Chapter 5

Ensuring the Safe Disposal of Nuclear Waste

Because the spent fuel removed from a nuclear reactor is highly radioactive, it must be disposed of in a way that protects the environment from contamination and living organisms from exposure. Radioactive isotopes can be spread by air or water, and can also become part of the food chain. While the radioactivity of spent fuel drops with time, according to a 1995 National Academy of Sciences study, the "peak risks [from a repository] might occur tens to hundreds of thousands of years or even farther into the future."[96] Isolating spent fuel from the environment is therefore a highly demanding task—for comparison, human civilization has existed for only some 10,000 years.

Several potential ways of handling spent fuel in the long term have been proposed—none of which are ideal. These include burying the waste below the seabed, launching it into outer space, and storing it on remote islands. However, the international scientific consensus is that spent fuel and other high-level waste should be stored underground in a "geologic" repository, where the geological properties of the surrounding area would provide the long-term stability needed to isolate the waste from the environment. The waste would sit inside tunnels drilled deep into the earth.

UCS concurs with this consensus, and believes that such a repository—if properly sited and constructed—can protect the public and the environment for tens of thousands of years. However, the choice of a repository location must be based on a high degree of scientific and technical consensus. When spent fuel is isolated in a geologic repository, the hazard to the public results from the slow corrosion of spent fuel and leakage of radionuclides into the environment—primarily through groundwater. The risk profile of a repository depends strongly on the geochemistry of the site, and changes with time as the result of radioactive decay.

Sweden, Switzerland, and the United States have decided to build such repositories, but none have begun to do so. Only the United States has chosen a potential site—at Yucca Mountain in Nevada. However, this facility faces several political and technical hurdles before it can be licensed. For example, although the site is unique among those proposed worldwide because it sits above the water table, leaks from the repository could still contaminate groundwater. In fact, analysts have found that rainwater travels much more rapidly through the layers of the proposed repository than originally believed, and thus that any leaked waste would also reach the groundwater more quickly.

Fortunately, there is no immediate need to open a permanent repository, as interim storage of spent fuel in dry casks at reactor sites is an economically viable and secure option for at least 50 years—if such sites are hardened against attack. New reactors could build in more robust interim storage from the beginning. However, the federal government must improve the security of these

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[96] National Academy of Sciences, *Technical bases for Yucca Mountain standards* (Washington, DC: National Academy Press, 1995).

onsite storage facilities, while also actively working to find a suitable permanent site.

Because 31 countries have power reactors and spent fuel, and about half of those have five or fewer reactors, it may ultimately be more practical to build several international repositories than for each nation to build its own repository. However, no country has seriously proposed hosting an international spent fuel repository.

U.S. Waste Disposal Framework

The Nuclear Waste Policy Act of 1982 established a legal framework for siting, constructing, and operating geologic repositories for high-level radioactive waste and spent nuclear fuel. The act directed the U.S. Department of Energy (DOE) to find at least five candidate sites across the country, and to recommend three to the president, who would choose one. The act also required the use of a similar process to select a second repository, so no single community would bear the entire burden of hosting all high-level waste.

According to the act, the first repository can accept up to 70,000 tons of high-level waste until the second repository begins operating. U.S. nuclear power plants have already produced 55,000 tons of spent fuel, and the 70,000-ton limit will soon be exceeded by the 104 reactors operating today.

The act stipulated that the NRC would license the repositories using standards set by the Environmental Protection Agency (EPA). The EPA initially required the repository to isolate the waste for at least 10,000 years. However, the 1992 Energy Policy Act nullified this standard, and directed the EPA to follow recommendations by the National Academy of Sciences. As noted, the 1995 NAS report found that the greatest risk to the public could occur long after 10,000 years: from tens to hundreds of thousands of years or even farther into the future."[97]

The 1982 act established the Nuclear Waste Fund to pay for the federal repository program. The law required that operators of nuclear power plants pay 0.1 cent per kilowatt-hour of electricity they generate, and that the federal government begin to accept spent fuel for disposal beginning in 1998. If reactor operators could not store all their spent fuel onsite before it was removed for disposal, the government would have to provide one or more interim storage facilities on government property.[98]

Yucca Mountain

In accordance with the Nuclear Waste Policy Act, the DOE identified eight potential repository sites. However, after several states with such sites objected, Congress amended the act in 1987, directing the DOE to assess only the Yucca Mountain site in Nevada.

