.

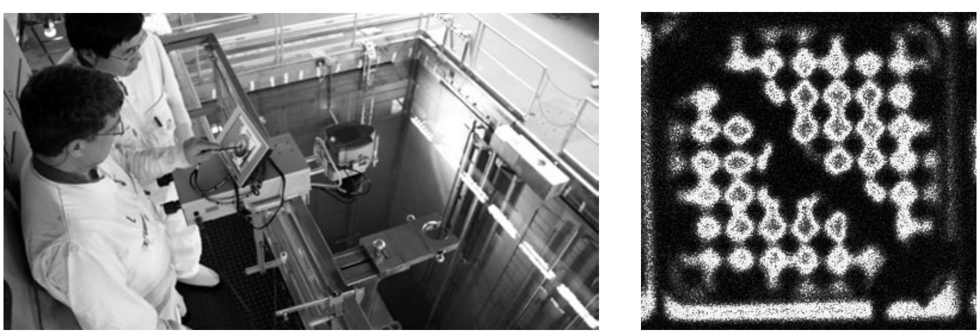

Figure 14.1: Left: IAEA inspectors use a Cherenkov viewing device to examine spent fuel assemblies in a storage pond. A Cherenkov viewing device (right) can detect missing rods, especially in BWR assemblies. The bright dots are the interstitial water spaces surrounded fuel rods where the Cherenkov radiation is generated. Images are displayed in real-time and are stored for later review. The dark band across the image is a metal-fitting at the top of the assembly that blocks the view of the water below. *Source: Channel Systems.*

It could, for example, help to detect missing fuel rods. A spent fuel assembly from which rods have been removed may have empty spaces where the rods were taken from. Empty spaces would be detectable with Cherenkov viewing if the spaces are not beneath the top assembly hardware. More likely, however, missing rods would be replaced with substitutes to maintain the structural integrity of the assembly, or simply to prevent CVD from observing an empty space. Hundreds of fuel rods would have to be replaced to divert one significant quantity of plutonium.

Another means to inspect a fuel assembly involves the use of high-resolution gamma ray tomography.[574] Using a collimator and viewing the assembly from the side, gamma rays emitted by individual rods can be seen as the assembly is rotated. Yet another method under development to enable measurements on fuel rods deep within the assemblies involves an array of very thin neutron and/or gamma ray detectors mounted on the "spider" frame of a control rod cluster to be inserted into a PWR fuel assembly in a storage rack. Such methods could detect unirradiated replacement rods. If rods were replaced with depleted, natural or low enriched uranium and returned to the core for irradiation, however, a later inspection using any of these methods would be unlikely to detect any anomaly.

Less sensitive are spent fuel attribute testers (SFATs) that can detect the gross radiation being emitted by a fuel assembly as a whole. They are typically fork detectors using helium-3 neutron detectors, gamma ray measurement systems or both. An assembly is raised or lowered through the detector giving a capability to detect whether the average irradiation of the assembly is grossly different from that expected.

Inspectors usually witness the loading of dry-storage casks and seal the casks when loaded. Given that the spent fuel may remain inaccessible for extended periods—perhaps decades—two different seals may be used to assure reliability. The IAEA will normally replace and check seals according to a schedule with either complete replacement or random seals chosen according to a sampling plan. For casks that will remain closed for very long periods and be exposed to weather, the IAEA also may request closures to be welded irregularly, establishing patterns that can be confirmed by visual examination against photographic records and measurements.

Inspectors may witness the loading of shipping casks, especially if they are scheduled to be shipped partially filled. They choose not to verify normal shipments because several casks are filled over a period that might last five weeks or more.

LWR inspections normally require about 7 to 10 inspector days per year per reactor. As noted, most of this is during refueling. This inspection effort increases if there are shipments of fuel to or from the plant or if dry storage casks are being loaded.

When MOX fuel is used, the IAEA implements more intensive safeguards to detect diversions of plutonium either by removal of entire fresh MOX assemblies or by replacement of individual fuel rods with identical-looking LEU fuel rods. Fresh MOX assemblies would be shipped under Agency seals to a reactor. Upon arrival, the seal would be removed by inspectors and the assemblies maintained under containment/surveillance thereafter. (Removing fresh MOX after inspectors have departed following a refueling could provide a means to secure plutonium that might go undetected if the state had access to a supply of substitute LEU fuel.)

In states with an Additional Protocol in place, the IAEA will have an improved chance to detect any clandestine reprocessing or enrichment activity. In such a case, the IAEA may de-emphasize routine inspections of LEU-fueled LWRs, with fewer, but short-notice inspections in exchange for broader coverage on a state level.

The following limitations remain in safeguarding light water reactors:

1. The IAEA has no sure means to detect unscheduled outages that might include undeclared refueling. A reactor operator could disable surveillance, claim that seal(s) were broken accidentally, or that an emergency repair required an unscheduled shutdown. The IAEA would not be able to detect at the next PIV inspection that irradiated fuel had been removed and replaced.

2. The IAEA has no means at present to independently verify the plutonium content of spent fuel discharged from a reactor.[575]

3. Detecting rod replacement requires extensive inspector time and prolonged operator involvement, and potential risks of damaging the fuel. As a result, with the exception of Cherenkov viewing, verification is not regularly implemented.

A new approach to the problem of monitoring replacement of the fuel in the core and diversion of the plutonium contained using antineutrino measurements nearby has recently been proposed.[576]

Pressurized heavy water reactors

After LWRs, pressurized heavy water reactors (PHWRs) represent the next major category of power reactors. PHWRs are in operation in Argentina, Canada, China, India, Pakistan, Romania and South Korea. Canada provided its CANadian Deuterium-Uranium or CANDU reactors to all of the other countries noted. Canada stopped all nuclear commerce with India following India's first nuclear explosive test in 1974, and India subsequently produced its own version for domestic use. For cooling the fuel, PHWRs use heavy water (D_2O) flowing in channels passing through the "calandria" vessel that contains heavy water used as moderator. The much lower neutron absorption in deuterium (D), which replaces ordinary hydrogen (H) in the water, allows the use of natural uranium fuel, though some PHWRs may in the future use slightly-enriched uranium.

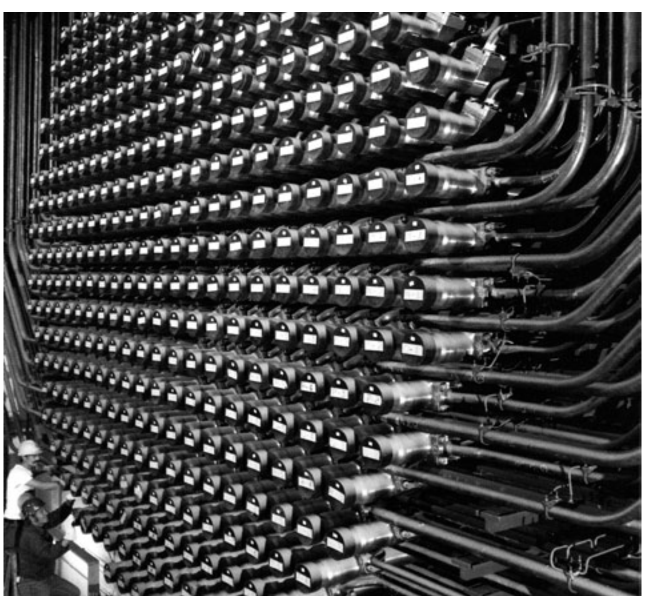

Figure 14.2: CANDU reactor face showing end fittings of the pressure tubes to which the refueling machine attaches. *Source: Atomic Energy of Canada Limited.*

Because natural uranium fuel contains a lower percentage of uranium-235 than LEU, refueling has to occur much more frequently. Therefore PHWRs are designed for on-load refueling and much more spent fuel storage is required.

In a 0.7 GWe CANDU, 380 pressure tubes pass through the calandria vessel that holds the heavy water (Figure 14.2). To facilitate fuel handling, PHWR fuel “bundles” are small in comparison with LWR fuel assemblies: about 0.5 meters long (versus about 4 meters for an LWR) and about 10 cm diameter. Each pressure tube holds 12 fuel bundles, end to end. Each bundle contains 19.2 kg of natural uranium.[577]

Refueling is accomplished by attaching a pair of fueling machines to the opposite ends of a pressure tube. Fresh bundles are inserted at one end and spent fuel is pushed out at the other. Refueling is typically in alternate directions in adjacent tubes so that the high reactivity of fresh fuel at the end of one is offset by the low reactivity of almost-spent fuel at the end of its neighbor. Fuel bundles in a pressure tube may be replaced one at a time, but in some plants up to ten are replaced at a time.

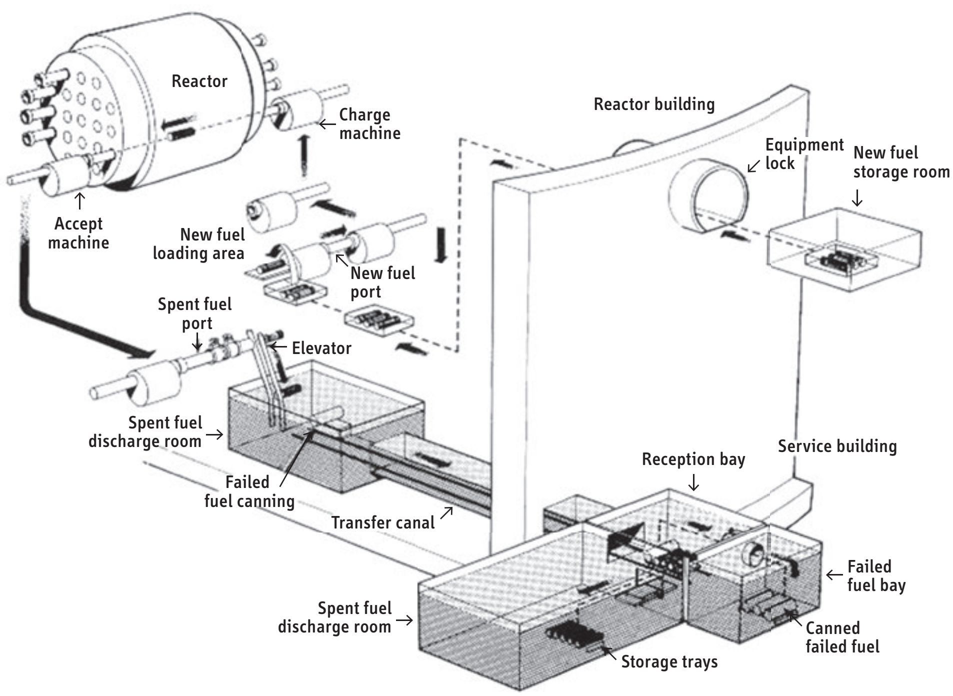

Figure 14.3: Flow of fuel through a CANDU reactor. *Source: Atomic Energy of Canada Limited.*

From a fueling machine, a spent fuel bundle is transferred through a port to a channel to the spent fuel storage pond (Figure 14.3). There, each fuel bundle is placed in a rack in a storage tray. The storage trays are stackable and, when a tray is full, it is placed into an open-top mesh frame. When the frame has been filled, a cover may be placed on top.

At normal 7.5 GWd/tHM burn-up, one spent fuel bundle will contain about 65 grams of plutonium. One significant quantity (8 kg) would therefore require about 120 PHWR fuel bundles. India routinely reprocesses its PHWR spent fuel but no other PHWR-operating state does so at present.

IAEA safeguards on spent fuel at PHWRs

In 1981, then Director General Sigvard Eklund reported to the IAEA Board of Governors that with the safeguards measures in place, Agency inspectors were not able to confirm that diversion had not taken place at the KANUPP reactor in Pakistan.[578] Canadian experts working with the IAEA developed the current safeguards system in the years that followed. The safeguards are designed to verify the flow of spent fuel bundles from the reactor to the spent fuel pond and thereafter to dry cask storage. This is accomplished by an extensive containment and surveillance system.[579] Provided the systems function as intended, IAEA safeguards would confirm that reactor refueling operations agree with operator declarations and that the spent fuel bundles remain properly accounted for thereafter. The safeguards equipment used in PHWRs is identified in Table 14.2.

Safeguards device	Location	Description
Core Discharge Monitor	Reactor Vault	A combination of neutron and gamma radiation detectors in the reactor vault is used to count irradiated fuel discharges from both reactor faces
Spent Fuel Bundle Counter	Irradiated Fuel Discharge Path	A set of radiation detectors is used to count irradiated fuel bundles as they are transferred through the irradiated fuel discharge port in the vault to the spent fuel bay.
CCTV Surveillance System	Spent Fuel Pond & Penetrations	Video cameras monitor for undeclared fuel movements. All CANDU facilities have cameras in the spent fuel bays. Cameras may also be located in other locations to monitor for undeclared removal of irradiated fuel.
Ultrasonic Sealing System	Spent Fuel Pond	Irradiated fuel is stored in tamper-indicating enclosures with a lid fastened using IAEA-approved seals to ensure that bundles are not removed.
Yes/No Radiation Monitor	Fresh Fuel Port, Auxiliary Port, Pipes in Spent Fuel Bay	Radiation detectors are used to detect discharge of irradiated fuel through vault penetrations other than the irradiated fuel discharge port; specifically, the fresh fuel port and the auxiliary port.
Spent Fuel Verifier	Spent Fuel Pond	A collimated gamma spectrometer is lowered into the spent fuel bay to verify the authenticity of spent fuel during IAEA inspections.
Cherenkov Viewing Device	Spent Fuel Pond	The CVD is used to verify the authenticity of spent fuel stored under water by amplifying the faint Cerenkov glow and making it visible to the inspector.

Table 14.2: IAEA safeguards equipment for PHWRs.[580]

Transfers to dry storage are scheduled over extended periods. Inspectors may have to witness transfers on a round-the-clock basis for several months, sometimes requiring 400 or more inspector days.

Dry-storage casks may also be fitted with ultrasonic seals.

With respect to safeguarding PHWRs, the following considerations pertain:

1. At multi-unit stations including several reactors, the level of effort required is very significant and much larger than at LWRs. The inspection effort can range from 50 to hundreds of inspector days per year, when transfers of spent fuel to dry casks are scheduled.

2. Dual containment and surveillance is essential to avoid the extreme workload required to re-establish continuity of knowledge for the huge number of spent fuel bundles if one of the critical verification systems fails.[581]

Safeguards on spent fuel after leaving the reactor site

Regardless of the destination, whenever spent fuel is transported, the following questions arise:

- Was the declared fuel actually loaded into the shipping casks?
- Was the amount declared accurate?
- Was the shipping cask routed to an intermediate location and if so, could the fuel assemblies have been replaced or modified before arriving at the storage facility?

If the IAEA monitors cask loading and seals the storage/shipping casks, then it could rely on the seals as the basis for detecting any diversion. However, the IAEA has seldom done this because of the costs involved. Typically, several casks come to a reactor at the same time and may remain there for a month or more before they are loaded and shipped. Cask loading happens when the operator can schedule the crews, which may be around the clock. Sometimes the IAEA applies surveillance over the cask-loading pit and can see the fuel assemblies being loaded. IAEA inspectors generally do not seal the shipping casks and hence are only able to infer the contents. Other than shipping records, the IAEA has no means available to verify shipping routes or intermediate stops. For States with an Additional Protocol in force, the IAEA could request complementary access to verify the locations of the shipping containers during transport, if it so chose.

Away-from-reactor storage (AFRS). If the AFRS is a storage pool, then the casks will be unloaded and the methods described for visual observation, Cerenkov light and radiation measurements may be applied in the same way they would have been applied at a reactor spent fuel storage pond.

If the AFRS is a dry storage facility, the IAEA would schedule inspections to verify the loading of the dry storage casks, just as they would if the casks were going to remain at the reactor site. If the dry storage casks are sealed, possibly with two different types of seals, inspections at the storage facility would likely be limited to item (cask) counting, and identification and verification of the integrity of the installed seals.[582]

Reprocessing plants. All reprocessing plants receive spent fuel and store it in storage ponds similar to those at reactors, only larger. The methods described above could be applied in the same way they would have been applied at a reactor spent fuel storage pond.

At a PUREX reprocessing plant, the only type in commercial use today, a fuel assembly is brought into the mechanical cell and is sheared into segments that are then placed in a dissolver to extract the uranium, fission products and transuranics, leaving leached cladding “hulls” and undissolved traces of spent fuel. The dissolver solution is filtered and undissolved fine particles are mixed with the leached hulls in concrete to form solid high-level waste.

High-level liquid wastes from a reprocessing plant typically contain all the fission products and minor transuranics plus on the order of one percent of the plutonium in the spent fuel. These wastes are then mixed with glass frit and melted to make vitrified high-level waste. IAEA verification of vitrification involves sampling the feed solution to the melter to determine the plutonium content and then witnessing the loading of canisters.

The IAEA has decided that safeguards on vitrified waste from reprocessing plants may be terminated if the content of plutonium is less than 2.5 kg per cubic meter. The termination conditions state that the state must inform the IAEA of the location of the vitrified waste. If it is to undergo any processing that might allow for further separation of plutonium, then the state is obligated to return the nuclear material to safeguards.[583] A geological repository holding only canisters of vitrified waste therefore would have no safeguards measures applied.

For waste meeting these criteria, the safeguards problem is principally the limited accuracy of assays of plutonium content, and the lack of criteria related to the other contained weapon-usable fissile materials: neptunium and americium. If a state declared amounts that were larger than the amounts actually in the canisters, it would be possible for it to divert material without the IAEA being able to detect the diversion.

Spent fuel in permanent storage in geological repositories

The IAEA has examined the requirements for geological disposal of spent fuel and has concluded that: [584]

> "with appropriate advance planning, the operational and safety impacts of applying routine traditional IAEA safeguards in a geological repository is no greater or more technically challenging than those affecting other types of nuclear facilities…The reliability of the techniques and procedures should be proven in site specific situations."

A repository would go through three operational phases and IAEA safeguards would have to begin early and remain throughout, changing in character as the repository advanced from phase to phase:

1. *Pre-operational phase: planning, construction, commissioning (10–20 years).* The IAEA would need to begin consultations with the repository developer and with the national or regional authorities in advance of the start of construction of the repository. During construction, design information verification would check the declared design of the repository and the absence of undeclared chambers or tunnels or facilities for opening spent fuel packages. Seismic, satellite and other geophysical monitoring techniques (Table 14.3) would be employed to verify declared excavation activities and detect undeclared activities. These techniques and satellite imagery could be implemented during the repository pre-operational and operational phases.

