Spent Fuel from Nuclear Power Reactors

An Overview of a New Study by the International Panel on Fissile Materials

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IPFM
INTERNATIONAL PANEL ON FISSILE MATERIALS

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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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Introduction

The International Panel on Fissile Materials (IPFM) is in the process of finalizing an analysis of the policy and technical challenges faced over the past four 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 spent fuel repository anywhere in the world.

The first section of the forthcoming IPFM research report covers *Technical Issues*. It describes our current understanding of several of the technical issues relevant to the disposal of spent fuel, and provides a background to the challenges facing individual countries. It includes a discussion of the current state of International Atomic Energy Agency safeguards on spent nuclear fuel and the prospects for effective monitoring of a spent fuel geological repository for the indefinite future.

The second section of the report is *Country Studies*, and summarizes how ten significant countries are managing their spent fuel and searching for ways to dispose of the fuel. The cases presented are on 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, including some 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.

This brief overview is intended as a discussion draft. It briefly describes first the technical challenges associated with spent fuel, then outlines the key policy findings from the various country studies, and finally provides a short summary of the individual country studies. It also includes at the end a list of contributors to the study.

Technical Issues

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 and, in some cases, the plutonium and uranium are recycled. This process also produces high-level wastes that contain the vast majority 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 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 are not diverted to weapon use.

Spent fuel characteristics and 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 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.

A typical modern reactor has a capacity of about 1 GWe (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 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 (as heavy metal) of 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 8500 tons of heavy metal going into long term storage and about 2000 tons of heavy metal allocated for reprocessing but much of it in interim storage.

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. 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.

Spent fuel inventories by country

The most systematic reporting on spent fuel inventories 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 national reports were mostly done in 2008 and gave inventories of spent fuel at the end of 2007. The spent fuel inventories for the countries covered in this study, which account for over 80% of global nuclear capacity, are shown in Table 2, with totals for France and Japan reported from other sources.

The U.S. 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.[4]

Country	Spent Fuel Inventory (tons of heavy metal) end of 2007	Spent Fuel Policy
Canada	37,300	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 2. Spent fuel inventories in cooling ponds and dry-cask storage at the end of 2007 for the 10 countries in the present study.

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 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.