In December 2001, the Government Accounting Office (GAO) found that some 300 technical issues regarding this site remained unresolved.[99] In January 2002, the U.S. Nuclear Waste Technical Review Board concluded that the scientific and technical basis for the DOE's assessment of Yucca Mountain was "weak to moderate."[100] Nevertheless, the secretary of energy recommended the site to the president, Congress supported the recommendation, and in July 2002 the DOE received authorization to apply to the NRC for a license to operate the site. The DOE plans to submit its application by June 2008, and to begin accepting spent fuel in 2017.[101]

However, the EPA was expected at press time to revise its standards for Yucca Mountain to require the government to show that it can protect the public for 1 million years after it closes the site. The DOE may be unable to meet such a standard, given limits in the ability of computer models to project what will occur at the site so far into the future.

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[97] Ibid.

[98] The maximum capacity of these facilities was set at 1,900 metric tons.

[99] U.S. General Accounting Office (GAO), "Technical, schedule, and cost uncertainties of the Yucca Mountain repository project," GAO-02-191 (December 2001).

[100] U.S. Nuclear Waste Technical Review Board, "2002 report to the U.S. Congress and the secretary of energy" (April 2003), online at *http://www.nwtrb.gov/reports/2002report.pdf.*

[101] According to DOE, an opening date of 2017 is a "best-achievable schedule." See *http://www.ocrwm.doe.gov/ym_repository/license/index.shtml.*

Recommendation:
Because licensing a permanent geologic repository for high-level waste may take a decade or more, especially if Yucca Mountain is found unsuitable, the Department of Energy should identify and begin to characterize other potential sites.

Interim Storage of Waste

Because a permanent repository is not yet available, the DOE has authorized many power plant owners to increase the amount of spent fuel in their storage pools by as many as five times the amount allowed by their original license. (Owners have filed nearly 60 lawsuits against the DOE seeking monetary damages for the costs of this storage, many of which have been settled, resulting in multimillion-dollar awards.)

As Chapter 4 notes, no containment buildings protect these pools, and an accident or terrorist attack that allows the water in a densely packed pool to rapidly drain away could cause the zirconium cladding on the fuel rods to catch fire and the spent fuel to melt, resulting in a significant release of highly radioactive isotopes such as cesium-137 (see Box 4, p. 48). Adding more spent fuel to these pools only compounds this potential problem, and increases the amount of radioactive material that could be released into the environment.

Plant owners whose storage pools are full have placed excess spent fuel in dry casks—typically steel cylinders welded or bolted closed to prevent leaks. These cylinders are placed inside a larger vault—typically made of concrete, which provides shielding from the radiation—and stored outdoors on concrete pads.

Dry casks used to store spent fuel

Although the dry casks would present less of a hazard than spent fuel pools if attacked, they remain vulnerable to weapons such as rocket-propelled grenades. These weapons could penetrate most dry casks and their vaults, igniting a zirconium fire and resulting in the release of significant amounts of radioactive material.

The security of these pools and dry storage sites is clearly unacceptable. However, interim storage of spent fuel in hardened dry casks can be made an acceptably safe and economically viable option for at least 50 years with a few relatively simple modifications, such as surrounding them with an earthen berm.[102]

CENTRALIZED INTERIM STORAGE

Given the delays and uncertainties surrounding Yucca Mountain, the Nuclear Energy Institute—an industry group—and some individual electric utilities have supported the idea of building one or more centralized interim storage facilities. Before spent fuel could be transported to such a facility, it would be placed in dry casks like those now used at some reactor sites (it would remain in those casks in a permanent repository). However, despite receiving a license from the NRC, a commercial facility on the Skull Valley Goshute Indian Reservation in Utah has encountered significant political roadblocks, including disapprovals by the Interior Department, and may never open.