2. *Operational phase: loading with spent fuel (20–40 years or longer).* In operation, verification of the contents of each cask should be carried out by means of a nondestructive assay. Whether this verification takes place at the reactors when the shipping cask is loaded and sealed, or at the repository conditioning facility would depend on the availability of sufficiently accurate methods and the relative costs and acceptability to operators of the possible alternatives.

3. *Post-operational phase: closure and long-term storage (indefinite).* The tunnels and shafts through which the spent fuel casks were transported and in which they were emplaced would back-filled. After closure, geophysical monitoring would provide assurance that the repository remains isolated.

Before and during construction, the IAEA will wish to establish baseline conditions for later comparison, using a combination of methods identified in Table 14.3.

Method	Technical features	Objective
Satellite monitoring prior to construction, during filling operations and when filled and closed	Optical, infrared and synthetic aperture radar	Detect road construction or digging; changes identified by overlaying images from different dates
Passive and active seismic monitoring	Low frequency (≤50 Hz) & microseismic monitoring (up to 500 Hz)	Detect excavation, blasting
Ground penetration by long electromagnetic waves		Detect changes caused by human activities
Measurement of resistivity to electric currents		Detect changes caused by human activities
Acoustic noise analysis		Detect activity where there should be none
Radiological mapping before construction, during filling and after closure	Air/water radioactivity monitoring	Detect radiation leakage

Table 14.3: Proposed geophysical techniques for monitoring a repository.

Synthetic aperture radar imagery might be used to detect changes in ground contours due to excavation or the dumping of excavated rock near a repository that is supposedly shutdown. Satellite imagery would be used to detect the construction of nearby roads, quarries and mines. Satellite images can be compared over time to detect changes, prompting on-site inspections (or complementary access under an Additional Protocol).

During the period of filling the repository, the safeguards measures in place at the repository would be based primarily on the verification of loading of shipment casks at the reactors (or AFRS) and maintaining continuity of knowledge thereafter.[585]

The IAEA proposes:[586]

> "A system of radiation monitors and surveillance cameras… be used to verify declared transfers of spent fuel casks from the surface buildings to the underground facility. These monitors and cameras would likely be located at the entrance to the transport shaft or ramp.
>
> Once nuclear material is underground, all openings that could potentially be used for the undeclared removal of nuclear material from the underground facility should be monitored. … At openings, where containment structures exist (for example, fan housings), seals could be used to provide assurance that nuclear

> materials could not be removed undetected through the opening. At openings having no safeguards seal and where radioactive material should not be present, radiation detectors and surveillance might be used. At the transport shaft or tunnel, the radiation monitors could be designed to determine the direction of movement of the nuclear material."

Casks would have to be tracked through the emplacement operations using seals and other containment and surveillance measures to ensure that the contents are not altered and that they are actually emplaced in their designated locations in the repository. If the repository were equipped with GPS satellite-mimicking capabilities, IAEA seals with positioning capabilities would allow automated tracking within the repository during the loading period.

An inspector would confirm emplacement, inspect the container one last time to detect any modifications, remove the electronic seals for re-use, witness the back-filling of each cell, and maintain surveillance until the repository tunnel is backfilled. Inspectors would be present whenever such operations and containment/surveillance system installations, servicing or removals were appropriate.

In the post-operational phase, the safeguards measures should give assurance that no intrusion into the repository occurs that could result in the retrieval of nuclear material.

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Endnotes

Chapter 1. Overview

1. Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 25 May 2011,www.iaea.org/programmes/a2/. Of the 64 reactors now under construction, 54 are PWRs.
2. The term heavy metal indicates that the fuel mass is being measured by its original uranium or uranium and plutonium content, i.e., not including the weight of structural materials or the oxygen in the uranium and plutonium oxides.
3. "Nuclear Waste: Amounts and On-Site Storage," Nuclear Energy Institute, www.nei.org/resourcesandstats/nuclear_statistics/nuclearwasteamountsandonsitestorage/; data as of February 201
4. Total for France is from *Plan National de Gestion des Dechets Radioactifs 2010–2012*, Autorité de Sûreté Nucléaire (French Nuclear Safety Authority, ASN), 2010. See chapter on Japan for references on Japanese inventories. Country chapters include more detail, and some include estimates for years after 2007.
5. Douglas Tonkay, U.S. Department of Energy, personal communication, 1 May 2011.
6. Jordi Bruno and Esther Cera, "Spent Fuel," in Allison Macfarlane and Rodney Ewing, eds., *Uncertainty Underground*, MIT Press, 2006, pp. 332-333, and *Integrated Data Base Report—1993: U.S. Spent Nuclear Fuel and Radioactive Waste Inventories, Projections, and Characteristics*, U.S. Department of Energy, DOE/RW-0006, Rev.
7. Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane, Gordon Thompson, and Frank N. von Hippel, "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *Science & Global Security*, Vol. 11, 2003, pp. 1–51.
8. Jungmin Kang, April 2011: based on data in *Status and Advances in MOX Fuel Technology*, IAEA Technical Report Series No. 415, International Atomic Energy Agency, Vienna, 2003; assumed plutonium fraction of 7.3 wt% for the 50 GWd/tHM spent MOX fuel, mixed with tails uranium of 0.25 wt% U-235.
9. The dose rate at five meters perpendicular to the center of the assembly would be about a factor of ten less than at one meter, and the dose rate one meter from the head or foot of the assembly would be about 10–20 percent that at the center perpendicular to the assembly, which is the direction of the maximum dose rate. The dose rate from a BWR fuel assembly, with a heavy metal mass about 40 percent of a PWR assembly, and of comparable burn-up, would be roughly one-half of that of a PWR assembly. Of course, twice as many assemblies would have to be handled to obtain the same amount of plutonium. W.R. Lloyd, M.K. Sheaffer, and W.G. Sutcliffe, *Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air,* Report No. UCRL-ID-115199, Lawrence Livermore National Laboratory, Livermore, CA, 31 January 1994; B.D Murphy, *Characteristics of Spent Fuel from Plutonium Disposition Reactors*, Report No. ORNL/TM-13170, Oak Ridge National Laboratory, 1996. In the latter, see Figures 17 and 18, pp. 29-31. Murphy assumed a total U fuel assembly of 0.424 metric tons, and a burn-up of 47.7 GWd/tHM. He calculated that the gamma dose rate at 1 meter perpendicular to a PWR spent fuel assembly at the center would be about 1.5 sieverts per hour at 100 years after discharge from the reactor.
10. Calculation by Jungmin Kang, with the following assumptions: a fuel enrichment of 3.2 wt% U-235 for the 33 GWd/tHM spent PWR fuel, and 4.2 wt% U-235 for the 50 GWd/tHM spent PWR

fuel; a homogeneous cylinder fuel assembly model: 3.6 meter height and 21.4 cm diameter with 460 kg HM for spent PWR fuel, and 50 centimeter height and 10 centimeter diameter with 18.8 kg HM for spent CANDU fuel. The gamma-ray source intensities within the fuel were calculated using ORIGEN2, grouped in 18 energy intervals. These radiation-source data were then used as input to the MCNP4C2 code, J. F. Briesmeister, ed., *MCNP—A General Monte Carlo N-Particle Transport Code, Version 4C*, LA-13709-M, Los Alamos National Laboratory, Los Alamos, NM, 2000. This was used to perform radiation transport calculations to obtain the flux and energy spectra of the gamma-rays 1 m from the center of the fuel assembly. The radiation doses were then calculated using the *American National Standard for Neutron and Gamma-Ray Fluence-to-Dose Factors*, ANSI/ANS-6.1.1, American Nuclear Society, La Grange Park, IL, 1991. A detailed study has concluded that "[d]epending on the size of the lattice and location of the detectors, the net effect of material homogenization on dose rate can be insignificant or range from a 6% decrease to a 35% increase relative to the detailed geometry model," T.H. Trumbull and D. R. Harris *The Effect of Material Homogenization in Calculating the Gamma-Ray Dose from Spent PWR Fuel Pins in an Air Medium,* Report No. LM-05K034, Lockheed Martin Corporation, Bethesda, MD, 2005.

11. A. Hedin, "Spent Nuclear Fuel – How Dangerous Is It?" *SKB Technical Report 97-13*, Swedish Nuclear Fuel and Waste Management Co., 1997.

12. "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *op. cit.*

13. A less costly strategy that has been suggested to protect against attack with anti-tank missiles from the ground outside the security perimeter is erecting berms around the casks to prevent direct line-of-sight targeting.

14. *Going the Distance? The Safe Transport of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States*, National Research Council, U.S. National Academy Press, 2006.

15. Roald Wigeland *et. al.*, "Spent Nuclear Fuel Separations and Transmutation Criteria for Benefit to a Geologic Repository," *Waste Management 2004 Conference*, 29 February – 4 March, 2004, Tucson, U.S.A.

16. *Technological Implications of International Safeguards for Geological Disposal of Spent Fuel and Radioactive Waste*, IAEA Nuclear Energy Series No. NW-T-1.21, International Atomic Energy Agency, Vienna, 2010.

17. *Nuclear Wastes: Technologies for Separations and Transmutation*, National Research Council, U.S. National Academy Press, 1996. The study estimated that the excess cost for a partitioning and transmutation disposal system over once-through disposal for the 62,000 tons of LWR spent fuel to be no less than $50 billion and easily over $100 billion in the United States.

18. ANDRA, "Cigéo : Centre industriel de stockage géologique pour les déchets (Industrial center for geological disposal of waste) HA et MA-VL, 2 May 2011, www.andra.fr/pages/fr/menu1/les-solutions-de-gestion/concevoir-un-centre-de-stockage-pour-les-dechets-ha-et-ma-vl-84.html

19. According to AREVA, had France not reprocessed, the area would have been 14 km^2, and if France reprocessed its spent LEU but not MOX fuel, the area would be 9.2 km^2, Dorothy R. Davidson, AREVA Federal Services LLC, "Leadership and the Future of Nuclear Energy," Presentation at Workshop on Leadership and the Future of Nuclear Energy, Chicago, June 10, 2011.

20. Juhani Vira, "Winning Citizen Trust: The Siting of a Nuclear Waste Facility in Eurajoki, Finland," *Innovations,* Vol. 1, No. 4, Fall 2006, pp. 67-82.

21. *Blue Ribbon Commission on America's Nuclear Future Draft Report to the Secretary of Energy*, Blue Ribbon Commission on America's Nuclear Future, 29 July 2011, brc.gov/sites/default/files/documents/brc_draft_report_29jul2011_0.pdf.

22. *Information Digest 2010-2011*, NUREG-1350, Vol. 22, U.S. Nuclear Regulatory Commission, August 2010, Figure 48, and Appendix I, www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1350/; and *Draft Fourth U.S. National Report under the Joint Convention on the Safety of Spent Fuel and the Safety of Radioactive Wastes*, U.S. Department of Energy, Annex D-1D. The inventory is as of the end of 2010.

23. Hojin Ryu, "Trend of Spent Fuel Management (SFM) in the World," Presentation at Interim Storage of Spent Fuel (ISSF-2010), International Atomic Energy Agency, Tokyo, 15-17 November 2010.

24. The earliest French and UK reprocessing contracts did not include this provision.

25. "A problem yet to be solved… is the management of the radioactive wastes from nuclear power plants. Such wastes remain radioactive for millions of years – a dangerous legacy for future generations. For this reason the Federal Government decided to completely phase out the production

of electricity from nuclear power." BMU, "Supply and Disposal—General Information," Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany, www.bmu.de/english/nuclear_safety/information/doc/4300.php.

Chapter 2. Canada

26. *Canada Enters the Nuclear Age: A Technical History of Atomic Energy of Canada Limited*, Published for Atomic Energy Canada Limited by McGill-Queen's University Press, 1997, pp. 67-68.

27. Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, www.iaea.org/programmes/a2/.

28. M Garamszeghy, *Nuclear Fuel Waste Projections in Canada—2010 Update*, NWMO TR-2010-17, Nuclear Waste Management Organization, Toronto, Ontario, December 2010, p. 2.

29. CANDU fuel bundles contain 19 kilograms of uranium, but NWMO estimates round this off to 20 kilograms.

30. M Garamszeghy, *op. cit.* The low scenario assumes that reactors are shut down at the end of the projected life of the fuel channels (i.e., nominal 25 effective full power years (equivalent to about 30 calendar years of operation). In the high scenario, the reactors would be refurbished with a new set of pressure tubes and other major components, then operated for a further 25 effective full power years (30 calendar years) to a total of 60 calendar years.

31. *Canadian National Report for the Joint Convention for the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management—Third Report*, Canadian Nuclear Safety Commission, Ottawa, ON, p. 137.

32. *Ibid.*, pp. 140-146.

33. The Gentilly-1 Nuclear Power Station began operation in 1972, and operated intermittently for a total of 183 effective full-power days until 1978, when it was determined that certain modification and considerable repairs would be required. In 1984, the reactor's decommissioning was initiated. *Ibid.*, p. 153.

34. Table 2.1 is based on data from M Garamszeghy, *op. cit.*; *Canadian National Report for the Joint Convention for the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management—Third Report*, *op. cit.*; and calculations by M. V. Ramana.

35. Genevieve Johnson, "The Discourse of Democracy in Canadian Nuclear Waste Management Policy," *Policy Sciences* Vol. 40, No. 2, 2007, pp. 79-99.

36. "With the current state of knowledge… there is no proven safe permanent disposal method," *Report to the Science Council of Canada*, Whiteshell Nuclear Research Establishment, Atomic Energy of Canada Limited, Pinawa, Manitoba, 1972; cited in Darrin Durant, "Radwaste in Canada: A Political Economy of Uncertainty," *Journal of Risk Research* Vol. 12, No. 7, 2009, pp. 897-919.

37. Jeremy Whitlock, "Waste Management," Canadian Nuclear FAQ, www.nuclearfaq.ca/cnf_sectionE.htm.

38. For example, on 28 February 1977, Atomic Energy of Canada Limited organized a seminar on "Proposed Canadian Fuel Cycle Program" for Federal Government Agencies in Ottawa, where it projected between 67 and 90 GW by the year 2000, and added that "there is no indication of saturation in nuclear capacity by the end of the century." Based on this, AECL projected that Canada would have committed its "measured resources" of natural uranium by 1978, its "indicated resources" by 1985, its "inferred resources" in the early 1990's and its "prognosticated resources" before 2006. This was used as an argument to embark on a program of reprocessing and fast breeder reactor construction. *AECL Seminar on plutonium recycle and the thorium cycle in Canada*, Ottawa, 28 February 1977, excerpts available at www.ccnr.org/aecl_plute_seminar.html

39. Durant, "Radwaste in Canada: A Political Economy of Uncertainty," *op. cit.*, p. 901.

40. A. M. Aikin, J. M. Harrison, and F. K. Hare, *The Management of Canada's Nuclear Wastes, Report of a Study Prepared under Contract for the Minister of Energy, Mines and Resources Canada*, Federal Department of Energy, Mines and Resources, Government of Canada, Ottawa, Ontario, 1977.

41. *Ibid.*, p. 5.

42. This is suggested by Gallup polls between September 1976 and October 1983, Michael D. Mehta, *Risky Business: Nuclear Power and Public Protest in Canada*, Lexington Books, 2005, p. 40.

43. The first location to be chosen was Mount Moriah in Ontario, where AECL initiated a program of geophysical work with possible drilling. See L. B. Geller and J. J. B. Dugal, *Minutes of the Jan. 13, 1977 Nuclear Waste Disposal Project Meeting re. Drilling Programme at Mt. Moriah*, Canmet, M.R.L., Rep. 77–7, Canada Center for Mineral and Energy Technology /Mining Research Laboratories, February 1977. This led to overwhelmingly negative public response. See Gordon Edwards, "High-level radioactive wastes in Canada," Canadian Coalition for Nuclear Responsibility, 1986, www.ccnr.org/hlw_history.html

44. Durant, "Radwaste in Canada: A Political Economy of Uncertainty," *op. cit.*

45. Frank King, "Recent Developments in Nuclear Waste Management in Canada," Presentation at the WM '02 Conference, Tucson, AZ, 24–28 February 2002.

46. N. A. Chandler, "Twenty Years of Underground Research at Canada's URL," Presentation at the WM '03 Conference, Tucson, AZ, 23–27 February 2003.

47. H. Y. Tammemagi and David Jackson, *Half-Lives: A Guide to Nuclear Technology in Canada*, Oxford University Press, 2009.

48. Tom Isaacs, "The Canadian Repository Program: Helping Society Make Up Its Mind," Presentation at the Symposium on Uncertainty in Long Term Planning-Nuclear Waste Management, Vanderbilt University, 7–8 January 2008.

49. Johnson, *op. cit.* The statement, however, explicitly stated that this "joint undertaking is not to be construed as a Canadian position on the question of the reprocessing of irradiated fuel. Canada's position in respect to its fuel cycle development program will be reviewed following the completion of the International Nuclear Fuel Cycle Evaluation now underway." See J. Boulton, *Management of Radioactive Fuel Wastes: The Canadian Disposal Program*, Atomic Energy of Canada Limited, Chalk River, Ontario, 1978, p. 127.

50. Ontario Hydro was to work on interim storage and transportation of radioactive wastes whereas AECL was to work on the immobilization and disposal of radioactive wastes from nuclear power reactors, including geological field and laboratory studies.

51. W. T. Hancox and K. Nuttall, "The Canadian Approach to Safe, Permanent Disposal of Nuclear Fuel Waste," *Nuclear Engineering and Design* Vol. 129, No. 1, 1991.

52. Darrin Durant, "Strategic Action in Nuclear Waste Disposal: Canada's Adaptive Phased Management Approach," Presentation at Values in Decisions On Risk, Stockholm, 14–18 May 2006.

53. Hancox and Nuttall, "The Canadian Approach to Safe, Permanent Disposal of Nuclear Fuel Waste," *op. cit.*, p. 110.

54. Durant, "Strategic Action in Nuclear Waste Disposal: Canada's Adaptive Phased Management Approach," *op. cit.* Titanium has also been considered for the outer shell.

55. Hancox and Nuttall, "The Canadian Approach to Safe, Permanent Disposal of Nuclear Fuel Waste," *op. cit.*

56. K. W. Dormuth, P. A. Gillespie, and S. H. Whitaker, "Disposal of Nuclear Fuel Waste," in Ronald E. Hester and Roy M. Harrison, eds., *Waste Treatment and Disposal*, Royal Society of Chemistry, 1995.

57. R. Zach et al., "Biosphere Model for Assessing Doses from Nuclear Waste Disposal," *Science of The Total Environment* Vol. 156, No. 3, 1994, pp. 217–234.