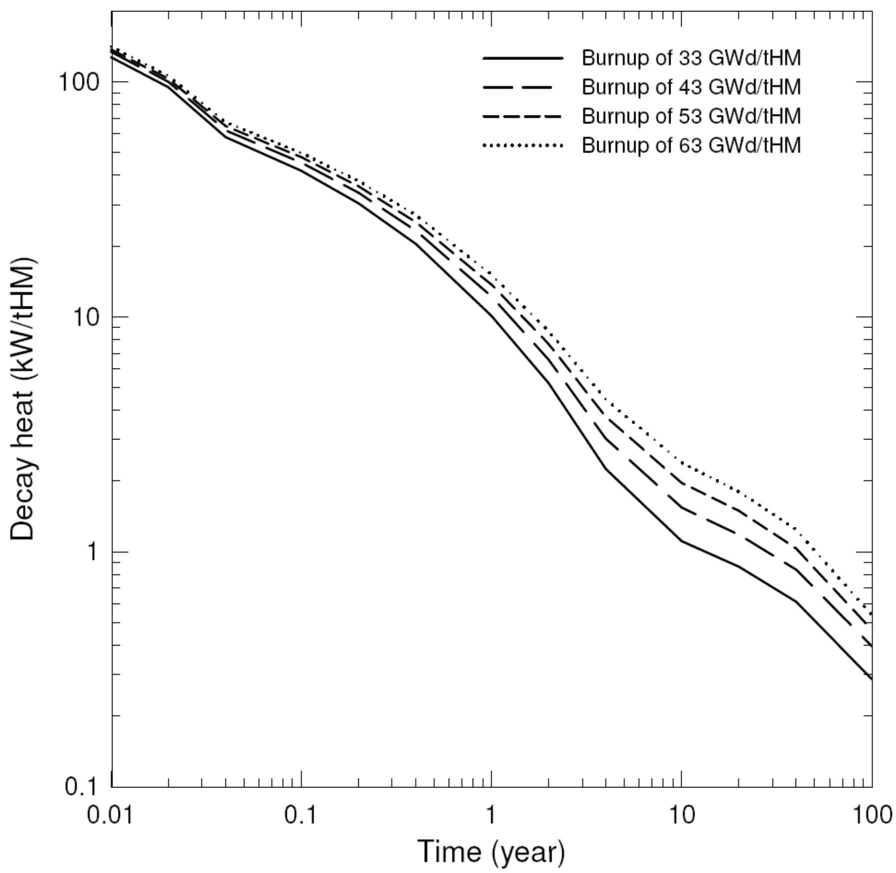

Figure 1. Decay heat as a function of time from 0.01 years (about 4 days) to 100 years for low-enriched uranium spent-fuel with burnups of 33, 43, 53 and 63 GWd/tHM. The lowest burnup was typical for the 1970s. Current burnups are around 50 GWd/tHM. Source: Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin 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 and Global Security*, volume 11, 2003, pp. 1-15.

As Figure 1 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 roughly by a further factor of ten. By 100 years after discharge, it is down by another factor or five.

For much of the first 100 years, the radioactivity 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.

As Figure 2 shows, it takes several hundred thousand years for the ingestion radiotoxicity of spent fuel to become less than that of natural uranium (including its associated decay products) from which it was derived.

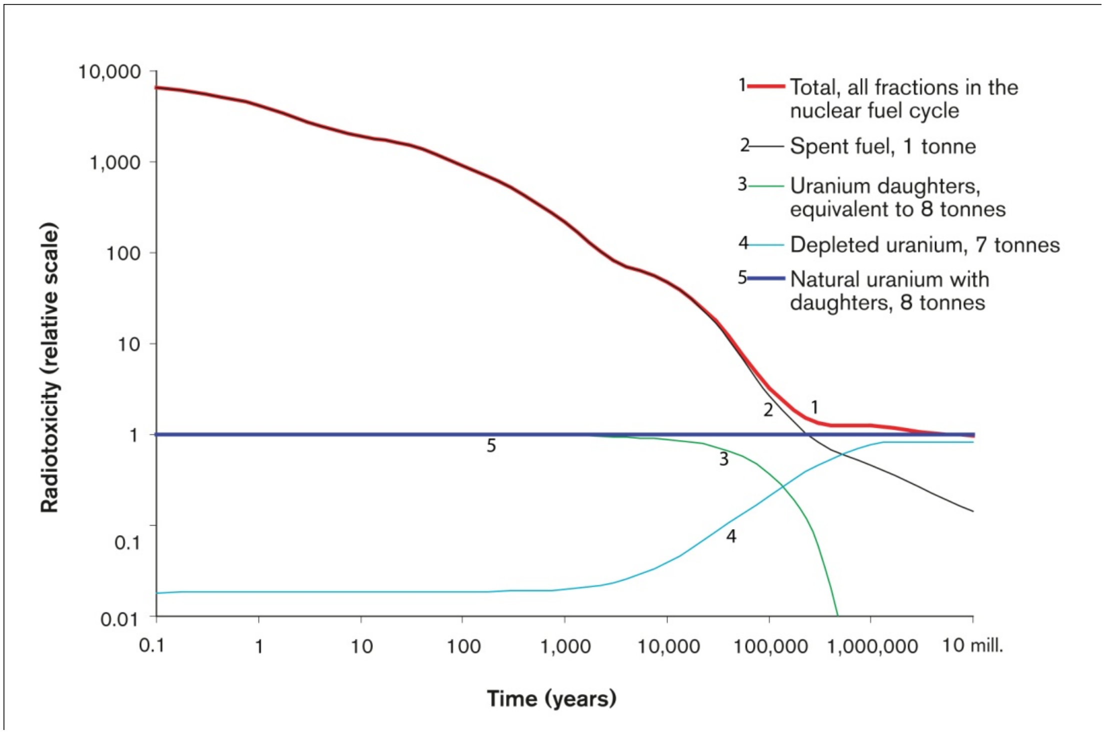

Figure 2. Relative ingestion radiotoxicity of uranium ore (line 5) and of the spent LWR fuel that could be derived from it (line 2). Line 3 describes the toxicity of the uranium decay products that are separated in the uranium mill and line 4 that of the depleted uranium that is stored at the enrichment 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, "Spent Nuclear Fuel - How Dangerous Is It?" SKB Technical Report 97-13, Swedish Nuclear Fuel and Waste Management Co., 1997.

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.

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 air to flow through to the wall of the canister and cool the fuel. 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 3 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 3. 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.[5]

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 has 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. Transport casks are typically thick-walled metal casks, and are subject to stringent tests against accident conditions.