The motive for centralized interim storage is largely political: it would provide a place for utilities to send their spent fuel in the event that a geologic repository is further delayed, thus satisfying the DOE's legal obligations. Consolidating spent fuel at one or more sites could also cut security costs and hence improve security. However, transporting spent fuel to these sites would entail safety and security risks. And even if spent fuel were

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[102] National Academy of Sciences, *Safety and security of commercial spent nuclear fuel storage* (Washington, DC: National Academies Press, 2005), pp. 60–73.

placed in dry casks and removed to an interim storage facility as soon as it was cool enough, all reactor sites would continue to store some spent fuel in pools. Thus centralized interim facilities would simply add to the number of spent fuel storage sites, unless they accepted fuel now stored at the 20 or so U.S. reactors that have been shut down or decommissioned.

Recommendation:
The federal government should take possession of spent fuel at reactor sites and upgrade the security of onsite storage facilities.

Box 4. Radioactive Isotopes

Spent fuel contains large quantities of radioactive isotopes, which are unstable and decay into other elements (called "daughter" elements) by emitting alpha or beta particles, gamma radiation, and/or neutrons. The new "daughter" element may itself be radioactive, and undergo further decay.

All four types of emissions are destructive to living cells, and can cause chromosome damage and cancer. If exposed to very high levels of radiation over a short period of time, a person will develop acute radiation syndrome, and will die in a matter of days or weeks from severe damage to organ tissue.

Different radioisotopes decay at different rates, expressed in terms of a "half-life," which is the time it takes for half of a quantity of isotope to decay. (Half of the remaining material—a quarter of the original amount—will then decay in another half-life, leaving one quarter. After three half-lives, an eighth of the material will remain, and so on.) Half-lives can vary from fractions of a second to millions of years. The more "radioactive" an isotope, the faster it decays, and the shorter its half-life. Thus isotopes with short half-lives emit high levels of radiation but for a relatively short amount of time, while isotopes with long half-lives emit lower levels of radiation but remain radioactive for a long period of time.

After irradiation for roughly three years, spent fuel from light-water reactors typically consists of about 1 percent uranium-235, 93–94 percent uranium-238, 4–5 percent fission products, 1 percent plutonium isotopes, and 0.1 percent other transuranic elements.

Fission products are created when uranium and plutonium split apart, and usually emit high-energy beta particles and/or gamma radiation, which can penetrate skin. Protection requires heavy shielding.

In the first several hundred years after spent fuel is removed from a reactor, the fission products pose the greatest risks to humans and other organisms (provided the spent fuel remains intact). After a few years, the gamma radiation from cesium-137 (Cs-137)—which has a relatively short half-life of 30 years—poses the greatest risk, and gives rise to the "self-protection" of spent fuel described in Chapter 4.

Transuranic elements do not exist in nature and are produced when uranium and then higher elements successively absorb a neutron. Transuranic isotopes, and uranium isotopes, usually emit alpha particles, which are stopped by the outer few layers of human skin. However, these particles can be very hazardous if they are inhaled or ingested, as they tend to deposit large amounts of energy in a small region, causing multiple DNA lesions in a single cell.

The most common transuranics in spent fuel are neptunium, plutonium, and americium. These elements are members of the actinide group, which includes uranium as well. While the radioactivity of these actinides varies, some isotopes are very long-lived, and hence less radioactive. Neptunium-237 has a half-life of about 2 million years, while plutonium-239, -242, and -244 have half-lives of 24,000, 380,000, and 80 million years, respectively.

Reprocessing as a Waste Management Strategy

Some argue that reprocessing spent fuel will reduce the volume of high-level waste needing disposal in a geologic repository. Because spent fuel from light-water reactors is mainly uranium, these proponents of reprocessing maintain that removing it would result in a smaller quantity of waste.