58. Don Hart and Don Lush, *The Chemical Toxicity Potential of CANDU Spent Fuel*, Nuclear Waste Management Organization, Toronto, Ontario, 2004.

59. Charles Hostovsky, "The Paradox of the Rational Comprehensive Model of Planning," *Journal of Planning Education and Research* Vol. 25, No. 4, 2006, pp. 382–395, p. 386.

60. Critics termed this an environmental assessment "without an environment."

61. Johnson, *op. cit.*

62. Brenda L. Murphy and Richard G. Kuhn, "Setting the Terms of Reference in Environmental Assessments: Canadian Nuclear Fuel Waste Management," *Canadian Public Policy/Analyse de Politiques* Vol. 27, No. 3, 2001, pp. 249–266.

63. *Canadian National Report for the Joint Convention for the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management—Third Report*, *op. cit.*, p. 13.

64. *Nuclear Fuel Waste Management and Disposal Concept: Report of the Nuclear Fuel Waste Management and Disposal Concept Environmental Assessment Panel*, Canadian Environmental Assessment Agency, Minister of Public Works and Government Services Canada, February 1998, p. 2.

65. *Ibid.*, p. 38.

66. *Ibid.*, p. 68.

67. Natural Resources Canada, "Government of Canada Response to Recommendations of the Nuclear Fuel Waste Management and Disposal Concept Environmental Assessment Panel," December 1998, www.cnp.ca/issues/hlw-goc-response-12-98.html

68. *Ibid.*

69. *Assessing the Options: Future Management of Used Nuclear Fuel in Canada*, Nuclear Waste Management Organization, 2004, Toronto, Ontario, p. 12.

70. *Choosing a Way Forward: The Future Management of Canada's Used Nuclear Fuel (Final Study)*, Nuclear Waste Management Organization, 2005, p. 4; See also Johnson, *op. cit.*.

71. *Choosing a Way Forward*, *op. cit.* p. 61.

72. Statement by Norm Rubin of Energy Probe. See Johnson, *op. cit.*, p. 84.

73. *Choosing a Way Forward*, *op. cit.*

74. *Ibid.,* p. 24.

75. For planning purposes, NWMO has adopted a base case of 3.6 million bundles, which represented a value between the lower and upper end forecasts to allow for some reactors being refurbished and some not.

76. The present value calculation is "based on a discount rate of 5.75% which assumes a 3.25% real rate of return over a projected long-term average increase in the Ontario Consumer Price Index of 2.5%." See Joint Waste Owners, *Costs of Alternative Approaches for the Long-Term Management of Canada's Nuclear Fuel Waste: Deep Geologic Disposal Approach*, Ontario Power Generation, Hydro Quebec, New Brunswick Power, Atomic Energy of Canada Ltd., 2004. Updated to January 1, 2010, the estimated present value of the cost of APM is $7 to $8 billion. *Moving Forward Together: Annual Report 2009*, Nuclear Waste Management Organization, Toronto, Ontario, 2010, p. 40.

77. *Canadian National Report for the Joint Convention for the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management—Third Report*, *op. cit.*, p. 7.

78. *Moving Forward Together: Canada's Plan for the Long-Term Management of Used Nuclear Fuel*, Nuclear Waste Management Organization, Toronto, Ontario, May 2010. See the Frequently Asked Questions section, www.nwmo.ca/sitingprocess_faqs#c0.

79. The nine steps in this process are described in *Steps in the Process*, Nuclear Waste Management Organization, Toronto, Ontario, 2010, www.nwmo.ca/uploads_managed/MediaFiles/1486_steps_in_the_process.pdf.

80. *Ibid.*

81. *Moving Forward Together: Canada's Plan for the Long-Term Management of Used Nuclear Fuel*, *Ibid.*, www.nwmo.ca/uploads_managed/MediaFiles/1480_coverletter.pdf.

82. See, for example, the NWMO presentation at the 2010 AMO Annual Conference, Windsor, Ontario, 16 August 2010, video available on the NWMO website: www.nwmo.ca/sitingprocess_amo/video:43/tag:amo2010.

83. These include Creighton, English River First Nation, and Pinehouse in Saskatchewan, and Ear Falls, Ignace, Schreiber and Homepayne in Ontario, and Big Lakes in Alberta. See Jonathan Montpetit, "Sask., N.B. reportedly receptive for nuclear waste dump," *Toronto Star*, 20 February 2011, Andrea Sands, "Northern area eyes nuclear-waste site," *Edmonton Journal*, 13 April 2011.

84. "Nuclear Waste," CBC Radio Broadcast, 23 December 2009, www.cbc.ca/thecurrent/episode/2009/12/23/december-23-2009/.

85. *Summary Report — Initial Screening — Township of Ignace, Ontario*, Nuclear Waste Management Organization, Toronto, Ontario, 24 March 2011, www.nwmo.ca/uploads/File/Ignace---Full-Report_med.pdf

86. James Wood, "No nuclear waste storage facility for Sask: Wall," *The StarPhoenix*, 15 April 2011.

87. In May 2011, the utility company Bruce Power withdrew its proposal to ship steam generators from decommissioned nuclear reactors through the Great Lakes in the face of strong opposition from environmental and Aboriginal groups. Mark Iype, "Bruce Power scraps plans to ship generators through Great Lakes," *The Vancouver Sun*, 16 May 2011.

88. U. Stahmer, "Transport of Used Nuclear Fuel—a Summary of Canadian and International Experience," Nuclear Waste Management Organization, Toronto, Ontario, 2009, p. 5.

89. Interestingly, in 1978, when the Federal and Ontario government laid statements on joint nuclear waste management, it was envisioned that a full-scale repository will be operational about 25 years later, around the turn of the century.

90. *Choosing a Way Forward*, *op. cit.*, p. 20.

91. *Canada's Nuclear Future: Clean, Safe, Responsible*, Natural Resources Canada, Canada News Center, Ottawa, Ontario, 14 June 2007, www.news.gc.ca/.

92. *Choosing a Way Forward*, *op. cit.*, p. 20.

93. John Cadham, *The Canadian Nuclear Industry: Status and Prospects*, Centre for International Governance Innovation, Waterloo, Ontario, 2009.

Chapter 3. France

94. Yannick Barthe, "Framing nuclear waste as a political issue in France," *Journal of Risk Research,* Vol. 12, No. 7–8, 2009, pp. 941–954.

95. *Council Directive 2011/70/Euratom establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste*, European Council, Brussels, 19 July 2011, eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:199:0048:0056:EN:PDF.

96. *Presentation to Joint Convention Third Review Meeting*, Autorité de Sûreté Nucléaire (Nuclear Safety Authority, ASN), Paris, 13 May 2009.

97. *Third National Report on Compliance With the Joint Convention Obligations,* Autorité de Sûreté Nucléaire, Paris, September 2008.

98. Half of the 6-year appointments of the National Review Board are renewed every 3 years. Appointments are renewable once. Members are prohibited from exercising directly or indirectly "any other function within or receive fees from any assessed organization and any company or establishment producing or holding radioactive waste."

99. All direct quotes of the Planning Act are from ANDRA, *Radioactive materials and waste—Planning Act of 28 June 2006*, Châtenay-Malabry cede, consolidated version established by ANDRA, November 2009.

100. For a detailed discussion see Mycle Schneider, "Fast Breeder Reactors in France" in *Fast Breeder Reactor Programs: History and Status*, IPFM Research Report No. 8, International Panel on Fissile Materials, February 2010, pp. 17–35, www.ipfmlibrary.org/rr08.pdf.

101. AREVA and EDF have been in a fierce battle for several years over a number of issues, including the two final operating years of the EURODIF uranium enrichment plant (EDF preferred cheaper Russian uranium enrichment services) and reactor building projects (the highly problematic EPR construction sites in Finland and France and the lost bid for the construction of four units in the United Arab Emirates). The media has extensively covered the conflict between the nuclear groups. The *Economist* magazine, for example, described the "deep animosity between EDF and AREVA" in a 2 December 2010 article entitled "Nuclear Power—Team France in disarray."

102. AREVA/EDF, Joint press statement, "AREVA and EDF create long-term used fuel management partnership," 19 December 2008. The 2040-time frame is particularly surprising as the current La Hague reprocessing plants were expected to be shut down around 2025. However, the National Plan 2010-2012 states that both lines, UP2-800 and UP3, are expected to be shut down in 2040. A study of the extension of their lifetimes has never been published.

103. A framework agreement is not a binding contract, however, and in January 2010, in the absence of a contract, AREVA stopped shipping spent fuel from EDF plants to La Hague.

104. AREVA/EDF, "AREVA and EDF reach agreement on used nuclear fuel management," 5 February 2010. It is remarkable that the press statement disappeared from AREVA's website, while it remained available on the EDF website at press.edf.com (accessed on 26 January 2011).

105. EDF, Direction Production Ingénierie, Jean Cyr Darby, personal communication, 30 March 2011.

106. 22,530 tons as of the end of 2008, according to AREVA, Annex to the letter by Jean-Luc Andrieux to Henri Revol, President of the HCTISN (High Committee for Transparency and Information on Nuclear Security), dated 12 November 2009.

107. Depending on the quality of the material, it takes between 120 tons and 170 tons of reprocessed uranium in order to fabricate one reload containing about 18 tons of re-enriched uranium.

108. Mycle Schneider, "End of reprocessed uranium exports to Russia?," 29 May 2010, www.fissilematerials.org/blog/2010/05/end_of_reprocessed_uranium.html

109. "Avis sur la transparence de la gestion des matières et des déchets nucléaires produits aux différents stades du cycle du combustible," High Committee for Transparency and Information on Nuclear Security, 12 July 2010

110. There is no plan to increase the number of "moxed" units beyond 24. The four Cruas units are to operate on reprocessed uranium fuel. The Fessenheim and Bugey reactors were not designed for MOX use. In the future, it is possible that the EPR, currently under construction at Flamanville, will operate with MOX fuel.

111. Plutonium could be chemically separated from fresh MOX in a glove box without shielding. Fresh MOX is therefore considered almost the equivalent to direct weapons usable material.

112. Spent MOX must be cooled at least 24 months prior to shipment compared to 18 months for spent UOX fuel.

113. Based on data from COGEMA, AREVA, and ASN.

114. According to the French government's annual INFCIRC-549a declarations to the IAEA.

115. French officials call it the "equal flow principle." See, for example, *Third National Report on Compliance With the Joint Convention Obligations*, *op. cit.* Sylvain Granger, director of EDF's fuel division, stated in 2005 that "it is a management rule that we fix for ourselves and the inventory of currently separated plutonium is maintained in a stock that corresponds to three years of MOX fuel fabrication, that's all!," Commission Particulière du Débat Public sur la gestion des déchets radioactifs, Minutes of the public hearing, 15 September 2005. There is no explanation why three years of consumption would be the appropriate "management rule." Furthermore, even then the figures don't add up. Until 2010 MELOX produced annually about 140 tons of MOX for EDF. At an average plutonium content of around 8 percent, three years of production would add up to about 34 tons, far from the over 47 tons of separated plutonium in stock at La Hague by as of the end of 2009, "Communication Received from France Concerning its Policies regarding the Management of Plutonium," INFCIRC/549/Add.5/14, International Atomic Energy Agency, 8 September 2010.

116. *Plan National de Gestion des Déchets Radioactifs 2010-2012*, ASN, 2010; The 2010 figures have been estimated by the author.

117. Commission Nationale d'Evaluation, *Rapport d'évaluation No. 4*, Vol. 1, June 2010, p. 106

118. The other La Hague reprocessing line UP3 is not designed for the treatment of MOX fuels.

119. *National Plan 2010–2012, ibid.* All numbers and direct quotes in this section are from the National Plan, if not otherwise noted.

120. There are also roughly 200 million tons of rock and ore residues and 50 million tons of ore processing waste generated at the approximately 200 uranium mining sites in France that have become de-facto low-level waste disposal sites.

121. The storage silos holding this graphite "are now inconsistent with current safety criteria", according to ASN. ASN has requested EDF "to take all appropriate steps to face the situation" and "EDF has proposed to implement a containment barrier around the silos and that proposal is being reviewed." See *Third National Report on Compliance with the Joint Convention Obligations*, 2008, p.148.

122. All direct quotes by Marie-Claude Dupuis, Director General of ANDRA, from her Testimony at the National Assembly, Economic Affairs Committee, 19 January 2011.

123. ANDRA, "Cigéo: Centre industriel de stockage géologique pour les déchets HA et MA-VL," 2 May 2011, www.andra.fr/pages/fr/menu1/les-solutions-de-gestion/concevoir-un-centre-de-stockage-pour-les-dechets-ha-et-ma-vl-84.html, accessed 16 June 2011.

124. Marie-Claude Dupuis, Director General of Andra, Testimony before the National Assembly Economic Affairs Committee, 19 January 2011.

125. Commissariat Général du Plan, "Penser l'avenir pour agir aujourd'hui (Think about the future to act now)," June 2000, p. 164.

126. ASN, *Joint Convention—Third Review Meeting—Questions asked to France and answers,* April 2009, answer to Ireland, question #4. It is unclear why ANDRA envisages *more* HLW with *less* reprocessing in scenarios 1b/c compared to 1a.

127. In fact, a government led working group, including the operators and ANDRA, has established a very large cost range between €13.5 and 58 billion, Rapport du groupe de travail relatif au "Coût d'un stockage souterrain de déchets radioactifs de haute activité et à vie longue, Direction générale de l'énergie et des matières premières (DGEMP, General Directorate for Energy and Raw Materials), July 2005. The reference all-reprocessing scenario has been put at the cost range cited by the Director General of Andra without providing the underlying hypothesis. See Mycle Schneider, Comparison among different decommissioning funds methodologies for nuclear installations - Country Report France, on behalf of the European Commission Directorate-General for Energy and Transport, Wuppertal Institute, 2007.

128. Marie-Claude Dupuis, *op. cit.*

129. Christian Bataille and Claude Birraux, *Rapport sur l'évaluation du plan national triennal de gestion des matières et déchets radioactifs*, Vol. 1, provisional document, OPECST, 19 January 2011.

130. *Rapport d'évaluation N°4 — Tome 1*, Commission Nationale d'Evaluation, June 2010.

131. *Ibid*.

132. *Baromètre d'opinion sur l'énergie et le climat en 2010*, CGDD, Ministry for Ecology, October 2010.

133. *Europeans and Nuclear Safety*, Special Eurobarometer 324, European Commission Directorate-General for Energy and Transport (DG-TREN), March 2010.

134. IFOP, "Les français et le nucléaire," commissioned by *Le Journal du Dimanche*, June 2011

Chapter 4. Germany

135. Act of 22 April 2002 amending the Act on the Peaceful Utilization of Atomic Energy and the Protection against its Hazards (Atomic Energy Act) of 23 December 1959, as amended and promulgated on 15 July 1985, Federal Law Gazette, Part I, page 1351, available online at www.bmu.de/files/pdfs/allgemein/application/pdf/atg_english.pdf

136. Nuclear power plant licenses did not originally include a formal time limit for operations. Safety assessments, however, assumed an operational time of 40 years.

137. Act of 8 December 2010 amending Act on the peaceful utilization of nuclear energy and the protection against its hazards (Atomic Energy Act), of 23 December 1959, as amended and promulgated on 15 July 1985, Federal Law Gazette, Part I, 2010, p. 1817; available online at www.bfs.de/de/bfs/recht/rsh/volltext/A1_Englisch/A1_12_10_AtG.pdf

138. Assuming a capacity factor of 95 percent declining to 85 percent over a period of ten years, the resulting average extension of the reactor operating times under this act would have been 8 years for seven older nuclear power reactors (i.e., to a total time of about 40 years), and 14 years for ten newer reactors that started operating after 1980 (i.e., to a total time of about 46 years)

139. The eight to be shut down immediately are Germany's seven oldest nuclear power plants, which had all started operating in the 1970s (Biblis A and B, Neckarwestheim-1, Brunsbuettel, Isar-1, Philippsburg-1, and Unterweser) plus the troubled Kruemmel nuclear power plant for a total nuclear generating capacity of 8.4 GWe.

140. The "Zwischenlager Nord"- ZLN (Northern Interim Storage) started operation in March 1998. Spent fuel as well as different kinds of low- and intermediate-level waste mainly from decommissioning of Rheinsberg and Greifswald NPPs is stored there.

141. Hagen, M. (German Ministry of Research and Technology), "Stand der Verwirklichung des Entsorgungskonzepts aus der Sicht der Bundesregierung" [Status of Realization of the Waste Management Concept from point of view of German Government], in *Kernforschungszentrum Karlsruhe: Sammlung der Vorträge anlässlich des 2. Statusberichtes des Projekts Wiederaufarbeitung und Abfallbehandlung am 18.11.1977* [Collection of Contributions to 2nd Status Report on the Reprocessing Project and Waste Treatment, 18 November 1977], KfK 2615, PWA 15/78

142. Anselm Tiggemann, *Der niedersächsische Auswahl- und Entscheidungsprozess, Expertise zur Standortauswahl für das Entsorgungszentrum [The Lower-Saxony Selection and Decision Process, Expertise on the Site Selection for the Waste Management Centre]*, 1976/77, May 2010, p. 5.

143. Much of this spent fuel was from the Mehrzweckforschungsreaktor – MZFR (Multi-purpose research reactor) at Karlsruhe, a heavy water PWR, 57 MWe with slightly enriched (0.85 %) uranium oxide fuel that operated from 1965 to 1984.

144. *Costs and Schedules*, WAK Wiederaufarbeitungsanlage Karlsruhe Rückbau- und Entsorgungs-GmbH, 9 March 2011, www.wak-gmbh.de/ewngruppe/wak/reprocessing-plant/facts-and-figures/kostentermine.html?L=1.

145. Act of 22 April 2002 amending Act on the Peaceful Utilization of Atomic Energy and the Protection against its Hazards (Atomic Energy Act), of 23 December1959, as Amended and Promulgated on 15 July 1985, Federal Law Gazette, Part I, page 1351.

146. Parliamentary groups SPD and BÜNDNIS 90/DIE GRÜNEN, *Entwurf eines Gesetzes zur geordneten Beendigung der Kernenergienutzung zur gewerblichen Erzeugung von Elektrizität; Begründung [Draft law on Termination of the Use of Nuclear Power for Commercial Electricity Production, Justification]*, Bundestags Drucksache [Bundestag printed paper] 14/6890, 11 September 2001.

147. *Deutschland ist auf dem Weg zum Ausstieg aus der Plutoniumwirtschaft [Germany is on the way to phase out plutonium economy]*, BMU Press release No. 166/05, Federal Ministry of the Environment, Berlin, 23 June 2005.