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.[6] 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 additional exposure of spent fuel to transportation hazards, especially since many transport routes run through or close to major cities. The danger of transport through cities in large countries like the U.S. could be reduced with regional repositories.

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. Many analysts expect emplacement of containers of spent fuel, high-level waste or plutonium waste into well-designed geological repositories reliably could prevent the escape of radioactive materials to the biosphere for at least several thousand years. There remain outstanding uncertainties, however, on the longer-term behavior of spent fuel, high-level and plutonium waste and their containers in a repository.

There are differences of opinion over the length of time spent fuel should be easily retrievable and the relative contributions of the geologic medium and the waste packaging to holding the radionuclides in place. As Figure 4 shows, transuranics are the most significant contributors to the heat (and also the radiotoxicity) of the spent fuel after the first 100 years.[7] For the viability of a geological repository, the solubility and mobility of the transuranics are critical long-term issues.

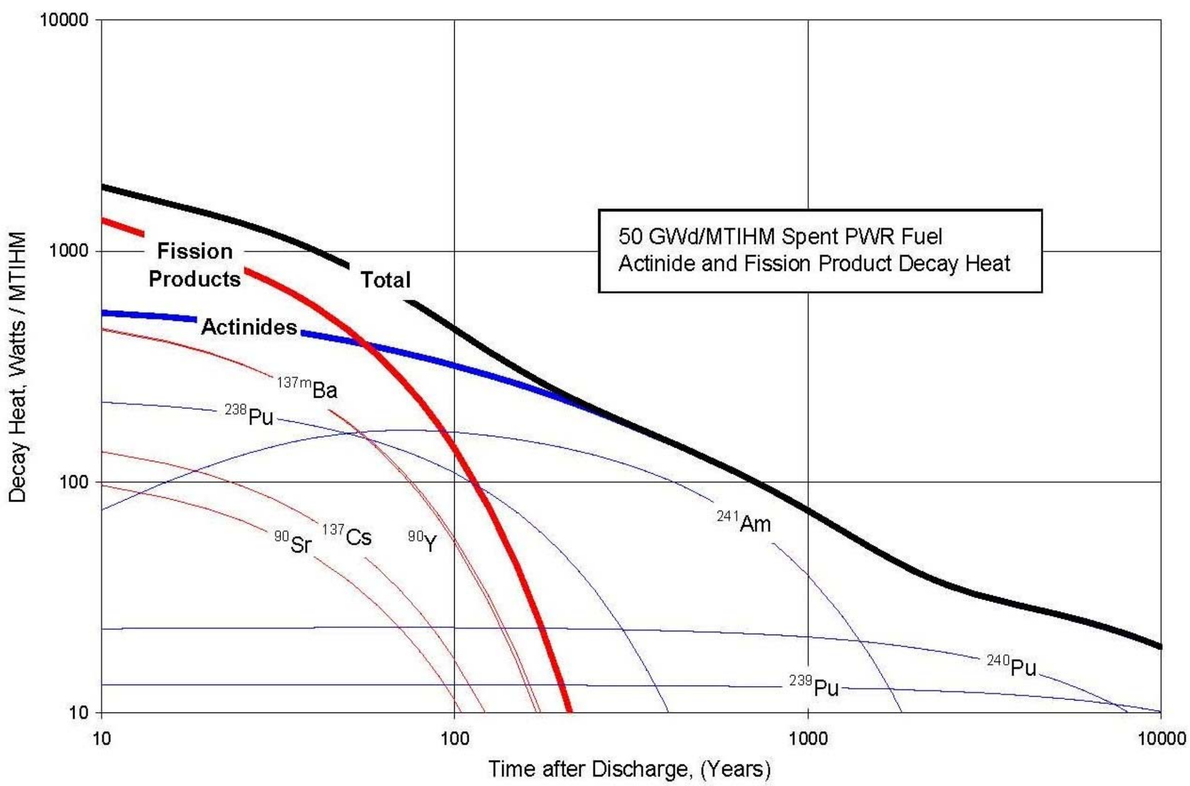

Figure 4. Decay heat generated by spent PWR fuel irradiated to 50 GWd/tHM. Source: Roald Wigeland, et al, "Spent Nuclear Fuel Separations and Transmutation Criteria for Benefit to a Geologic Repository," Waste Management 2004 Conference, February 29-March 4, 2004, Tucson, USA.