However, it is the level of heat generated by the waste—not the volume—that determines how much waste a repository can store. If the waste is packed too densely in the tunnels, and the heat output is high enough that the temperature exceeds the boiling point of water, permanent changes could occur in the chemical, mechanical, and hydrological properties of the surrounding rock. Such changes could compromise the ability of the repository to isolate the waste from the environment over the required time period.

As Chapter 4 noted, some countries have used the PUREX method to reprocess spent fuel over the past several decades (or contracted with other countries to do so). This process separates both plutonium and uranium from spent reactor fuel, and then from each other. The transuranic elements plutonium, americium and curium are the main sources of heat in spent fuel after a few hundred years; americium and curium remain in the waste stream and would require disposal in a permanent repository. Thus, the PUREX process does not significantly reduce the heat output, or the size of the required repository.[103]

Countries that reprocess spent fuel stockpile the plutonium in interim storage facilities. Some of these countries, including Great Britain, have no plans for this material. Other countries have used some of the plutonium as MOX fuel in reactors, or plan to do so.

However, separating the plutonium for potential use does not eliminate its hazards—it greatly aggravates them, as the stockpiles are much more vulnerable to release from an accident or a terrorist attack than if they were immobilized in a stable matrix such as glass and placed in a permanent repository. Transporting, processing, and irradiating the plutonium also increase the risk that it will be released into the environment.

If the plutonium is used in MOX fuel, the spent MOX fuel contains more long-lived transuranics than spent uranium fuel. No country has reprocessed the plutonium in spent MOX fuel and then reused it, because the costs and safety risks rise with each reprocessing cycle. In fact, although France has a policy of reusing the plutonium in spent MOX fuel, it has not done so, and ultimately may not (see Box 5, p. 50). Thus, spent MOX fuel must also be placed in a permanent geologic repository, further diminishing the benefits of the repository.

Moreover, while spent fuel consists mostly of uranium with roughly the same composition as natural uranium, separated uranium is contaminated with other uranium isotopes that are more radioactive, and with trace quantities of transuranic isotopes. This contaminated uranium can cause difficulties for enrichment plants and reactors. Thus France and other countries that reprocess spent fuel have not used the separated uranium as new fuel, but have instead stockpiled it. This uranium is not high-level waste, but it is difficult to classify in the U.S. system, so the method for disposing of it is uncertain. It would most likely require disposal in a geologic repository similar to the Waste Isolation Pilot Plant (WIPP) in New Mexico. (WIPP itself can accept only transuranic waste from military activities, and could not accept such uranium—see Box 6, p. 52)

WASTES FROM REPROCESSING

As noted, reprocessing also generates additional waste streams. When spent fuel is chopped and

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[103] If spent fuel is directly disposed of in the Yucca Mountain repository, the rock surrounding the fuel would reach its peak temperature in about 2,000 years. If the spent fuel was reprocessed, and the plutonium used to manufacture MOX fuel for existing reactors, much of it would fission, but the spent MOX fuel would also contain other transuranic isotopes that contribute more decay heat in the first few thousand years. Steve Fetter and Frank N. von Hippel, "Is reprocessing worth the risk?," *Arms Control Today*, September 2005, online at *http://www.armscontrol.org/act/2005_09/Fetter-VonHippel.asp.*

Box 5. Nuclear Power in France

Some proponents of expanding nuclear power in the United States point to the French nuclear program as worth emulating. France's 58 pressurized light-water reactors produce 75–80 percent of its electricity demand.[104] (The 104 U.S. reactors produce about 20 percent of U.S. electricity.)

Électricité de France—a government-owned entity—produces all the country's electricity. Government-owned companies have built all the French nuclear reactors, and Cogema, also government-owned, reprocesses the spent fuel.

Because the French government controls all aspects of the industry, it was able to significantly expand nuclear power after the 1973 oil crisis. As a high-level nuclear official recently cautioned, the French period of nuclear power expansion was specific to its time and place, and could not be extrapolated to other countries, or even duplicated in France today.[105]

Centralized control has also enabled the government to limit reactors in France to a few standardized designs. In contrast, the U.S. electricity sector is a patchwork of privately and publicly owned regional and national utilities, and U.S. reactors are of many different designs. Thus the French industry benefits from a shared learning curve, but also has a greater risk of "common-mode" problems than the U.S. industry.