148. *Convention on Nuclear Safety – Report for the Fifth Review Meeting in April 2011*, Government of the Federal Republic of Germany, Bonn, 4 August 2010.

149. *Antwort der Bundesregierung auf die kleine Anfrage der Fraktion Die Linke — Sicherheit bei Transport, Lagerung und Einsatz von MOX-Brennelementen [Federal Government's answer to the inquiry of the parliamentary group Die Linke — Safety at Transport, Storage and Use of MOX fuel]*, Bundestags Drucksache (Bundestag printed paper) 17/1323, Government of the Federal Republic of Germany, 8 April 2010.

150. *Convention on Nuclear Safety – Report for the Fifth Review Meeting in April 2011*, *op. cit.*

151. *Return of radioactive waste from the reprocessing of spent fuel elements in France and Great Britain*, The Federal Office for Radiation Protection, www.bfs.de/en/endlager/abfaelle/rueckfuehrung.html.

152. A repository for the disposal of waste with negligible heat generation is expected to be available in Germany by about 2019. This repository, "Schacht Konrad", is to come into operation near the town of Salzgitter in Lower Saxony. Construction work started in March 2007, *Schacht Konrad 2 wird saniert [Konrad 2 will be renovated]*, http://www.endlager-konrad.de/cln_117/nn_1072854/sid_E0AF79FD6FD21BF66DA12B379A185BDA/DE/Aktuelles/Artikel/Einfuehrung.html?__nnn=true.

153. Hans-Helge Jürgens and Katrin Hille, *Atommülldeponie Salzbergwerk Asse II - Gefährdung der Biosphäre durch mangelnde Standsicherheit und das Ersaufen des Grubengebäudes [Atomic Waste Dump Salt Mine Asse — Threat to the Biosphere due to lack of Stability and Flooding of the Drift]*, Braunschweig, March 1979.

154. *Verantwortlichkeiten für Endlagereinrichtung und -betrieb sowie Finanzierungsregelungen [Responsibilities for organisation and operation of disposal facilities and rules for financing]*, Federal Ministry of the Environment, Nature Conservation and Nuclear Safety, February 2011.

155. *Herkunft der in der Schachtanlage Asse II eingelagerten radioaktiven Abfälle und Finanzierung der Kosten [Origin of Radioactive Wastes disposed of in the Asse II Mine and Financing of Costs]*, Federal Ministry of the Environment, Nature Conservation and Nuclear Safety, 5 March 2009.

156. *Konzeptionelle und sicherheitstechnische Fragen der Endlagerung radioaktiver Abfälle - Wirtsgesteine im Vergleich [Conceptual and Safety related Questions of Nuclear Waste Disposal — Comparison of Host Rocks]*, Federal Office for Radiation Protection (BfS), Salzgitter, November 2005.

157. *Röttgen: Wir müssen uns der Verantwortung für die Entsorgung radioaktiver Abfälle endlich stellen [Röttgen: We must face responsibilities of Nuclear Waste Management]*, Press release No. 037/10, Federal Ministry of the Environment, Berlin, 15 March 2010.

158. "Mc Allister fordert Endlagergesetz" ["McAllister calls for disposal act"], *Radio eins*, 18 June 2011

159. *Site Selection Procedure for Repository Sites – Recommendations of the AkEnd*, Committee on a Site Selection Procedure for Repository Sites, Köln, December 2002.

160. *Site Selection Procedure for Repository Sites – Recommendations of the AkEnd*, *ibid.*

161. Some of the geological criteria for site evaluation (e.g. the model of the "isolating rock zone") can be found in the recently published *Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste,* Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 30 September 2010.

162. A transfer of the exploration activities from the mining law to the atomic law could have created an opportunity for a formal public hearing as part of the licensing procedure.

163. *Ein konstruktiver Dialog – wie ist das möglich?* Gorleben Dialog, www.gorlebendialog.de/mitreden/doc/37.php.

164. *Vorschlag zur Gestaltung eines Dialog- und Beteiligungsprozesses*, Gorleben, Unabhängige Nationale Expertengruppe Endlager [National Independent Expert Group repository], February 2011, www.gorlebendialog.de/files/pdf/application/pdf/grafik_dialog_beteiligung.pdf.

Chapter 5. Japan

165. The JAEC has published Long-Term Plans for Nuclear Energy approximately every 5 years since 1956. The 1961 Plan placed the goal of FBR commercialization in the 1970s. The 2005 version is titled Framework for Nuclear Energy Policy and a tentative English translation of its main part can be found at www.aec.go.jp/jicst/NC/tyoki/taikou/kettei/eng_ver.pdf.

166. One reactor (Tsuruga Unit 1) is scheduled to be shut down in 2016. www.meti.go.jp/english/press/data/20100618_08.html.

167. Press conference of 18 May 2011, www.kantei.go.jp/jp/kan/statement/201105/18kaiken.html.

168. "Hamaoka Genpatsu: Teishi Yosei" (Hamaoka nuclear power plant: request for halting of operation), *Mainichi Shimbun*, 8 May 2011.

169. Hamaoka units 1 and 2 already had been shut down for decommissioning and Unit 3 for periodic inspection. The Nuclear and Industrial Safety Agency (NISA) stated that it would take a couple of years for Hamaoka to complete the upgrades to protect against earthquake and tsunami risks that the company had announced to make, including the construction of a tide embankment at least 15 meters high. Kan explained that the reason for his request was in consideration of the Ministry of Education, Culture, Sports, Science & Technology's prediction of an 87 percent chance of a magnitude-8.0 quake hitting the area within the next 30 years.

170. "Hamaoka Genpatsu: Teishi Yosei" [Hamaoka nuclear power plant: request for halting of operation], *Mainichi Shimbun*, 8 May 2011.

171. The status of Rokkasho is reported on in English regularly on website of the Citizens' Nuclear Information Center, www.cnic.jp/english/cnic/index.html.

172. "Genshiryoku Hakusho Heisei 10 Nen Ban" [White Paper on Nuclear Energy], Japan Atomic Energy Commission, 1998, www.aec.go.jp/jicst/NC/about/hakusho/hakusho10/siryo2082.htm.

173. "Purusaamaru no Genjo" [The present situation of plans to use MOX in LWRs], Federation of Electric Power Companies, www.fepc.or.jp/present/cycle/pluthermal/genjou/index.html.

174. Kyushu Electric Power Company Genkai Unit 3, Shikoku Electric Power Company Ikata Unit 3, Tokyo Electric Power Company Fukushima Daiichi Unit 3, and Kansai Electric Power Company Takahama Unit 3.

175. "Aomori Kennai 'Genpatsu Chushiwo' 48%—Asahi Shimbun Seron Chosa" [Within Aomori Prefecture 'Stop Nuke Construction' 48%— Asahi Shimbun Public Opinion Survey], *Asahi Shimbun*, 30 May 2011, www.asahi.com/special/08003/TKY201105290389.html. The Prefecture has only one power reactor operating: Tohoku Electric Power Company's Higashidori Unit 1. The construction of TEPCO's Higashidori Unit 1 started in January 2011 but was halted after the March 11 earthquake. The two companies share the same site.

176. "Mihamanokai, 5/18 Keisansho Kosho Hokoku" [Report on the dialogue with METI on 18 May], 18 May 2009, www.jca.apc.org/mihama/stop_pu/meti_kousyou090518.htm.

177. The estimate of the total number was changed from 850 to 830 in October 2010. "Garasu Kokatai Eikokubun no Umpan Kakunin Shinsei" [Vitrified Waste—British portion transportation verification application], *Daily Tohoku*, 14 October 2010, www.cgi.daily-tohoku.co.jp/cgi-bin/tiiki_tokuho/kakunen/news/news2010/kn101014a.htm.

178. Nuclear Waste Management Organization of Japan, "Siting Factors for the Selection of Preliminary Investigation Areas," December 2002, www.numo.or.jp/en/what/pdf/3.pdf

179. "Chiji to Kataro Meeting," [Let's talk with the Governor meeting], Kagoshima Prefecture,15 March 2010, www.pref.kagoshima.jp/chiji/katarokai/h21/kishirakatarokai.html and "Kaku Hai Saishu Shobunjo ha Hakushi—Minami Osumi Chocho ga Gikai Toben," [No decision on nuclear waste final disposal site—Replies Minami Osumi Mayor at a town council meeting] 9 December 2009, *Kyodo*, www.47news.jp/localnews/kagoshima/2009/12/post_20091209122849.html.

180. Tatsuki Takamatsu, "Metal Casks Storage Schedule of Recylable Fuel Storage Center in Mutsu," November 2010, www.criepi.denken.or.jp/result/event/seminar/2010/issf/pdf/2-1_powerpoint.pdf.

181. According to the White Paper on Nuclear Energy of 2009 (the most recent one available) the total amount of spent fuel in storage facilities at commercial power plants as of the end of September 2009 was 12,840 tHM. Comparing with the amount, 12,320 tHM as of the end of September 2008 in the White Paper on Nuclear Energy of 2008, one can see an increase of 520 tHM in one year. Japan Nuclear Fuel Ltd. data for the transportation of spent fuel to the Rokkasho reprocessing plant between October 2008 and September 2009 show that a total of 339 tHM was sent to the plant. This means that some 859 tHM were discharged from the commercial reactors in this one-year period. See "Heisei 20 Nendo Shiyozumi Nenryo no Yusokeikaku Oyobi Jisseki," [Spent fuel transportation plans and actual records, FY2008], Japan Nuclear Fuel Ltd, www.jnfl.co.jp/daily-stat/transport-schedule/recycle-execution2008.html and "Heisei 21 Nendo Shiyozumi Nenryo no Yusokeikaku Oyobi Jisseki," [Spent fuel transportation plans and actual records, FY2009], Japan Nuclear Fuel Ltd, www.jnfl.co.jp/daily-stat/transport-schedule/recycle-execution2009.html.

182. This is data provided by the Federation of Electric Power Companies in an October 2010 Nuclear and Industrial Safety Agency (NISA) document, Kojima Shuhei (Director, Nuclear Fuel Transport and Storage Regulation Division. Nuclear and Industrial Safety Agency [NISA]), "Shiyozumi Nenryo Chozo no Hitsuyosei to Kokunaigai no Doko ni Tsuite" [Concerning the need for spent fuel storage and the domestic and overseas trends], 8 October 2010, www.nisa.meti.go.jp/koho/symposium/files/nisakaigi/1/s9_05.pdf. The table in the NISA document has the following footnote: The management capacity of Hamaoka Units 1 and 2 of Chubu Electric Power Company is considered the same as the actual amount stored since their operation has been terminated.

183. Reloading takes place at the time of periodic inspection. In Japan, each nuclear power reactor is obliged to have a periodic inspection within 13 months of its previous periodic inspection. This inspection normally lasts 2-3 months but often takes much longer. This means that refueling normally takes place every 15-16 months. These long inspections may help account for the fact that the lifetime energy availability factor for Japan's nuclear power reactors through 2010 was 71.1% vs. a global average of 77.2%, Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, www.iaea.org/programmes/a2/. Due to the complaints by power companies about this point, a new rule was introduced in 2009 to make it possible to for this maximum period between periodic inspections to increase to 24 months, depending on the history of each unit.

184. What to do with the melted-down fuel is a separate issue.

185. A total of 7,100 tons of Japanese spent fuel was sent to the United Kingdom and France, beginning in 1969 and 1978, respectively, including about 1,500 tons of gas cooled reactor fuel shipped to British Nuclear Fuel Limited (BNFL). See page107 in National Report of Japan for the third Review Meeting of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, www.nsc.go.jp/anzen/shidai/genan2008/genan063/siryo4.pdf (English Section starts after the Japanese Section, which ends on page 132).

186. JNFL, "Saishori Kojo no Sagyo Jokyo" [Operation situation of the reprocessing plant], www.dailydb.jnfl.jp/daily-stat/cgi/pub_preview.cgi?d&1&20110302.

187. Office for Atomic Energy Policy, Cabinet Office, "Kakunenryo Saikuru wo Meguru Genjo ni Tsuite [Concerning the present situation related to nuclear fuel cycle]," 21 February 2011, www.aec.go.jp/jicst/NC/tyoki/sakutei/siryo/sakutei4/siryo2-1.pdf.

188. "Sogo Enerugii Chousakai, Genshiryoku Bukai Chukan Hokoku—Risaikukru Nenryo Shigen Chukan Chozo no Jitsugen ni Mukete," [Nuclear power working group, Advisory committee on energy, interim report—Toward realization of recycle fuel resource interim storage], 11 June 1998, www.kakujoho.net/npp/i90913dj.pdf. (This report is not found at the METI site. It is reproduced at the Kakujoho [nuclear information] site run by Takubo.)

189. Thick metal casks were chosen as the first method to be used at off-site "interim storage" facilities. In October 2002, the Nuclear Safety Commission issued "Safety Examination Guidelines for Spent Fuel Interim Storage Facilities Using Metal Dry Casks." Use of reinforced concrete shielding casks around a thin inner metal canister, the most common form of dry-cask storage in the United States, is also being considered.

190. JAPC is the only power company in Japan solely engaged in generating nuclear power and sells its electricity to utilities. It operates the Tsuruga reactors in Fukui Prefecture and the Tokai Daini reactor in Ibaraki Prefecture.

191. Tatsuki Takamatsu, "Metal Casks Storage Schedule of Recylable Fuel Storage Center in Mutsu," November 2010, www.criepi.denken.or.jp/result/event/seminar/2010/issf/pdf/2-1_powerpoint.pdf.

192. *Risakuiru Nenryo Chozo Gijutu [Recyclable fuel storage technology]*, Central Research Institute Of Electric Power Industry (CRIEPI), October 2009, www.criepi.denken.or.jp/research/pamphlet/chozou.pdf.

193. Jigyo Gaiyo [Operation overview], Recyclable Fuel Storage Company, www.rfsco.co.jp/about/about.html.

194. Mitamura was reelected on 5 June 2011 by an overwhelming majority.

195. I"sogareru Chukan Chozo Shisetu" [Interim storage facility urgently required], *Yomiuri Shimbun*, 23 November 2010, www.yomiuri.co.jp/e-japan/fukui/feature/fukui1290259811609_02/news/20101123-OYT8T00027.htm.

196. These facilities were licensed before the introduction of the 2002 Safety Examination Guidelines for Spent Fuel Interim Storage Facilities Using Metal Dry Casks. The preexisting law made it possible to have such onsite facilities using simplified versions of transportation casks.

197. Yumiko Kumano, "Integrity Inspection of Dry Storage Casks and Spent Fuels at Fukushima Daiichi Nuclear Power Station," *Third International Seminar on Interim Storage of Spent Fuel*, Central Research Institute of Electrical Power Industry (CRIEPI), Japan, 15-17 November 2010, www.criepi.denken.or.jp/result/event/seminar/2010/issf/pdf/6-1_powerpoint.pdf.

198. Takeshi Fujimoto, "Inspection of Fuel Cladding and Metal Gasket in Metallic dry cask at Tokai No. 2 Power station," *Third International Seminar on Interim Storage of Spent Fuel*, Central Research Institute of Electrical Power Industry (CRIEPI), Japan, 15-17 November 2010, www.criepi.denken.or.jp/result/event/seminar/2010/issf/pdf/6-2_powerpoint.pdf.

199. Yumiko Kumano, "Integrity Inspection of Dry Storage Casks and Spent Fuels at Fukushima Daiichi Nuclear Power Station," *ibid*.; Takeshi Fujimoto, "Inspection of Fuel Cladding and Metal Gasket in Metallic dry cask at Tokai No. 2 Power station," *Ibid*.; *Genshiryoku Hatsudensho Naino Shiyozumi Nenryo no Kanshiki Chozo Kyasuku Chozo ni Tsuite [Concerning dry-cask storage of spent fuel at nuclear power plant sites]*, Nuclear Security Commission, 27 August 1992, www.nsc.go.jp/shinsashishin/pdf/1/ho006.pdf.

200. *Hamaoka Nuclear Power Station Replacement Plan, etc.,* Chubu Electric Power Co., December 2008, www.chuden.co.jp/english/resource/en_others_20090212_02.pdf

201. Kono's blog www.taro.org/2011/04/post-972.php and *Impact to last decade or more if existing nuclear plants shut down*, Japan Center for Economic Research Report, 2011, www.jcer.or.jp/eng/research/pdf/pe(iwata20110425)e.pdf.

202. The tenth regional electric power company, the Okinawa Electric Power Company, is the smallest and does not have nuclear power plants.

203. Prime Minister's Office, Press Conference by Prime Minister Naoto Kan, 18 May 2011 [Provisional Translation] www.kantei.go.jp/foreign/kan/statement/201105/18kaiken_e.html.

204. *Takaki Yoshiaki Monbudaiji Kishakaiken [Minister Yoshiaki Takaki's press conference]*, 15 July 2011, www.mext.go.jp/b_menu/daijin/detail/1308386.htm.

205. "Kan comes out for a society with no nuclear power plants," *Asahi Shimbun*, 14 July 2011.For the entire text of Kan's talk see: Prime Minister's Office, Press Conference by Prime Minister Naoto Kan, Wednesday, 13 July 2011 [Provisional Translation], www.kantei.go.jp/foreign/kan/statement/201107/13kaiken_e.html. "Kan says nuclear phaseout comments 'personal' view," *Kyodo*, 15 July 2011, www.mdn.mainichi.jp/mdnnews/national/news/20110715p2g00m0dm102000c.html.

Chapter 6. South Korea

206. Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, www.iaea.org/programmes/a2/; National Energy Committee, *The 1st National Energy Basic Plan (2008-2030)*, August 2008 (Korean).

207. In response to a request with financial incentives made by Korea Hydro and Nuclear Power, as of 28 February 2011, two additional communities had volunteered to host nuclear power plants: Yeongdeok, and Samcheok.

208. Ki-Chul Park, "Status and Prospect of Spent Fuel Management in South Korea," *Nuclear Industry*, August 2008 (in Korean).

209. In pyroprocessing, spent fuel is dissolved in molten salt and uranium and the transuranic elements are separated electrochemically. In PUREX reprocessing, which is the form of reprocessing that is used commercially today, spent fuel is dissolved in nitric acid and the uranium and plutonium are separated by solvent extraction.

210. The United States reserves "consent rights" over the reprocessing of spent fuel that contains LEU enriched in the U.S. or has been irradiated in reactors with U.S. designs or major components. Most South Korean and Japanese spent fuel is subject to these consent rights.

211. Seong-won Park, Miles Pomper and Lawrence Scheinman, "The Domestic and International Politics of Spent Nuclear Fuel in South Korea: Are We Approaching Meltdown," *KEI Academic Paper Series*, Vol. 5, No. 3, March 2010.