In general, it appears that reducing (i.e. oxygen-free) conditions in the repository will reduce the solubility and mobility of actinides in the disposal environment. Such conditions are expected in deep granite and clay. Transuranics are more soluble and mobile under oxidizing conditions, however. From this perspective, the proposed repository in Yucca Mountain, which was designed to be above the water table where the water flowing down through the repository would be oxygen rich, was a poor choice on technical grounds.

During the past decade, there has been renewed interest in an alternative to a geologic repository – the disposal of spent fuel (or other radioactive wastes) in deep boreholes of 3-5 kilometers – made possible by technological advances in recent years 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 than the near-term proliferation risk from reprocessing.

At the reactor site, the IAEA installs remote surveillance systems viewing the spent fuel storage pool, the dry cask loading area and fuel transfer gates. 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.”

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 observations 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.

Policy Lessons

An analysis of the national histories of spent-fuel management, presented at length in the forthcoming report and summarized below, yields the following key 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 will likely require robust waste packaging and backfill, appropriate geology, and possibly retrievability for up to several hundred years;
- Most countries have adopted dry cask spent-fuel storage as an interim strategy since no repository has yet been licensed;
- 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 similar 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 large-scale 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 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". The study also concluded that this would be extraordinarily costly.[8]

Plutonium is recycled in a few countries today. This results in a net reduction of the plutonium in the spent fuel by about half. France, which has the most extensive reprocessing and MOX 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.

Countries that reprocess produce wastes that require about the same size geological repository as would direct disposal of the unreprocessed spent fuel. For example, 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– about the same area that would have been required had France not reprocessed at all. 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 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. 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”.[9]

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.

Multiple barriers and reversibility

In many countries, the initial idea behind the pursuit of an underground geological repository for waste disposal was that the geological barrier, in and of itself, would prevent the exposure of members 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 beds 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 (Figure 5).

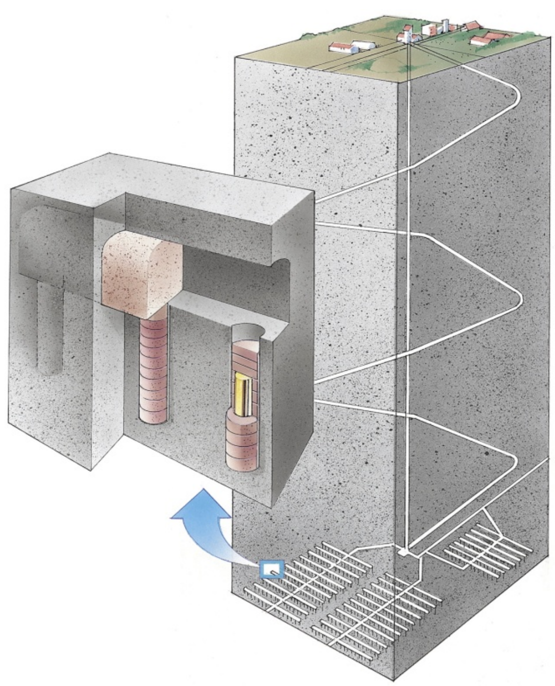

Figure 5. The proposed design of Sweden’s repository includes a 5-cm-thick copper cask surrounded by a bentonite clay buffer embedded in the floor of a tunnel 500 meters deep in granite bedrock. Source: SKB.

Both approaches have encountered problems. Salt has been found to often have been penetrated by human-made water channels and experiments have found that copper corrosion rates may be much higher than originally projected. 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, as with disposal 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 recommended a retrievable period of approximately 240 years. The French 2006 Planning Act 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 U.S., Canada, Germany, South Korea, and Russia. In the U.S., as of the end of 2010, 37 of the 65 U.S. sites with operating nuclear reactors had associated dry storage facilities. U.S. citizens groups have indicated that they prefer on-site dry cask storage 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."[10] 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.[11] According to France's 2006 Act on Sustainable Management of Radioactive Materials and Waste, "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 fuel sent to Russia is from "Russian-origin" fuel, i.e., fuel provided by Russia and/or 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. However, the fuel stored there will not necessarily be reprocessed. 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.

Multinational repositories

The idea of countries sharing a geological repository has been around since the 1970s. Three efforts in the 1990s to consider an international repository, involving 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.

Success with a national repository may be a necessary though not sufficient condition for a multinational one. Moreover, 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

All stakeholders, whatever their view of nuclear power, realize that spent fuel and any high level waste expected to be generated by existing nuclear programs must be disposed of eventually. Proposals to build new nuclear power plants are seen by some as compounding the problem by requiring larger or more repositories and potentially increasing environmental and public health risk.