An example is the impact of rising surface temperatures on nuclear power plants. During the heat waves of 2003 and 2006 in Europe, drought reduced the volume of some of the bodies of water used to cool reactors in France and other countries, raising the potential for excess heating of these bodies of water. As electricity demand peaked, Électricité de France sought waivers of the environmental restrictions, while countries such as Germany and Spain reduced power levels or shut down plants entirely. Even so, France ended up having to shut some plants and import electricity to meet demand.[106]

Thus excessive reliance on nuclear power increases the vulnerability to common-mode phenomena that could affect the performance of many or all nuclear plants.

Shortfalls in Economics and Safety

Although France has recently been forced to open its borders to the European electricity market, French nuclear power did not previously compete in the energy market, and thus did not have to respond to cost-cutting pressures. The French government provides little public information on the sector, making it difficult to compare the cost of electricity generated by nuclear power in France and the United States. The French government also releases far less information on safety practices or its safety record than the U.S. Nuclear Regulatory Commission. However, despite the lack of public information, the French experience reveals clear economic and safety downsides to an electricity grid that is highly dependent on nuclear energy.

For example, regional demand for electricity can fluctuate during the course of a day by 50 percent or more, depending on the seasons and the day of the week. In the United States, nuclear power plants usually continue to operate at their peak capacity to provide baseline electricity. Fluctuating demand is met by coal or natural gas plants, which can easily adjust their output, or "load-follow." (The NRC does not prohibit load-following by U.S. reactors, but it occurs only rarely.) Because fuel and operating costs are a relatively small component of the cost of the electricity reactors generate, operating them at full capacity is most economical.

However, because nuclear plants generate so much of its electricity, France must use some of its nuclear

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[104] Uranium Information Centre, "Nuclear power in France," Briefing Paper 28 (March 2007), online at *www.uic.com.au/nip28.htm.*

[105] Remarks by Olivier Caron, governor for France, to the IAEA Board of Governors, Carnegie Institute of International Peace, January 18, 2007.

[106] Susan Sachs, "Nuclear power's green promise dulled by rising temps," *Christian Science Monitor*, August 10, 2006. Because these restrictions are designed to limit the increase in the temperature of the water, a smaller volume of cooling water would lower the acceptable thermal emissions rate.

reactors to load-follow—either by lowering and raising reactor power levels, or by shutting down reactors during times of low demand, such as on weekends. Thus the average “capacity factor”—the amount of electricity reactors produce versus what they are capable of producing—is less than 80 percent in France, which is low by world standards. In the United States, the average capacity factor has been roughly 90 percent during the 2000s.

Using nuclear reactors to load-follow also raises safety risks. For example, when a reactor’s power level is allowed to fluctuate, the potential for sudden power spikes rises. These spikes could produce significant fuel damage, which could lead to a fuel meltdown. Variations in power output also put cyclic stresses on fuel pellets, cladding, and structural materials in the reactor, which could lead to fatigue and other damage. And the risk of accidents does not fall when the reactor is shut down for short periods, as the decay heat of the fuel remains high. Thus during these periods there is risk but no benefit. Optimizing the electricity grid so nuclear plants do not have to load-follow is a more efficient and safer policy.

Stockpiles of Nuclear Waste and Plutonium

Like the United States, France has made little headway in developing a geologic repository for long-lived nuclear wastes. However, France’s approach has created problems that the United States does not have. France ships spent reactor fuel to a complex in La Hague, Normandy, for storage and eventual reprocessing. However, the uranium from its reprocessed spent fuel is not being consumed, as it is more expensive to turn into reactor fuel than mined uranium, so thousands of tons have accumulated.

But perhaps the biggest failure of this program is its nearly 50-ton stockpile of separated plutonium. France initially intended to use the plutonium in its fast-breeder reactor program. However, this program failed on performance and safety grounds (Phénix and Superphénix were plagued with liquid sodium leaks, and Phénix experienced unexplained reactivity increases).