212. Tadahiro Katsuta and Tatsujiro Suzuki, *Japan's Spent Fuel and Plutonium Management Challenges,* Research Report No. 2, International Panel on Fissile Materials, 2006. See also the chapter on Japan in this volume.

213. Heon Kim, "Challenges of New National Organization for Radioactive Waste Management in Korea," *Technical Meeting on the Establishment of a Radioactive Waste Management Organization*, Paris, France, June 7–9, 2010.

214. J.H. Mok et al., *Sayonghuhaekyonryo jeojangryang josa mich pohwasijum geomjung [Examination on Amount of Spent Fuel Stored and Verification on Saturation Time of Pool Capacities]*, Kookmin University, May 2009.

215. Projections of spent fuel generation depend on assumptions concerning capacity factors and thermal efficiencies of the reactors and the burnups of the spent fuel. The author assumes: capacity factors of 90 percent, thermal efficiencies of 33 percent and average discharged burnups level of 50,000 MWd/ton and 7,100 MWd/ton for spent PWR fuel and spent CANDU fuel, respectively.

216. The dry storage in place in 2005 was installed in 1990 (680 tons), 1998 (907 tons) and 2002 (680 tons).

217. Matthew Bunn et al., *Interim Storage of Spent Nuclear Fuel: A Safe, Flexible, and Cost-Effective Near-Term Approach to Spent Fuel Management*, A Joint Report from the Harvard University Project on Managing the Atom and the University of Tokyo Project on Sociotechnics of Nuclear Energy, June 2001, p. 40. There are complaints from the communities hosting reactors that the payments that they currently receive are used to pay for roads and infrastructure that is funded in other ways for communities that do not host nuclear power plants.

218. A site with 4 GWe of generating capacity operating at 90% capacity would produce 30 billion kWh of electric energy per year. A $10 million payment would increase the cost of this electric energy by $0.0003/kWhr.

219. Seong-Kyung Cho and Jooho Whang, "Status and Challenges of Nuclear Power Program and Reflections of Radioactive Waste Management Policy in Korea," *2009 Advanced Summer School of Radioactive Waste Disposal with Social-Scientific Literacy*, Berkeley, CA, 3 — 10 August 2009, www.goneri.nuc.berkeley.edu/pages2009/slides/Whang.pdf

220. Seong-Kyung Cho and Jooho Whang, *op. cit.*, Heon Kim, *op. cit.* and Ki-Chul Park, *op. cit.*

221. Seong-won Park et al., *op. cit.;* Ji-Bum Chung and Hong-Kyu Kim, "Competition, economic benefits, trust, and risk perception in siting a potentially hazardous facility," *Landscape and Urban Planning* Vol. 91, No. 1, 2009, pp. 8-16. The high vote for Gyeongju may be due to the fact that more than 90% of Gyeongju's 200,000 voters live on the other side of a mountain from the site. Of the remaining 10% who live within about 10 km of the site, fewer than 60% voted affirmatively, Taehyun Kim and Hongkyu Kim, "Gyeongju bangsasung pyeogimul cheorijang yipji jumintoopyo gyeolgwaye gongganjuk paetun bunsuk" [Analysis of Spatial Patterns on the Result of Referendum for Siting a Radioactive Waste Disposal Facility in Gyeongju], *Journal of the Korean Urban Geometry Society*, Vol.13, No.2, 2010, pp. 117-128 (in Korean).

222. "Radioactive waste management in Rep. of Korea," www.nea.fr/rwm/profiles/Korea%20report%202010%20web.pdf.

223. Won Il Ko and Eun-ha Kwon, "Implications of the new National Energy Basic Plan for nuclear waste management in Korea," *Energy Policy*, Vol. 37, No. 9, 2009, pp. 3484–3488.

224. According to the IAEA's Power Reactor Information System, South Korea generated 35% of its electricity with 19 GWe of nuclear capacity in 2009. Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, www.iaea.org/programmes/a2/. At 75 GWe operat-

ing at the same capacity factor, South Korea's nuclear power plants would generate 140% of South Korea's electrical power requirements or the equivalent of 100% of U.S. electric power production per capita in 2009.

225. Jongyoul Lee, *et al*, "Concept of a Korean Reference Disposal System for Spent Fuels," *Journal of Nuclear Science and Technology*, Vol. 44, No. 12, 2007, pp. 1565–1573.

226. U.S. State Department, "Discussions on the New U.S.-ROK Civil Nuclear Cooperation Agreement," 26 October 2010, www.state.gov/r/pa/prs/ps/2010/10/150026.htm; "Korea, U.S. agree on pyroprocessing study," *The Korea Herald,* 26 October 2010, www.koreaherald.com/national/Detail.jsp?newsMLId=20101026000734; and "South Korea, U.S. Plan 10-Year Reprocessing Study," Global Security Newswire, 14 January 2011, www.globalsecuritynewswire.org/gsn/nw_20110114_7546.php.

227. Seong-Kyung Cho and Jooho Whang, *op. cit.*

228. Gordon Mackerron and Frans Berkhout, "Learning to listen: institutional change and legitimation in UK radioactive waste policy," *Journal of Risk Research*, Vol. 12, Nos. 7–8, October–December 2009, pp. 989–1008; see also their updated analysis in the chapter on the UK experience in this volume.

229. See the chapter on Sweden in this volume.

230. This is based on several South Korean news items in 2009.

231. A recent study proposed a design in which a public-consensus committee, working groups and discussion groups would be set up independently from the utility and national government, with seminars, workshops and public hearings for local communities to facilitate public education, Jooho Whang et al, *A Study on a Design for Facilitating the Public Consensus Process on the Spent Fuel*, May 2009 (Korean).

232. J.H. Mok et al., *op. cit.* Estimates by Jungmin Kang of potential expansion of pool storage.

Chapter 7. Russia

233. The numerical suffixes denote the approximate gross generating capacities of the units. The net generating capacity is typically about 7 percent less.

234. Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, www.iaea.org/programmes/a2/.

235. The reactors under construction as of the end of 2010 were: two VVER-1200s at Rostov (Volgodonsk) nuclear power plant (NPP), two VVER-1200s at Leningrad-2 NPP, two VVER-1200s at Novovoronezh-2 NPP, one VVER-1000 at Kalinin NPP, one BN-800 at Beloyarskaya NPP, and the floating power plant (two KLT-40S units). The Kursk-5 (RBMK-1000) is listed as under construction since 1985, www.rosenergoatom.ru/rus/development.

236. The spent fuel of IRT-1000, IRT-2M, IRT-3M, WWR-(S, M, M2, M3, M5, M7) and MR reactors is reprocessed at RT-1, which uses aqueous (PUREX) extraction technology. The spent fuel of the experimental research reactors BOR-60, BR-10, IBR is reprocessed with the use of pyro-electrochemical technology at the Research Institute of Atomic Reactors.

237. Spent fuel from the high-powered research reactors SM-3 (100 MWt, previously known as the SM-2) is made of uranium dioxide dispersed in a copper-magnesium matrix that cannot be reprocessed at Mayak. This fuel is proposed for long-term storage and ultimate disposal without reprocessing.

238. Russian Federation Second National Report prepared for the Third Review Meeting of the Joint Convention on the Safety of Spent Fuel Management and Safety of Radioactive Waste Management, Moscow, 2009.

239. E. Kudryavtsev and A. Khaperskaya "Development of Spent Nuclear Fuel Management Infrastructure in the Russian Federation," *IAEA International Conference on Management of Spent Fuel from Nuclear Power Reactors*, Vienna, Austria, 31 May - 4 June 2010.

240. "GKHK do konza goda uvelichit mochshnost 'mokrogo' khranilichsha OYAT do 8400 ton" [MCC will increase capacity of the wet spent fuel storage to 8400 tonnes by the end of the year], Press-center of atomic energy, 3 August 2010.

241. "The construction of initial units of the SNF storage facility will be finished in the middle of August," MCC, *Nuclear Ru*, 7 June 2010.

242. "Emil Tomov about Bulgarian NSF," *Atominfo Ru*, 18 July 2010; www.atominfo.ru/news2/b0540.htm.

243. K.G. Kudinov, "Creating an Infrastructure for Managing Spent Nuclear Fuel," in Glenn E. Schweitzer and A. Chelsea Sharber, ed., *An International Spent Nuclear Fuel Storage Facility-Exploring a Russian Site as a Prototype*, National Academies Press, 2005, pp. 145-151, www.nap.edu/catalog/11320.html.

244. "Zaporozhskaya AES," Energoatom, www.energoatom.kiev.ua/ru/nuclear_plants/npp_zp/info.

245. E. Kudryavtsev and A. Khaperskaya "Development of Spent Nuclear Fuel Management Infrastructure in the Russian Federation"; and A.V Zrodnikov, "Innovative Nuclear Power for 21st Century," Presentation at the 16th annual conference of the Russian Nuclear Society, 18-30 June 2006, Moscow, Russia.

246. "On the Program of Development of the State Corporation Rosatom for 2009-2015," Government of Russian Federation, Order No. 705, 20 September 2008, www.government.ru/gov/results/6515/.

247. "The government of Russian Federation has adopted the federal targeted program on the development nuclear energy technologies," 21 January 2010, atominfo.ru/news/air8811.htm.

248. Andrei Zolotkov, "Comment: Russia's new radioactive waste law: Wanted the best, but it turned out as always," Bellona, 28 November 2010, www.bellona.org/articles/articles_2010/zolotkov_radwaste-bill.

249. Rosatom hoped to pass the Federal Law "Management of Radioactive wastes" at the end of 2010. Ye. Yevstratov: GK «Rosatom» nadyeyetsya na prinyatiye zakona ob obrashshyenii s RAO v etom godoo [E. Yevstratov, "State Corporation 'Rosatom' hopes to enact a law on the treatment of waste this year,"] www.nuclear.ru/rus/press/oyatrao/2117819/.

250. *On compliance with the obligations of the joint convention on the safety of spent fuel management and the safety of radioactive waste management*, Prepared for the third Review Meeting in frames of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management, State Atomic Energy Corporation 'Rosatom' and Federal Environmental, Industrial and Nuclear Supervision Service, Moscow, 2008, p. 12.

251. The RSFSR law "On protection of environment" of 19 December 1991, Article 50(3). This article also prohibited dumping of the "radioactive waste and materials" in water as well as disposing of them by launching into space.

252. Mark Hibbs, "Spent fuel import blockage meant RT-1 plant is reprocessing less," *Nuclear Fuel*, 4 January 1993. Although spent fuel was not mentioned in the law, custom regulations *de facto* prohibited bringing spent fuel (including that from Soviet-built power plants) into Russia (State Customs Committee Order No. 01-12/71, 8 July 1992). This ban was apparently extended to the fuel from the former Soviet republics that did not make special arrangements, Karoly Ravasz, "Hungary assured that Ukraine won't stop spent fuel shipments to Russia," *Nuclear Fuel*, 24 May 1993.

253. In particular, the government allowed bringing spent fuel from Hungary and Czechoslovakia (Government of Russian Federation, Order No. 1437-r, 8 August 1992). Finland resumed its spent fuel shipments in late 1993. Ariane Sains, "Finns resume shipping spent fuel to Chelyabinsk complex in Urals," *Nuclear Fuel*, 3 January 1994.

254. The major point of disagreement between Russian and Ukraine was the price of reprocessing. Karoly Ravasz, "Hungary assured that Ukraine won't stop spent fuel shipments to Russia," *Nuclear Fuel*, 24 May 1993. Lithuania complained about Russia's refusal to accept spent fuel from RBMK reactors of the Ignalina power plant. However, there were no plans for reprocessing RBMK spent fuel and hence no plans for transporting it.

255. Presidential Decree No. 472 of 21 April 1993. The decree also called for agreements with Belarus, Kazakhstan, and Lithuania that would resolve the spent fuel issue. Ukraine and Armenia were not mentioned – the power plant in Armenia was shut down at the time. (Russia agreed to take its spent fuel when the plant resumed its operations.) The decree also established the practice of allocating a portion of the proceeds (25 per cent in that case) to environmental rehabilitation and other similar programs.

256. Presidential Decree No. 389, 20 April 1995.

257. Government of Russian Federation, Order No. 773, 29 July 1995. See Article I.

258. *Ibid*. The rules established by this order became effective on 1 September 1995.

259. For the Soviet contracts, signed before 1991, an intergovernmental agreement would suffice. *Ibid*., Article II.

260. The country would also have to demonstrate that it had the organizational and technical infrastructure for handling radioactive materials. *Ibid.*, Article II.

261. Government of Russian Federation, Order No. 745, 10 July 1998, Article 2(v).

262. "On amending Article 50 of the Federal Law of RSFSR 'On protection of the environment'," Federal Law, 10 July 2001 No 93-FZ. In 2002 the Duma passed a new Federal Law "On protection of the environment." The amendments introduced in 2001 are in the Article 48.4 of the new law.

263. Federal Law "On protection of the environment," 10 January 2002, No. 7-FZ, Article 48.4.

264. *Ibid.*, Article 51.

265. Federal Law "On special ecological programs of rehabilitation of radioactively contaminated areas," 10 July 2001, No. 92-FZ, Article 4.5. The other 25 per cent of the profit is to be directed to the regions that host fuel-handling facilities. *Ibid.*, Article 5.5.

266. "On special commission on the issues related to transfer to the territory of Russian Federation of irradiated fuel assemblies of foreign origin," Decree of the President of Russian Federation, No. 828, 10 July 2001.

267. "On approval of the Statute of the commission on the issues related to transfer to the territory of Russian Federation of irradiated fuel assemblies of foreign origin," Decree of the President of Russian Federation, No. 858, 31 July 2003. The statute specifies among other things that, as its title implies, contracts that involve the import of Russian-origin spent fuel will be outside of the scope of the commission review. In a reshuffle in 2005 the commission all its members who were critical of the fuel import plans were removed from the commission, Presidential Decree No. 705, 18 June 2005.

268. Russia signed a nuclear cooperation agreement with Iran in 1992. The return of fuel from Iran is covered by a protocol to that agreement that was signed in 2005.

269. "On transfer of irradiated fuel assemblies of nuclear reactors into Russian Federation," Government of Russian Federation, Order No. 418, 11 July 2003, Article 3.

270. *Ibid.*, Article 10(v) and Article 11.

271. *Ibid.*, Article 10(g) and Article 11(d).

272. *Ibid.*, Article 10(b).

273. *Ibid.*, Article 10(v) and Article 10(g).

274. *Global Fissile Material Report 2007*, International Panel on Fissile Materials, October 2007, www.ipfmlibrary.org/gfmr07.pdf, p. 99.

Chapter 8. Sweden and Finland

275. The national referendum allowed a vote on three alternatives, two of which were very similar. One alternative, Proposition 3, was for a rapid phase-out and the other two were for allowing a maximum of 12 reactors and a phase-out by 2010. The two "2010 alternatives" were put forward by the Social Democrats and Liberals (Proposition 2) and the Conservatives (Proposition 1), all three officially pro-nuclear parties. With this confusing choice of alternatives, Proposition 3 ("no to nuclear power") received 38.7% of the vote, Proposition 2 received 39.1% and Proposition 1 received 18.9%. With a majority against a rapid phase-out, Sweden's last six reactors were started up between 1980 and 1985.

276. After the 2006 elections brought a four-party right-wing/centre coalition into power, the strongly pro-nuclear Liberal Party started to push the possibility to build new nuclear reactors in Sweden. This caused a struggle within the coalition resulting in an energy policy with a strong focus on accelerating the production of renewable electricity while allowing new-build of nuclear reactors, but only if older reactors were shut down. It has been seen as somewhat ironic that the legislation allowing new build was passed in 2010, the same year that nuclear power was to have been phased out according to the 1980 referendum.

277. In national surveys in 97 countries covering three decades by the World Value Survey Project, Sweden stands out in this regard. See the cultural map developed from this data: Ronald Inglehart and Christian Welzel, *The WVS Cultural Map of the World*, www.worldvaluessurvey.org/wvs/articles/folder_published/article_base_54.

278. The Canadian and UK programs for management of high-level wastes have had major set-backs and at present both countries claim that they are open with regard to the choice of method for final disposal of high-level waste. If the KBS method is licensed in Sweden, however, it is very likely that the method would soon be the favored option in these and other countries.

279. The reprocessing contracts with Cogema in France were taken over by German and Japanese interests. The 57 tons of spent nuclear fuel that had been sent to France were traded for 23 tons of German spent MOX fuel that will be disposed of in Sweden. The 140 tons of spent fuel that were sent to BNFL in the United Kingdom were finally reprocessed in 1997 and the plutonium is to be returned to the Oskarshamn nuclear power plant in the form of MOX fuel. The high-level reprocessing waste will be traded for low-level waste with a comparable activity to be returned to Sweden.

280. AKA Commission, *Spent Fuel and Radioactive Waste*, Government reports SOU 1976:30, SOU 1976:31 and SOU 1976:32 (in Swedish).

281. The AKA commission also recommended that a national research body independent from the nuclear industry be set up. The Program Council For Radioactive Waste (PRAV, Programrådet för radioaktivt avfall) was created. PRAV worked so closely to the KBS project, however, that its independence was soon questioned and PRAV was shut down in 1981. Since then all Swedish resources for research on nuclear waste have been controlled by the nuclear industry.

282. KBS-1, *Handling of Spent Nuclear Fuel and Final Storage of Vitrified High Level Reprocessing Waste*, 5 volumes, Kärnbränslesäkerhet, Stockholm, 1977. All reports from KBS, SKBF and SKB can be downloaded from www.skb.se.

283. KBS-2, *Handling and Final Storage of Unreprocessed Spent Nuclear Fuel*, 2 volumes, Kärnbränslesäkerhet, Stockholm, 1978.

284. After the completion of KBS-1 and KBS-2 reports, the KBS project was integrated into the nuclear industry's company for nuclear fuel supply SKBF. In 1984 the company was renamed the Swedish Nuclear Fuel and Waste Management company and the acronym was changed to SKB.

285. KBS-3, *Final storage of spent nuclear fuel*, summary and 4 volumes, Swedish Nuclear Fuel Supply Co., Division KBS (SKBF/KBS), Stockholm, 1983.

286. *Copper as canister material for unreprocessed nuclear waste—evaluation with respect to corrosion,* Report KBS TR-90, Kärnbränslesäkerhet, Stockholm, 1978; *Canister materials proposed for final disposal of high level nuclear waste—a review with respect to corrosion resistance*, Report KBS TR 81-05, Swedish Nuclear Fuel Supply Co/Division KBS (SKBF/KBS), Stockholm, 1981; and *Corrosion resistance of a copper canister for spent nuclear fuel*, Report KBS TR 83-24, Swedish Nuclear Fuel Supply Co/Division KBS (SKBF/KBS), Stockholm, 1983.