In the UK, the Committee on Radioactive Waste Management sought to draw a clear distinction between legacy waste and “new-build” waste in drawing up a proposed national disposal policy – but with renewed UK Government interest in building a new generation of nuclear power plants, the effort to develop a disposal policy may bog down. A similar argument has been 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.”

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.[12] 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.

Summary of Country Studies

We summarize below the findings of the forthcoming report on the history and current status of radioactive waste management in a number of key countries, including those with the largest and oldest nuclear-power programs. These include four countries that reprocess (France, Japan, Russia, and the United Kingdom), five countries that are planning on direct disposal of spent fuel (Canada, Germany, the United States, Finland and Sweden) and one country (South Korea) whose disposal plans are currently a subject of domestic debate and 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 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.[13] 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 m 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 U.K. for reprocessing, with the separated plutonium being fabricated into mixed oxide fuel (MOX) and returned to Germany to be loaded into LWRs. High-level reprocessing waste is being returned to a centralized interim storage facility at Gorleben where it awaits final disposal in a repository together with spent nuclear fuel. In the 2000 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. It was decided that exploration of the Gorleben salt dome for a repository also would be suspended while the framework of a criteria-based site selection procedure was developed and implemented and generic safety-related issues that are independent of specific sites were clarified. 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.

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 U.K. for reprocessing. Then Japan built a domestic reprocessing plant at Rokkasho with a design capacity of 800 tons per year. However, full operation of the plant has been delayed repeatedly and is currently scheduled for 2012. The storage pool at Rokkasho is now full. Almost all of Japan's other spent fuel is stored in pools at the reactor sites with a small amount stored in casks on two sites. 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 Fukushima earthquake. Japan has decided on deep geological disposal for its high level wastes and has committed that no waste will stay for more than 50 years in Aomori Prefecture, which hosts the Rokkasho Reprocessing Plant. Solicitation of volunteer communities to host a national geological repository has, however, not yet produced any candidates.

South Korea. At present, South Korea stores its spent fuel on-site at its four nuclear reactor sites. One of these sites, the Wolsong nuclear power plant, has four CANDU heavy-water reactors whose spent-fuel pools are full. 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. This situation has been used by the Korea Atomic Energy Research Institute (KAERI) as an argument 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 in Siberia near Krasnoyarsk, 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 State 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 will 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, a design developed in Sweden starting the 1970s. 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 public Committee on Radioactive Waste Management (CORWM) to consider long-term strategy both for intermediate and high-level reprocessing waste. CORWM had as one of its charges "to inspire public confidence." 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 constructing 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 $10 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. In the meantime, almost all spent fuel in the U.S. 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 did 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 is to produce an interim report by July 2011 and a final report by January 2012.

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Endnotes

[1] International Atomic Energy Agency, Power Reactor Information System, 25 May 2011: 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, i.e. not including the weight of structural materials or the oxygen in the uranium and plutonium oxides.

[3] Nuclear Energy Institute (NEI), Resources and Stats: Nuclear Waste: Amounts and On-Site Storage, p. 1; data as of February 2010.

[4] Personal communication, Douglas Tonkay, U.S. Department of Energy, May 1, 2011.

[5] A less costly strategy to protect against attack with anti-tank missiles from the ground outside the security perimeter that has been suggested is erecting berms around the casks to prevent direct line-of-sight targeting.

[6] National Research Council, *Going the Distance? The Safe Transport of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States*, National Academies Press, Washington, D.C., 2006.

[7] Actinides refers to the class of elements that includes actinium, thorium, protactinium, uranium, and the transuranics. A few very long-lived fission products such as Tc-99 are also of concern.

[8] U.S. National Research Council, *Nuclear Wastes: Technologies for Separations and Transmutation*, 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.

[9] Juhani Vira, "Winning Citizen Trust: The Siting of a Nuclear Waste Facility in Eurajoki, Finland," *Innovations*, Fall 2006.

[10] Hojin Ryu, "Trend of Spent Fuel Management (SFM) in the World," International Atomic Energy Agency, ISSF-2010, Tokyo, 15-17 November 2010.

[11] The earliest reprocessing contracts did not include this provision.

[12] "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." http://www.bmu.de/english/nuclear_safety/information/doc/4300.php.

[13] Despite its longstanding reprocessing program, France has accumulated over 13,000 tons of spent fuel.

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