Stuck with a growing stockpile of plutonium, France required Électricité de France to start using MOX fuel made from this plutonium in its light-water reactors—even though MOX is several times more expensive than low-enriched uranium, and its use required reactor modifications and restrictions on operations. So far France has licensed only 20 of its first-generation pressurized-water reactors to use MOX fuel. At today’s rate of use of MOX, eliminating the 50-ton stockpile of separated plutonium will take decades.

Security measures for this stockpile are inadequate. France does not employ armed guards at nuclear power plants, even plants storing and using MOX fuel. And vehicles containing plutonium and MOX traveling on French roads are poorly guarded. After extensively videotaping the trucks used to transport plutonium oxide from La Hague to MOX fuel fabrication facilities in Cadarache and Marcoule, and recording their license plates, Greenpeace activists intercepted a truck carrying 150 kilograms of plutonium and chained themselves to it. Even though this incident occurred within meters of a French military base, off-site responders took two hours to arrive and arrest the activists.[107]

Meanwhile, France has blocked implementation of binding physical protection standards by the International Atomic Energy Agency, which could have compelled France to upgrade its security. If France were to adopt standards for protecting plutonium appropriate for the post-9/11 era, the already poor economics of its program for using plutonium would only worsen.

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[107] Greenpeace, “Greenpeace blocks top secret transport of plutonium in France, revealing global proliferation threat is not in Iraq,” online at *http://www.greenpeace.org/international/press/releases/greenpeace-blocks-top-secret-t or http://tinyurl.com/3a2643.*

dissolved for reprocessing, volatile fission products—such as the noble gases and the halogens—are released as gases. These radioactive gases are either vented through smokestacks or trapped on filters. If released, the gases contribute to both near-term and long-term radiological exposure. If captured, the spent filters must be disposed of as radioactive waste. (Whether they are considered low-level or transuranic waste depends on the concentrations and types of radionuclides—see Box 6.)

Besides the high-level liquid waste from the first extraction cycle, reprocessing plants have also generated large volumes of liquid wastes. For example, liquids used to clean solvents and flush pipes become radioactive. After some radionuclides are removed, their volume can be reduced through evaporation; the water vapor is vented out the smokestack. The remaining concentrated waste will be low-level or transuranic waste, depending on its composition. But there is a trade-off between reducing or eliminating liquid waste and increasing the volume of solid low-level and transuranic wastes that require disposal beneath the earth's surface.

Reprocessing also generates large amounts of solid wastes ranging from the cladding removed from spent fuel to contaminated clothing. When a reprocessing plant is eventually deactivated and decommissioned, it also must be disposed of in a waste facility (the type of facility will again depend on the type and quantity of contamination).

Recommendation:

The United States should drop its plans to begin a reprocessing program.

Box 6. Three Types of Nuclear Waste

According to the 1982 Nuclear Waste Policy Act, "**high-level radioactive waste**" is either "the highly radioactive material resulting from the reprocessing of spent nuclear fuel," or other highly radioactive material that must be permanently isolated according to the NRC. For instance, the intensely radioactive liquid waste resulting from the reprocessing of uranium to produce plutonium for U.S. nuclear weapons falls into this category. Yucca Mountain is intended to store such waste.

The Department of Energy defines **transuranic waste** as radioactive waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram with half-lives of more than 20 years. The DOE requires that this waste be buried in a geologic repository. The Waste Isolation Pilot Plant in New Mexico is the only licensed repository for such waste.

The 1982 Nuclear Waste Policy Act defines "**low-level radioactive waste**" as all radioactive material that is not high-level radioactive waste, spent nuclear fuel, or transuranic waste. However, the NRC does not recognize "transuranic waste," considering it instead as a type of low-level waste known as "greater than Class C," which it judges "not generally acceptable for near-surface disposal." Thus commercial low-level waste facilities, which bury waste in shallow trenches, do not accept transuranic waste.