287. *Copper canisters for nuclear high level waste disposal*, Report SKB TR 92-26, Swedish Nuclear Fuel and Waste Management Co, Stockholm, 1992; *Copper corrosion under expected conditions in a deep geologic repository*, Report TR-01-23, Swedish Nuclear Fuel and Waste Management Co., Stockholm, 2001; and *Corrosion calculations report for the safety assessment SR-Site*, Report TR 10-66, Swedish Nuclear Fuel and Waste Management Co., Stockholm, 2010.

288. The KBS-method is often described as a multi-barrier system or as a system of barriers for defence in depth. The terminology comes from the field of nuclear reactor safety. This analogy was well received by the regulator, the Swedish Nuclear Power Inspectorate, SKI. The regulator was well acquainted with nuclear reactor safety work and even made it part of its nuclear waste regulation that a repository should rely on a multi-barrier system.

289. *Final disposal of spent nuclear fuel: Importance of the bedrock for safety*, Report SKB TR 92-20, Swedish Nuclear Fuel and Waste Management Co., Stockholm, 1992; *Deep repository for spent nuclear fuel*: *SR 97 - Post-closure safety. Main report*—Vol. I, Vol. II and Summary, Report TR-99-06, Swedish Nuclear Fuel and Waste Management Co., Stockholm, 1997; *Long-term safety for KBS-3 repositories at Forsmark and Laxemar - a first evaluation. Main report of the SR-Can project*, Report TR-06-09, Swedish Nuclear Fuel and Waste Management Co., Stockholm, 2006; and *Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project*. 3 volumes, Report TR-11-01, Swedish Nuclear Fuel and Waste Management Co., Stockholm, 2011.

290. *Long-term safety for the final repository for spent nuclear fuel at Forsmark, op. cit*. For the figure and the assumptions regarding corrosion and shear. See Vol. 1, p.44.

291. *Regulations on the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste*, SSMFS 2008:37, Swedish Radiation Safety Authority, Stockholm, 2008. Available in English as *SSI FS 1998:1* on the regulator's web site www.ssm.

se; and *The Swedish Nuclear Power Inspectorate's Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste*, SSMFS 2008:21, Swedish Radiation Safety Authority, Stockholm, 2008. Available in English as *SKIFS 2002:1* at www.ssm.se.

292. The latest Fud program report was published in October 2010, *RD&D Program 2010: Program for research, development and demonstration of methods for the management and disposal of nuclear waste*, SKB TR-10-63, Swedish Nuclear Fuel and Waste Management Co., Stockholm, 2010.

293. Äspö Hard Rock Laboratory. Annual Report 2009, Report TR 10-10, Swedish Nuclear Fuel and Waste Management Co., Stockholm, 2010.

294. *Quality Assurance Review of SKB's Copper Corrosion Experiments*, SSM Report 2010:17, Swedish Radiation Safety Authority, Stockholm, 2010.

295. G. Hultquist, P. Szakálos and G. Wikmark, "Corrosion of Copper by Water," *Electrochemical and Solid-State Letters,* Vol. 10, 2007, pp. C63–C67. The researchers did not mention the KBS method or nuclear waste in the article but, in the general public debate, the copper corrosion work of SKB has been criticized and discussions have begun about how the safety of the KBS concept could be influenced by the results.

296. G. Hultquist, P. Szakálos, M. J. Graham, G. I. Sproule and G. Wikmark, "Detection of Hydrogen in Corrosion of Copper in Pure Water," *International Corrosion Congress, ICC 2008*, Paper no. 3884, Las Vegas, 2008, and G. Hultquist, P. Szakálos, M. J. Graham, A. B. Belonoshko, G. I. Sproule, L. Gråsjö, P. Dorogokupets, B. Danilov, T. AAstrup, G. Wikmark, G. K. Chuah, J.-C. Eriksson and A. Rosengren, "Water Corrodes Copper," *Catalysis Letters*, Vol. 132, No. 3-4, 2009, pp. 311-316.

297. *Mechanisms of Copper Corrosion in Aqueous Environments: A report from the Council's scientific workshop on November 16, 2009*, Report 2009:4e, Swedish Council for Nuclear Waste, Stockholm, 2009.

298. *Nuclear Waste State-of-the-Art Report 2010—Challenges for the Final Repository Program*, Swedish Council for Nuclear Waste, Stockholm, 2010.

299. In a recent development another research group at the Royal Institute of Technology, KTH, in Stockholm has done experiments examining the effects of radiation on copper corrosion in an anoxic environment. Although the results are still unpublished, the result appears to have been "unexpected high corrosion." SKB has financed a continuation of the project.

300. D. D. Macdonald and S. Sharifi-Asl, *Is Copper Immune to Corrosion When in Contact With Water and Aqueous Solutions?* SSM Rapport 2011:09, Swedish Radiation Safety Authority, 2011.

301. The Government's policy was to issue the reactor permits if the regulator, the Nuclear Power Inspectorate, SKI, first approved the bedrock as suitable for a repository. This was acceptable to the anti-nuclear Center Party in the coalition as the hydro-geological criteria to be used were regarded as so strict that they were unlikely to be met. SKI set up a panel of geologists to evaluate the Sternö drilling results and make a recommendation about the bedrock. The panel voted seven to one that the results did not meet the required bedrock criteria. The board of SKI, which is almost entirely politically appointed, had the final say, however. As the pro-nuclear Social Democrats were able to muster a majority that approved the bedrock with the argument that the expert panel had not ruled out the possibility that there could be bedrock in Sternö that could meet the criteria. When the Center Party understood that the decision had been rigged, it brought down the coalition Government.

302. One of the best versions of the story of the early siting process is told in a report called "Nuclear Waste in Sweden—The Problem Is Not Solved!" that can now be only found on the web site www.folkkampanjen.se/nwfront.html. A more academic account can be found in a book by the sociologist Göran Sundquist, *The Bedrock of Opinion: Science, Technology and Society in the Siting of High-Level Nuclear Waste*, Dordrecht: Kluwer Academic Publishers, 2002. And there is of course the nuclear waste company SKB's version of the siting process as described in the license application, *Site selection – siting of the final repository for spent nuclear fuel*, Report R-11-07, Swedish Nuclear Fuel and Waste Management Co., SKB, March 2011.

303. *Final disposal of spent nuclear fuel. Importance of the bedrock for safety, op. cit.*

304. RD&D-Program 92, Treatment and final disposal of nuclear waste: Program for research, development, demonstration and other measures, Swedish Nuclear Fuel and Waste Management Co., Stockholm, 1992.

305. Support for a repository in both the communities of Östhammar and Oskarshamn increased from about 50% to about 80% during the ten-year period of the site investigation. SKB's efforts included intensive information campaigns, including paid weekend information trips to nuclear facilities

in the other community (the low-level waste repository SFR is in Forsmark and the CLAB interim storage facility and the Äspö Hard Rock laboratory are in Oskarshamn), and sponsorship of local sports clubs and events.

306. The waste company's plan was to first submit an application for a spent-fuel encapsulation plant. A second licensing application for the repository itself would come later. This plan to split the application was criticised as not allowed by the Environmental Act. The company reconsidered, but only to the extent that it submitted a license application for an encapsulation plant only under the Nuclear Act. The Nuclear Power Inspectorate, SKI, accepted the application but after an initial review decided not to proceed with the licensing process until the application for a repository was submitted.

307. *Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation*, *op. cit.*

308. The present legal framework does have its complications and a lack of clarity, even though the basic principles from the Environmental Act have already been incorporated into the Nuclear Activities Act and the Radiation Protection Act. A recent Government study has, however, proposed that the Nuclear Activities Act and the Radiation Protection Act shall be merged into the Environmental Act. This may take place already by the end of 2012 and the license application will then continue to be reviewed according to the new legislation.

309. The latest SKB plan in Swedish is SKB 2010. The latest plan document translated into English is SKB 2009.

310. For more information see the Nuclear Waste Fund's website, www.karnavfallsfonden.se/informationinenglish.

311. Clifford I. Voss and Alden M. Provost, *Recharge-area Nuclear Waste Repository in Southeastern Sweden, Demonstration of Hydrogeologic Siting Concepts and Techniques,* SKI Report 01:44, Swedish Nuclear Power Inspectorate, November 2001.

312. P. Särkkä, Rock Engineering Characteristics of the Investigated Sites for Final Disposal of Spent Nuclear Fuel in Finland, *Proceedings of the International Conference on the Safety of Radioactive Waste Management*, Cordoba, 13-17 March 2000, International Atomic Energy Agency, IAEA-CN-78/28, pp. 115–119.

Chapter 9. United Kingdom

313. This chapter is adapted and updated from Gordon MacKerron and Frans Berkhout, "Learning to listen: institutional change and legitimation in UK radioactive policy," *Journal of Risk Research*, Vol. 12, Nos. 7–8, 2009, pp. 989–1008.

314. G. MacKerron, "Decommissioning costs and British nuclear policy," *The Energy Journal*, No 1, pp. 13–28.

315. The NDA uses a real discount rate of 2.2% p.a. The undiscounted cost that corresponds to this £44 bn. is probably of the order of £70 bn. ($112 bn.) as the timescale for discharging all liabilities is a century and more.

316. *Strategy Effective from April 2011,* UK Nuclear Decommissioning Authority (NDA), Moor Row, Cumbria, UK, 2011, p. 90.

317. Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 26 June 2011, www.iaea.org/programmes/a2/. Shutdown dates of the remaining Magnox plants according to NDA, *Strategy Effective from April 2011,* pp. 85, 86.

318. *The United Kingdom's Third Annual Report on Compliance with the Obligations of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*, Health and Safety Executive, United Kingdom, 2008.

319. In April 2005, the UK's THORP (Thermal Oxide Reprocessing Plant) was shut down by a major pipe break. At that time, it had uncompleted contracts to reprocess about 750 tons of foreign light-water reactor fuel (mostly from Germany) and 3100 tons of domestic AGR fuel, Martin Forwood, *The Legacy of Reprocessing in the United Kingdom*, IPFM Research Report No. 6, International Panel on Fissile Materials, 2008, www.ipfmlibrary.org/rr06.pdf, p. 11. Reprocessing resumed in 2008 but throughput was limited by failures in high-level waste evaporators. A new evaporator is consequently under construction. According to Nuclear Decommissioning Authority's (NDA's) annual reports, THORP reprocessed 385 tons of spent fuel during the three fiscal years ending on

31 March 2010, www.nda.gov.uk/documents. During 2010-11, 336 tons were reprocessed, (Martin Forwood, personal communication, 27 June 2011) for a total of 721 tons. It has been assumed that about 80% of the reprocessed spent fuel was AGR fuel, Martin Forwood, *Ibid.* All AGR spent fuel will be shipped to Sellafield but, beyond the amount that is to be reprocessed under the contracts, the contracts give NDA the option of storing the remainder.

320. NDA, *Strategy Effective from April 2011, op. cit.*, p. 80.

321. Nuclear Decommissioning Authority. www.nda.gov.uk/sites/

322. *The 2010 UK Radioactive Waste Inventory, Main Report*, URN 10D/985NDA/ST/STY(11)0004, Nuclear Decommissioning Authority, 2011, pp. 47 - 78. It is expected that each m^3 of liquid HLW will be converted into 0.3 m^3 of vitrified waste (p. 38).

323. *Managing Radioactive Waste Safely: A Framework for Implementing Geological Disposal*, Presented to Parliament by the Secretary of State for Environment, Food and Rural Affairs, London, June 2008

324. Nuclear Decommissioning Authority, “NDA Statement on Future of the Sellafield MOX Plant,” 3 August 2011.

325. *Communication Received from the United Kingdom of Great Britain and Northern Ireland Concerning its Policies Regarding the Management of Plutonium*, INFCIRC/549/Add.8/13, International Atomic Energy Agency, 16 August 2010.

326. *Global Fissile Material Report 2010,* International Panel on Fissile Materials, 2010, www.ipfmlibrary.org/gfmr10.pdf, p. 19.

327. *Management of the UK’s Plutonium Stocks: A consultation on the long-term management of UK owned separated civil plutonium*, Department of Energy and Climate Change, London, February 2011, www.parliament.uk/deposits/depositedpapers/2011/DEP2011-0241.pdf.

328. F. Berkhout, *Radioactive Waste: Politics and Technology,* Routledge, 1991.

329. R.Williams, *The Nuclear Power Decisions*, Croom-Helm, 1980.

330. F. Berkhout, *Radioactive Waste: Politics and Technology.*

331. P.L. Cook and J. Surrey, *Energy Policy,* Martin Robertson, 1978.

332. *Nuclear Power and the Environment,* 6th Report, Royal Commission on Environmental Pollution, HMSO, London, 1976.

333. RWMAC gave advice to the Environment Minister. Originally, its membership of senior academic and industry scientists was determined via a closed appointments system. In the mid-1990s there was a new process in which membership was made open to a wider range of applicants. This increased the diversity of the committee. With the formation of CoRWM, RWMAC was put into ‘abeyance’ in 2003 and then formally closed down in 2006.

334. Mr Justice Parker, *The Windscale Inquiry,* HMSO Report, London, 1978.

335. F. Berkhout, *Radioactive Waste: Politics and Technology.*

336. G. MacKerron, “Nuclear Power under Review” in J. Surrey, ed., *The British Electricity Experiment,* Earthscan, 1996, pp. 138–163.

337. *Review of Radioactive Waste Management Policy – Final Conclusions,* Cm 2919, UK Government, HMSO, London, 1995.

338. *Decommissioning on Nuclear Licensed Sites,* Nuclear Safety Directorate, HSE (Health and Safety Executive), Bootle, 13 March, 2001.

339. Sellafield (previously Windscale) is BNFL’s main site in the north-west of England with nuclear reactors (now shut down), reprocessing plants, research facilities and waste management installations.

340. Doureay is the site of a major UKAEA research facility in the north of Scotland with three reactors and waste management facilities.

341. P. Styche, *Secretary of State’s Decision Letter on Nirex Appeal,* 17 March 1997.

342. *Management of Nuclear Waste,* House of Lords Science and Technology Committee, 3rd Report, Session 1998–1999, HL 41, HMSO, London, 1999.

343. *UK National Consensus Conference on Radioactive Waste Management.* Final Report, UK Centre for Energy, Environment and Development (UK CEED), August 1999.

344. *Managing Radioactive Waste Safely,* Proposals for developing a policy for managing solid radioactive waste in the UK, Department of Environment, Food and Rural Affairs (Defra), HMSO, London, September 2001.

345. *Managing the Nuclear Legacy: a Strategy for Action,* CM 5552, Department for Trade and Industry (DTI), HMSO, London, July 2002.

346. One of the present authors (MacKerron) chaired this committee from 2003 until 2007.

347. *Managing our Radioactive Waste Safely,* CoRWM's recommendations to Government, The Committee on Radioactive Waste Management, Doc 700, HMSO, London, July 2006, p. 189.

348. *Ibid.*, pp. 187–192.

349. CoRWM set up an internal working group to pursue "Public and Stakeholder Engagement" and one of its earliest acts was to set up a first round to promote this engagement. *Ibid.*, pp. 50–65.

350. *GM Nation? The findings of the public debate*, Agriculture and Environment Biotechnology Commission (AECB), London, 2003, www.aebc.gov.uk/aebc/reports/gm_nation_report_final.pdf.

351. O. Renn, *Analytic-deliberative processes of decision-making: linking expertise, stakeholder experience and public values,* The Committee on Radioactive Waste Management, Doc 847, HMSO, London, 2004.

352. *Managing our Radioactive Waste Safely*, *op. cit.*, p. 2.

353. P. Simmons and K. Bickerstaff, *CARL Country Report UK Summary,* March 2006, webhost.ua.ac.be/carlresearch/docs/20060418224351XBQK.doc.

354. D. Ball, "Deliberating over Britain's Nuclear Waste," *Journal of Risk Research*. 9, no 1, 2006, pp. 1–11.

355. *Managing our Radioactive Waste Safely*, *op. cit.*, pp. 66–74.

356. *Ibid*.

357. *Ibid.*, p. 3.

358. House of Lords, *Radioactive Waste Management: an Update,* House of Lords Science and Technology Committee, 4th Report Session 2006–2007, HL 109, HMSO, London, 3 June 2007.

359. Wastes from past nuclear activities and projected to be generated in the future by existing reactors.

360. Greenpeace, "Greenpeace response to draft recommendations by CoRWM," 26 May 2006, www.greenpeace.org.uk/tags/corwm.

361. *Managing Radioactive Waste Safely*, *op. cit*.

362. *Managing Radioactive Waste Safely: A Framework for Implementing Geological Disposal,* Cm 7386, HMSO, Defra/BERR, London, June 2008.

363. *Re-iteration of CoRWM's Position on Nuclear New Build,* The Committee on Radioactive Waste Management, Doc 2162.2, HMSO, London, September 2007.

364. *The Energy Challenge: Energy Review: A Report*, Department for Trade and Industry (DTI), Cm 6887, HMSO, London, July 2006.

365. Mr. Justice Sullivan, *Judgment CO/8197/2006*, Royal Courts of Justice, Strand, London, 15 February 2007.

366. *Managing Radioactive Waste Safely: A Framework for implementing geological disposal*, *op. cit.*

367. R.E. Kasperson, ed., *Equity Issues in Radioactive Waste Managemen,* Oelgeschlager, Gunn & Hain, Cambridge, MA, 1983.

368. For instance, will standards of risk protection remain the same? Or is it acceptable for current beneficiaries of nuclear technologies to leave a legacy of radiological risk to many future generations?

Chapter 10. United States

369. The Blue Ribbon Commission on America's Nuclear Future, www.brc.gov/

370. Until 1992, U.S. naval-reactor spent fuel was reprocessed at the Idaho Chemical Processing Plant to recover the contained HEU to fuel the U.S. plutonium and tritium production reactors at the Department of Energy's Savannah River Site in South Carolina.

371. Hannah Northey, "NNSA official laments that spent fuel has nowhere to go," *Environment and Energy Daily*, 3 March 2011.

372. *Plutonium: The First 50 Years,* U.S. Department of Energy, DOE/DP-0137, 1996, www.ipfmlibrary.org/doe96.pdf.

373. *Fiscal Year 2010 Congressional Budget Request, Vol. 5. Environmental Management,* U.S. Department of Energy, 2010.

374. As of the end of 2010, cleansing the West Valley site, which was contaminated by reprocessing 640 tons of spent fuel has cost about $3 billion, *The Western New York Nuclear Service Center (The West Valley Site)*, New York State ERDA, www.nyserda.org/programs/West_Valley/default.asp.

375. This estimate is based on the assumption that about half of the contained U-235 in the net U.S. production of 164 tons of super-grade (>96% enriched) HEU for naval-reactor use between 1962 and 1992 was fissioned, *Highly Enriched Uranium: Striking a Balance. A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 through September 30, 1996*, Draft, Rev. 1., U.S. Department of Energy, January 2001 (publicly released in 2006), www.ipfmlibrary.org/doe01.pdf, Tables 5.4 and 6.1 and *Global Fissile Material Report 2010*, *op. cit.*, p. 32.

376. Douglas Tonkay, U.S. Department of Energy, personal communication, 1 May 2011.

377. *Report to Congress on the Demonstration of the Interim Storage of Spent Nuclear Fuel from Decommissioned Nuclear Power Reactor Sites*, DOE/RW-0596, U.S. Department of Energy, Office of Civilian Radioactive Waste Management, 2008.

378. Anthony Andrews, *Nuclear Fuel Reprocessing: U.S. Policy Development*, U.S. Congressional Research Service, Washington, D.C., 2008; and J. Michael Martinez, "The Carter Administration and the Evolution of American Nuclear Nonproliferation Policy, 1977–1981," *Journal of Policy History*, Vol.14, No. 3, 2002, pp. 261–292.

379. *Nuclear Waste Policy Act of 1982*, epw.senate.gov/nwpa82.pdf, Sec. 302.

380. *Disposal Subcommittee Report to the Full [Blue Ribbon] Commission*, 1 June 2011, brc.gov/sites/default/files/documents/draft_disposal_report_06-01-11.pdf, p. 43.

381. *Nuclear Waste Policy Act of 1982*, epw.senate.gov/nwpa82.pdf, Sec. 160.

382. "Department of Energy Files Motion to Withdraw Yucca Mountain License Application," U.S. Department Of Energy Press release, 3 March 2010.

383. *Memorandum and Order (Granting Intervention to Petitioners and Denying Withdrawal Motion)*, U.S. Nuclear Regulatory Commission, Atomic Safety and Licensing Board, 29 June 2010, www.state.nv.us/nucwaste/licensing/order100629deny.pdf; for additional background, see Richard M. Jones, "Nuclear Regulatory Commission Board Rejects Administration's Attempt to Stop Yucca Mountain Construction Authorization Review," Bulletin of Science Policy News, American Institute of Physics, www.aip.org/fyi/2010/072.html.

384. "Members of Congress Urge NRC Chairman to Continue Yucca Mountain Review," *Nuclear Power Industry News*, 15 October 2010; and *Effects of a Termination of the Yucca Mountain Repository Program and Lessons Learned,* U.S. Government Accountability Office, 2011.

385. See e.g. *Transportation and Storage Subcommittee Report to the Full [Blue Ribbon] Commission,* 31 May 2011, brc.gov/sites/default/files/documents/draft_ts_report_6-1-11.pdf, Figure 6.

386. Douglas Tonkay, U.S. Department of Energy, personal communication, 1 May 2011.

387. U.S. Nuclear Regulatory Commission, "U.S. Independent Spent Fuel Storage Installations," www.nrc.gov/waste/spent-fuel-storage/locations.pdf.

388. *Report to Congress on the Demonstration of the Interim Storage of Spent Nuclear Fuel from Decommissioned Nuclear Power Reactor Sites, op. cit*.

389. *NRC approves 40-year license renewal for independent spent fuel storage installation at Surry Nuclear Plant*, U.S. Nuclear Regulatory Commission, www.nrc.gov/reading-rm/doc-collections/news/2004/04-156.html, 8 December 2004.

390. *Transportation and Storage Subcommittee Report to the Full [Blue Ribbon] Commission, op. cit.,* pp. viii-ix.

391. Three casks contain decommissioning waste from the reactor. A tally of spent fuel tonnage stored at this site and at nine other shutdown U.S. nuclear power plants can be found in U.S. Department of Energy, *Report to Congress on the Demonstration of the Interim Storage of Spent Nuclear Fuel from Decommissioned Nuclear Power Reactor Sites*, *op. cit.,* Table 1.

392. “Principles for Safeguarding Nuclear Waste at Reactors,” signed by 21 national and 151 local citizens groups as of 24 March 2010, www.psr.org/nuclear-bailout/resources/principles-for-safeguarding.pdf.

393. U.S. Nuclear Regulatory Commission, “Waste Confidence Decision Update,” *Federal Register,* Vol. 75, 23 December 2010, p. 81037. See also discussion in the chapter on Interim Storage and Transport.

394. Where references are not provided in this section, the source is Matthew Bunn, John Holdren, Allison MacFarlane, Susan Pickett, Atsuyuki Suzuki, Tatsujiro Suzuki and Jennifer Weeks, *Interim Storage of Spent Nuclear Fuel,* Project on Managing the Atom, Kennedy School of Government, Harvard University, 2001, pp. 47–56.

395. Frank Pittman, “Management of Commercial High-Level Radioactive Waste,” in Milton H. Campbell, ed., *High-Level Radioactive Waste Management,* American Chemical Society, Washington, D.C., 1976.

396. Nuclear Waste Policy Act, *op. cit.*, Subtitle C.

397. Nuclear Waste Policy Act, *op. cit.*, Sec. 148.1.d.1.

398. *Nuclear waste: Is there a need for federal interim storage?* Report of the Monitored Retrievable Storage Review Commission, 1 November 1989.

399. H. Josef Hebert, “Store nuclear waste on reservation? Tribe split,” *Associated Press*, 27 June 2006, www.msnbc.msn.com/id/13458867/.

400. The Nuclear Regulatory Commission Memorandum and Order authorizing the license is CLI-05-19, dated 9 September 2005; and Judy Fahs, “Interior won’t fight ruling on nuclear site,” *Salt Lake Tribune*, 27 September 2010. For a full file of reports, see www.healutah.org/news/private-fuel-storage.

401. Figure from www.privatefuelstorage.com. For a description of the site, see *Final Environmental Impact Statement for the Construction and Operation of an Independent Spent Fuel Storage Installation on the Reservation of the Skull Valley Band of Goshute Indians and the Related Transportation Facility in Tooele County, Utah*, U.S. Nuclear Regulatory Commission, NUREG-1714, 2001, Vol. 1, p. 2–4.

402. *The Disposal of Radioactive Waste on Land,* National Research Council, U.S. National Academy Press, 1957. It appears from the academy report that it was assuming that high-level liquid wastes would not be solidified before disposal.

403. Solution mining involves injecting water into a formation, then pumping out the saturated solution and separating out the chemical of interest — in this case, salt, J. Samuel Walker “An ‘Atomic Garbage Dump’ for Kansas: The Controversy over the Lyons Radioactive Waste Repository, 1970–1972,” *Kansas History*, Vol. 27, Winter 2006–2007, pp. 266–285.

404. Jon Goldstein, “Breaking the ‘Groundhog Day’ Cycle: Lessons Learned from the Waste Isolation Pilot Plant,” to be published by the *Bulletin of the Atomic Scientists*, September 2011; “History of the Waste Isolation Pilot Plant,” Citizens for Alternatives to Radioactive Dumping, www.cardnm.org/backfrm_a.html

405. *The Waste Isolation Pilot Plant Land Withdrawal Act*, Public Law 102-579 as amended by Public Law 104-201, H.R. 3230, 104th Congress, www.westgov.org/wga/initiatives/wipp/PIG-Web/Introduction/WIPP%20Land%20Withdrawl%20Act.pdf.

406. This corresponds to about 70 tons of weapon-grade plutonium.

407. Allison MacFarlane and Rodney Ewing, eds. *Uncertainty Underground: Yucca Mountain and the Nation’s High-Level Nuclear Waste*, MIT Press, 2006.

408. *A Multi-attribute Utility Analysis of Sites Nominated For Characterization For the First Radioactive Waste Repository - A Decision Aiding Methodology,* U.S. Department of Energy, DOE/RW-0074, 1986, www.energy.gov/media/Multiattribute-Utility-Analysis_HQS-19880517-1167_pp1–250.pdf.

409. Yucca Mountain is located on a corner where the territories of the Nevada Test Site, the Nellis Air Force Range and Bureau of Land Management lands meet.

410. *Multi-attribute Utility Analysis of Sites Nominated For Characterization For the First Radioactive Waste Repository, op. cit.*

411. *United States Nuclear Tests: July 1945 through September 1992*, U.S. Department of Energy, DOE/NV—209-REV 15, 2000.

412. Nuclear Waste Policy Act, *op. cit.*, Sec. 160.

413. *Ibid.*, Sec. 161.

414. *Ibid.*, Sec. 114, d.

415. *Ibid.*, Sec. 161.

416. *The Report to the President and the Congress by the on the Need for a Second Repository,* U.S. Department of Energy, DOE/RW-0595, 2008.

417. *Room at the Mountain,* Electric Power Research Institute, 2007.

418. Roald A. Wigeland, Theodore H. Bauer, Robert N. Hill, and John A. Stillman, "Repository Impact of Limited Actinide Recycle," *Proceedings of GLOBAL 2005,* Tsukuba, Japan, Oct 9-13, 2005, Paper 496.

419. Removing the cesium-137 and strontium-90 alone from spent fuel does provide benefits but this is a peculiarity of the hot Yucca Mountain design in which the repository would operate above boiling temperature for thousands of years and the ultimate capacity of the repository would be determined by the need to keep a strip of rock between the tunnels below boiling temperature to allow water to percolate through. The cumulative amount of heat generated by the spent fuel over thousands of years is dominated by the transuranic elements. For other repository designs, such as the Swedish design, in which the radioactive waste would be emplaced below the ground-water level, however, the limiting temperature requirement is to keep the bentonite clay around the canister below boiling temperature. This requirement would be most demanding soon after the burial of the canister while cesium-137 and strontium-90 would still be contributing significantly to the heat generated within the canister.

420. *Fiscal Year 2012 Congressional Budget Request*, U.S. Department of Energy, DOE CF 0063, Vol. 7, Nuclear Energy, p. 69.

421. See the recommendations of the *Reactor and Fuel Cycle Technology Subcommittee Report to the Full [Blue Ribbon] Commission,* Draft, June 2011, brc.gov/sites/default/files/documents/rfct_fullreport_rev20june11.pdf.

422. John J. Fialka, "The 'screw Nevada bill' and how it stymied U.S. nuclear waste policy," *New York Times,* 11 May 2009.

423. Francis S. Kendorski, "Review and Critique of Drip Shield Concept and Retrieval Concept Planned for the Yucca Mountain Project, Nevada," U. S. Nuclear Waste Technical Review Board Meeting, 8–9 November 2005, Las Vegas, Nevada.

424. *Effects of a Termination of the Yucca Mountain Repository Program and Lessons Learned,* U.S. Government Accountability Office, 2011. See also *Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007,* U.S. Department of Energy, DOE/RW-0591, 2008.

425. *Yucca Mountain Science and Engineering Report Technical Information Supporting Site Recommendation Consideration,* U.S. Department of Energy, DOE/RW-0539-1, 2002, Fig. I-3.

426. *Viability Assessment of a Repository at Yucca Mountain,* U.S. Department of Energy, DOE/RW-0508, 1998.

427. *Final Report, Total System Performance Assessment Peer Review Panel*, 1999, www.energy.gov/media/FinalRept-TotalSystemPerformanceAssessment-PRP.pdf.

428. "Topic: Yucca Mountain," *Las Vegas Sun,* undated, www.lasvegassun.com/news/topics/yucca-mountain/, accessed 13 November 2010. Figure I-3.

429. *Technical Bases for Yucca Mountain Standards,* National Research Council, U.S. National Academy Press, 1995, p. 2.

430. U.S. Environmental Protection Administration (EPA), "Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada; Final Rule," *Federal Register*, 15 October 2008, p. 61256. EPA initially set a post-10,000 year standard of 3.5 mSv/yr but this was challenged as posing too high a lifetime risk to those exposed. See www.state.nv.us/nucwaste/news2005/pdf/nwtrb051108_gilinsky.pdf and www.brc.gov/pdfFiles/May2010_Meeting/Attachment%204_nuc_08010701A.pdf.

431. Based on a sex-averaged estimated extra risk of cancer death from a radiation dose of 0.1 Sv of 0.26–1.2 percent, *Health Risks from Exposure to Low Levels of Ionizing Radiation (BEIR VII Phase 2)* National Research Council, U.S. National Academy Press, 2006, Table ES-1.

432. "Secretary Chu Announces Blue Ribbon Commission on America's Nuclear Future," U.S. DOE Press release, 29 January 2010.

433. *Blue Ribbon Commission on America's Nuclear Future Draft Report to the Secretary of Energy*, Blue Ribbon Commission on America's Nuclear Future, 29 July 2011, brc.gov/sites/default/files/documents/brc_draft_report_29jul2011_0.pdf.

Chapter 11. Multinational Repositories

434. IAEA, *Developing Multinational Radioactive Waste Repositories: Infrastructural Framework and Scenarios of Cooperation*, IAEA-TECDOC-1413, October 2004, P. 8.

435. *Ibid.*, p. 8.

436. *Ibid.*, p.11.

437. *Ibid.*, p. 11

438. IAEA, *Developing Multinational Radioactive Waste Repositories, op. cit. n*, p. 12.

439. Ken Silverstein, "Nuclear Burial in the Pacific," *The Progressive*, Vol. 61, No. 11, November 1997, pp. 32-34.

440. *Russia: Archived Spent Fuel and Radioactive Waste Developments*, Nuclear Threat Initiative, www.nti.org/db/nisprofs/russia/reactor/waste/wastedev.htm

441. Ken Silverstein, "Nuclear Burial in the Pacific" *op. cit.*. There is a history of opposition from the South Pacific Forum to the idea of nuclear waste disposal in the Pacific. See, for example, www.forumsec.org.fj/resources/uploads/attachments/documents/1983%20Communique-Canberra%20 29-30%20Aug.pdf

442. IAEA, *Developing Multinational Radioactive Waste Repositories, op. cit.,* p. 13. The parliaments of two states, South Australia and Western Australia, passed legislations prohibiting nuclear waste storage.

443. Gregory Palast, "To Russia with love and $15bn, *The Guardian,* 29 July 2001, www.guardian.co.uk/business/2001/jul/29/columnists.theobserver1 and IAEA, *Developing Multinational Radioactive Waste Repositories, op. cit*, p. 13;

444. The ban on importing "foreign," i.e., non-Russian-origin spent fuel was confirmed again by Sergei Kiriyenko, the head of Rosatom, in April 2011. www.fissilematerials.org/blog/2011/04/rosatom_confirms_it_will_.html

445. IAEA, *Developing Multinational Radioactive Waste Repositories, op. cit*.

446. *Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report Submitted to the Director General of the IAEA*, INFCIRC/640, International Atomic Energy Agency, February 2005.

447. IAEA, *Developing Multinational Radioactive Waste Repositories*, *op. cit.*, pp. 44–45.

448. IAEA, *Multilateral Approaches to the Nuclear Fuel Cycle*, *op. cit.*,p. 8.

449. *Ibid*.

450. *Factors Affecting Public and Political Acceptance for the Implementation of Geological Disposal*, IAEA-TECDOC-1566, International Atomic Energy Agency, October 2007.

451. *The Uncertain Future of Nuclear Energy,* IPFM Research Report 9, International Panel on Fissile Materials, 2010, p. 57.

452. These include the Slovak Republic, Finland, Hungary, Argentina, Brazil, Bulgaria, Mexico, Pakistan, Romania, South Africa, Armenia, Netherlands, and Slovenia. Pakistan is a nuclear weapon state with plans for substantial civilian-nuclear expansion and Finland, as discussed elsewhere in this Report, has already made significant efforts to locate a geological repository within the country. Of course the choice of 5 reactors as a dividing line is arbitrary.

453. Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 20 May 2011, www.iaea.org/programmes/a2/

454. World Nuclear Association, *Emerging Nuclear Energy Countries*, 25 May 2010 lists in Europe: Italy, Albania, Serbia, Portugal, Norway, Poland, Belarus, Estonia, Latvia, Ireland, Turkey; in the Middle East and North Africa: Iran, Gulf states including UAE and Saudi Arabia, Yemen, Israel, Syria, Jordan, Egypt, Libya, Algeria, Morocco; in west, central, and southern Africa: Nigeria, Ghana, Senegal,

Uganda, Namibia; In South America: Chile, Ecuador, Venezuela; in central and southern Asia: Azerbaijan, Georgia, Kazakhstan, Mongolia, Bangladesh; in SE Asia: Indonesia, Philippines, Vietnam, Thailand, Malaysia, Singapore Australia, New Zealand; and in northeast Asia: North Korea.

455. IAEA, Factors Affection Public and Political Acceptance for the Implementation of Geological Disposal, IAEA-TECDOC-1566, October 2007, p. 37.

456. IAEA, *Managing Spent Nuclear Fuel: Global Overview*, Issue Brief, www.iaea.org/NewsCenter/Focus/RadWaste/nuclfueloverview.html, 2008.

457. IAEA, *Managing Spent Nuclear Fuel: Global Overview*, *op.cit*. Putting off a decision for 100 years does, of course, contradict the principle that spent fuel disposal should be the responsibility of today's generation.

458. IAEA, Factors Affection Public and Political Acceptance for the Implementation of Geological Disposal, IAEA-TECDOC-1566, October 2007, p. 37.

459. Nuclear Energy Agency, Radioactive Waste Management Programmes in OECD/NEA Member Countries, 2009.

460. *ibid.*

461. *ibid.*

462. IAEA, *Vision for the Future: Background Report by the Director General for the Commission of Eminent Persons*, 2008, quoted in McCombie, Chapman , and Isaacs, "Global Developments in Multinational Initiatives at the Backend of the Nuclear Fuel Cycle," *Proceedings of the 12th International Conference on Environmental Remediation and Radioactive Waste Management*, ICEM2009, October 11-15, 2009; see also IAEA, *Developing and Implementing Multinational Repositories, op. cit*.

463. Neil Chapman, Charles McCombie and Phil Richardson, *Economic Aspects of Regional Repositories,* 2008, www.erdo-wg.eu/ERDO-WG_website/Documents_files/SAPIERR II WP-3 web.pdf

464. F. von Hippel, editor, "The Uncertain Future of Nuclear Energy," International Panel on Fissile Materials, *Research Report 9*, September 2010, p. 57.

465. This argument also applies to the politics of hosting spent fuel within a country, but is moderated in that case by some general sense that the benefits and costs of nuclear power within a country are shared by all citizens.

466. One legal expression of this principle is the Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and their Disposal signed by 175 countries, www.basel.int/index.html.

467. See, for example, Alan Marshall, "Questioning the Motivations for International Repositories for Nuclear Waste," *Global Environmental Politics*, 5:2, May 2005.

468. Charlies McCombie, "Evaluating solutions to the nuclear waste problem," *Bulletin of the Atomic Scientists*, November/December 2009, pp 42-48.

469. This initiative involves mostly the import of spent fuel containing HEU that the U.S. or the Soviet Union/Russia originally exported but it also includes as an incentive to convert a limited amount of U.S.-origin LEU spent fuel from reactors after they convert.to LEU if foreign spent-fuel management services are not available, "Receipt and Financial Settlement Provisions for Nuclear Research Reactor Fuels," *Federal Register* Vol. 51, No. 32, 18 February 1986 / Notices 5754.

470. Mark Hibbs, "Reprocessing cost might exceed KHNP's spent fuel management fees," *Nuclear Fuel* 13 July 2009; "Koeberg to reprocess spent fuel overseas," www.iol.co.za/ 27 August 2008.

471. The Netherlands has renewed it reprocessing contract for its single power reactor and it paying France to keep its plutonium. France has offered both to South Korea and to South Africa to reprocess their spent fuel, with agreement that the HLW will be sent back but not the separated plutonium; France would keep the low and intermediate radioactive wastes from the reprocessing. Mark Hibbs, "Reprocessing cost might exceed KHNP's spent fuel management fees," *Nuclear Fue*l, Vol. 34, No. 14, 2009; "Koeberg to reprocess spent fuel overseas," *IOL News*, 27 August 2008; Ann MacLachlan, "EDF-Areva pact ensures reprocessing, recycle," *Nuclear Fuel*, Vol. 33, No. 52, 2008.

472. Ana Uzelac, "Arbat Traffic Stops for Waste Debate," *Moscow Times*, 4 June 2001.

473. The Russian bill that enabled the import of spent nuclear fuel was part of a larger set of measures to weaken the country's environmental laws, including the dissolution of the State Agency for Environmental Protection, Jane I. Dawson and Robert G. Darst, "Russia's Proposal for a Global Nuclear Waste Repository: Safe, Secure, and Environmentally Just?," *Environment*, Vol. 47, No. 4, 2005, pp. 10-21, p. 10.

474. In all cases to date, the fuel has also been used in reactors exported by either the Soviet Union or Russia.

475. Private communication, Anatoli Diakov, 11 February 2011.

476. Atsuyuki Suzuki, Chapter 4; Frank von Hippel, Chapter 5; Ellen Tauscher, Chapter 6, *Multinational Approaches to the Nuclear Fuel Cycle,* American Academy of Arts and Sciences, 2010.

477. One condition appears to be that the fuel is of Mongolian origin. "Draft accord notes Mongolia as home for spent nuclear fuel," *Mainichi Daily News*, 19 July 2011.

478. "Japan, U.S. plan nuclear waste storage in Mongolia -paper," Reuters, 8 May 2011, www.reuters.com/article/2011/05/09/energy-nuclear-mongolia-idUSL3E7G80HD20110509.

479. Embassy of Mongolia in Vienna, Press release, 10 May 2011, www.embassymon.at/news/emb_news_53.html; Pavel Podvig, "Conflicting reports about spent fuel disposal in Mongolia," 10 May 2011, www.fissilematerials.org/blog/2011/05/conflicting_reports_about.html

480. The Man in Seat 61, www.seat61.com/Trans-Siberian.htm

481. Charles McCombie, "Evaluating solutions to the nuclear waste problem," *Bulletin of the Atomic Scientists*, November/December 2009, pp. 42-48. McCombie was also a key figure in the Pangea proposal to build a geological repository in Australia.

482. Charles McCombie, Neil Chapman, and Thomas Isaacs, *Global Developments in Multinational Initiatives at the Back End of the Nuclear Fuel Cycle*, Proceedings of the 12th International Conference on Environmental Remediation and Radioactive Waste Management, October 11-15, 2009, ICEM09-16294. The meeting of potential participants in the Working Group included participants from Austria, Bulgaria, Czech Republic, Denmark, Estonia, Ireland, Italy, Latvia, Lithuania, Netherlands, Poland, Romania, Slovakia, and Slovenia. The first phase of the project, (SAPIEER I - Support Action on Pilot Investigations on European Regional Repositories), looked at the technical and economic feasibility of a multinational repository in Europe while SAPIERR II examined in more detail specific issues that directly impact the practicability of such facilities. One of the spurs of SAPIERR has been Arius (Association for Regional and International Underground Storage), an organization located in Switzerland, whose Executive Director is Charles McCombie, and whose founding members were Belgium, Bulgaria, Hungary, Italy, Japan, and Switzerland. In addition to its main focus on Europe, Arius is also now looking to promote shared spent fuel facilities in other regions, including Arab Gulf States and Southeast Asia.

483. *Council Directive 2011/70/Euratom establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste*, European Council, Brussels, 19 July 2011, eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:199:0048:0056:EN:PDF.

Chapter 12. Interim Storage and Transport

484. Based on Table III in *Survey of Wet and Dry Spent Fuel Storage*, International Atomic Energy Agency, IAEA-TECDOC-1100, 1999, p. 10.

485. *Ibid.*, p. 9.

486. The heat of vaporization of water at 100 °C is 2.26 GW-seconds per metric ton.

487. Information on Fukushima Daiichi Unit #4 spent fuel pool and core from TEPCO, Masa Takubo, personal communication, 18 March 2011. Fortunately, the accident occurred 4 months after the core was unloaded into the pool, by which time the decay power had declined to about 25 kWt/ton.

488. *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report,* National Academies Press, Figure 3.1.

489. Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison MacFarlane, Gordon Thompson and Frank von Hippel, "Reducing the Hazards from Stored Spent Power-reactor Fuel in the United States," *Science & Global Security, op. cit.*

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491. Alvarez *et. al.,* "Reducing the Hazards from Stored Spent Power-reactor Fuel in the United States," o*p. cit.*

492. The NRC argued that "the recommendation for an accelerated program of complex and costly measures does not have a sound technical basis. In the United States, spent fuel, in both wet and dry configurations, is safe and measures are in place to adequately protect the public." See "Nuclear Regulatory Commission Review of 'Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States,'" *Science & Global Security,* Vol. 11 (2003), p. 203. See also Alvarez, *et. al.*, "Response by the Authors to the NRC Review of 'Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States,'" *Science & Global Security,* Vol. 11, 2003, pp. 213-223.

493. *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report,* National Academies Press, 2006.

494. U.S. Nuclear Regulatory Commission, "The Attorney General of Commonwealth of Massachusetts, The Attorney General of California; Denial of Petitions for Rulemaking," *Federal Register* Vol. 73, August 8, 2008, p. 46204.

495. The technical study cited in the NRC Waste Confidence Rule update (see below) is a draft report from Sandia National Laboratory, *MELCOR* ***1.8.5*** *Separate Effect Analyses of Spent Fuel Pool Assembly Accident Response* by KC Wagner et al, 2003. The NRC has released a 12-page redacted version of this 95-page report. Not including the Table of Contents, only approximately 2 pages of text remain unredacted.

496. The previously published NRC reports were reviewed in "Reducing the Hazards from Stored Spent Power-reactor Fuel in the United States," o*p. cit.* See also Gordon Thompson, *Environmental Impacts of Storing Spent Nuclear Fuel and High-Level Waste from Commercial Nuclear Reactors: A Critique of NRC's Waste Confidence Decision and Environmental Impact Determination,* Institute for Resource and Security Studies, 2009.

497. "Nuclear Crisis: NRC Says Spent Fuel Pool at Unit Four Lost Massive Amounts of Water; Japan Disputes Claims," ABC News, 16 March 2011.

498. "US: spent fuel pool never went dry in Japan quake," Associated Press, 15 June 2011.

499. "Theory of Fukushima Daiichi 4 explosion," World Nuclear News, 17 May 2011.

500. Assuming a burnup of 50 MWt-days/kgU and a heat to electricity conversion efficiency of 1/3.

501. Klaus Janberg and Frank von Hippel, "Dry Cask Storage: How Germany led the way," *Bulletin of the Atomic Scientists,* September/October 2009.

502. Private Fuel Storage Safety Analysis Report, Fig. 1.3-1, Nuclear Regulatory Commission Accession # ML072990220.

503. Based on the Private Fuel Storage design, U.S. Nuclear Regulatory Commission, *Final Environmental Impact Statement for the Construction and Operation of an Independent Spent Fuel Storage Installation on the Reservation of the Skull Valley Band of Goshute Indians and the Related Transportation Facility in Tooele County, Utah* (NUREG-1714, 2001) Vol. 1, p. 2-3.

504. *Transportation, Aging and Disposal Canister System Performance Specification* (U.S. Department of Energy, DOE/RW-0585, 2008.

505. Hitachi-GE Nuclear Energy Ltd., "Spent Fuel Interim Storage Facility," www.hitachi-hgne.co.jp/en/activities/fuelcycle/storage/index.html.

506. A cask 5.5 meters high and with a diameter of 3.5 meters holding 10 tons of 5-year-old spent LWR fuel putting out 20 kilowatts of heat, would establish black-body radiative equilibrium with its environment at a temperature of about 60 ^{o}C above ambient.

507. *Safety and Security of Commercial Spent Nuclear Fuel Storage, op. cit.* p. 69.

508. "Principles for Safeguarding Nuclear Waste at Reactors," March 2010,, www.psr.org/nuclear-bailout/resources/principles-for-safeguarding.html, www.ananuclear.org/Portals/0/documents/GTCC/PrinciplesSafeguardingIrradiatedFuel.pdf

509. See chapter on France.

510. France's 63 GWe of generating capacity discharge about 1300 tons per year.

511. Of the 3,217 spent fuel assemblies stored at the Morris facility, as of November 1994: 1,054 (32.8 percent) were BWR assemblies discharged from the still operating Cooper [spelled "Copper" in source] Station reactor in Nebraska, 1,058 (32.9 percent) were BWR assemblies discharged from the still operating Monticello reactor in Minnesota, 753 (23.4 percent) were BWR assemblies from the still operating Dresden 2 reactor; 270 (8.4 percent) were PWR assemblies from the shutdown

San Onofre 1 reactor in California (but 2 newer units were still operating on the site; and 82 (2.5 percent) were PWR assemblies from the shutdown Haddam Neck reactor in Connecticut, "The Transportation of Spent Nuclear Fuel and High-Level Radioactive Waste: A Systematic Basis for Planning and Management at the National, Regional, and Community Levels," Planning Information Corporation, Denver, Colorado, 1996, www.state.nv.us/nucwaste/trans/1pic06.htm.

512. See chapter on Russia.

513. Tadahiro Katsuta and Tatsujiro Suzuki, *Japan's Spent Fuel and Plutonium Management Challenges*, International Panel on Fissile Materials, 2006.

514. See chapter on U.S.

515. Eric Seigemann, "Zircaloy Cladding" in Allison MacFarlane and Rodney Ewing, eds., *Uncertainty Underground: Yucca Mountain and the Nation's High-level Nuclear Waste,* MIT Press, 2006, p. 317.

516. *Spent Fuel Transportation Applications—Assessment of Cladding Performance: A Synthesis Report*, Electric Power Research Institute, Report #1015048, December 2007.

517. U.S. Nuclear Regulatory Commission, "Waste Confidence Decision Update," *Federal Register,* 23 December 2010, pp. 81037-76.

518. The first U.S. nuclear power plant, Shippingport, went into operation in 1957 but the reactor was originally designed for an aircraft carrier and the fuel was highly-enriched uranium in plates rather than rods, www.asme.org/about-asme/history/landmarks/topics-a-l/electric-power-production-nuclear/-47-shippingport-nuclear-power-station-%281958%29. It was probably reprocessed with naval reactor fuel. There are on-site spent fuel storage facilities associated with the Dresden I, Humboldt and Yankee Rowe reactors, however, all of which came into operation in 1960. For reactor operating dates, see Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, www.iaea.org/programmes/a2/. For U.S. spent-fuel storage facilities, see *United States of America Third National Report for the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management,* U.S. Department of Energy, DOE/EM-0654, Rev. 2, 2008, Annex D1.

519. U.S. Nuclear Regulatory Commission, "Waste Confidence Decision Update," *op. cit.*

520. U.S. Nuclear Regulatory Commission, "Backgrounder on Transportation of Spent Fuel and Radioactive Materials," January 2005, www.nrc.gov/reading-rm/doc-collections/fact-sheets/transport-spenfuel-radiomats-bg.html.

521. *Regulations for the Safe Transport of Radioactive Material*, 2005 Edition, IAEA No. TS-R-1, International Atomic Energy Agency, paras 726-730.

522. *Going the Distance*, *op. cit.*, p. 3.

523. *Going the Distance, op. cit.*, p. 215.

524. Kevin Crowley, Director, Board on Radioactive Waste Management, National Research Council, personal communication, 30 October 2010.

525. See e.g. "High-Level Radioactive Waste Shipped from the UK," Citizens Nuclear Information Center, Tokyo, 1 March 2010, www.cnic.jp/english/topics/radwaste/hlwreturn1mar10.html.

526. Michael Slackman, "Despite Protests, Waste Arrives in Germany in Gorleben," *New York Times*, 8 November 2010.

527. "'Mobile Chernobyl' - High-Level Radioactive Waste Transport," Nuclear Information and Resource Service, www.nirs.org/radwaste/hlwtransport/mobilechernobyl.htm, accessed 12 November 2010.

528. "Nuclear Waste Transportation," www.state.nv.us/nucwaste/trans.htm.

Chapter 13. Geological Disposal

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530. "Agreement between the Government Of The United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as no Longer Required for Defense Purposes and Related Cooperation," as amended in 2010, www.fissilematerials.org/blog/docs/PMDA2010.pdf.

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532. *Management of the UK's Plutonium Stocks A consultation on the long-term management of UK owned separated civil plutonium,* UK Department of Energy and Climate Change, February 2011, www.decc.gov.uk/assets/decc/Consultations/plutonium-stocks/1243-uk-plutonium-stocks.pdf

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Chapter 14. International Monitoring

569. Safeguards at reprocessing plants and fuel-fabrication facilities are not discussed here.

570. In the early 1990s, as part of the effort to strengthen the safeguards system in the light of limitations demonstrated in Iraq and South Africa, the IAEA returned to this issue, requesting advice from the NPT nuclear-weapon States. Only one of the five responded and it recommended leaving the values unchanged.

571. The ID is somewhat more difficult to read after irradiation darkens the assembly.

572. Westinghouse reports that, during 1988 to 2009, it carried out 700 fuel assembly repairs replacing defective rods with stainless steel dummy rods, www.westinghousenuclear.com/products_&_services/docs/flysheets/NS-FS-0043.pdf.

573. The May 2011 U.S. National Nuclear Security Administration Strategic Plan sets the following goal "By 2013, deploy new non-destructive assay technologies to directly quantify plutonium in spent fuel," www.nnsa.energy.gov/mediaroom/pressreleases/2011strategicplan51811.

574. A survey of 11 alternative methods that might be used to detect such partial defect diversion scenarios is presented in S. Tobin, S. Demuth, M. Fensin, J. Hendricks, H. Menlove, and M. Swinhoe, "Determination of Plutonium Content in Spent Fuel with NDA — Why an Integrated Approach?" *49th INMM Annual Meeting*, Nashville, TN, 2008.

575. Developing the ability to measure plutonium in spent fuel is a top priority in the 2011 NNSA Strategic Plan.

576. A. Bernstein et al, "Nuclear security application of antineutrino detectors: Current capabilities and future prospects," *Science & Global Security,* Vol. 18, 2010, pp. 127-192.

577. "CANDU 6 Technical Summary," Atomic Energy of Canada Limited, June 2005.

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580. J.J. Whitlock and A.G. Lee, "CANDU: Setting the Standard for Proliferation Resistance of Generation III and III+ Reactors," *International Conference on Opportunities and Challenges for Water Cooled Reactors in the 21st Century*, Vienna, Austria, 27-30 October 2009.

581. If re-verification of a dry-storage cask becomes necessary, e.g., to maintain confidence in the containment and surveillance devices installed or if they fail to operate, *in situ* verification could help to avoid the need to require re-opening one or more storage casks. Gamma scanning and muon tomography are under investigation for this purpose. Scanning is limited to outer bundles. For a discussion of muon tomography, see G. Jonkmans*et al*, "Muon Tomography for Imaging and Verification of Spent Fuel," *Proceedings of the Symposium on International Safeguards,* Vienna, 1-5 November 2010, IAEA-CN-184/9.

582. A new dry storage facility is being constructed in Mutsu, northern Japan. See Tatsuki Takamatsu, "Metals Casks Storage Schedule of Recyclable Fuel Storage Center in Mutsu," November 2010, www.criepi.denken.or.jp/result/event/seminar/2010/issf/pdf/2-1_powerpoint.pdf.

583. See *IAEA Safeguards Glossary*, International Nuclear Verification Series No. 3, IAEA, 2001, §2.12.

584. *Technological Implications of International Safeguards for Geological Disposal of Spent Fuel and Radioactive Waste*, IAEA Nuclear Energy Series No. NW-T-1.21, International Atomic Energy Agency, Vienna, 2010.

585. An approach emphasizing receipt verification at the repository canister preparation facility would be possible if a new technique could be developed, such as a subcritical reactor that would measure the reactivity worth of each assembly. The measured worth would be compared to calculated estimates based on reactor operator burn-up calculations, and IAEA spent fuel assembly certifications based upon antineutrino monitoring.

586. *Technological Implications of International Safeguards for Geological Disposal of Spent Fuel and Radioactive Waste*, *op. cit.*, pp. 12-13.

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The spent fuel from nuclear power reactors, and the high-level wastes produced in the few countries where spent fuel is reprocessed to separate plutonium, must be stored in a manner that will minimize releases of the contained radioactivity into the environment for up to a million years. Safeguards also will be required to ensure that any contained plutonium is not diverted to nuclear-weapon use.

This report analyzes the efforts to manage and dispose of spent fuel by ten countries that account for more than 80 percent of the world's nuclear power capacity: Canada, Finland, France, Germany, South Korea, Japan, Russia, Sweden, the United Kingdom and the United States. It also provides an overview of the technical issues relating to interim storage and transport of spent fuel, geological repositories, and the challenge of the associated international safeguards.

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