REPORT OF THE AMERICAN NUCLEAR SOCIETY PRESIDENT'S SPECIAL COMMITTEE ON USED NUCLEAR FUEL MANAGEMENT OPTIONS

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EXECUTIVE SUMMARY

Most discussions of significant expansion of commercial nuclear power eventually get around to the question "What about the waste?" In early 2010, American Nuclear Society (ANS) President Tom Sanders formed the ANS President's Special Committee on Used Nuclear Fuel Management Options (the Committee) to explore the options for managing used nuclear fuel (UNF). The Committee's charge was to prepare a comprehensive report for citizens who want to understand the issue or participate in the discussion and for policy makers who must choose a path forward. Such a report would describe currently feasible UNF management options and explore the advantages and disadvantages of each. Environmental, economic, and social factors as well as proliferation risk would be considered. The time frame for the study would be 2010 through the end of the 21st century. Thus, we present "Report of the ANS President's Special Committee on Used Nuclear Fuel Management Options" (the Report).

Part I of the Report, "Current Status and History of Used Nuclear Fuel Management," provides background information, including a summary of UNF management policies currently used in other countries. Part II of the Report, "Options for Used Nuclear Fuel Management for the Next Century," describes options for storage of UNF and for treatment and final disposal of that fuel. Factors likely to be important when selecting options for storage, treatment, and disposal of the UNF are identified and discussed.

Methods selected for storage, treatment, and disposal of UNF will depend, in part, on the numbers and types of nuclear power plants operating in the United States for the remainder of this century. The Committee members did not attempt to predict the mix of nuclear power plants but rather defined two bounding scenarios and identified UNF management options for those two scenarios. Fuel management options for any alternative mix of nuclear power plants will be encompassed by those identified for the bounding scenarios.

Since many people reading the Report will already be familiar with the background information in Part I, the "Executive Summary" focuses on Part II.

Options for Storage of UNF

Over the next century, UNF assemblies will continue to be put into water-filled pools at the nuclear power plant when they are first removed from the reactor. They will remain in the pool for at least 5 years while they cool and some of the fission products decay. Following the cooling period, UNF assemblies can be put into dry casks for storage either at the reactor or at a centralized interim storage facility. A centralized facility could be national or regional and could be operated either by the federal government or by a private company. Currently, a consortium of utilities, Private Fuel Storage, LLC, has received a U.S. Nuclear Regulatory Commission license for a storage facility on the Goshute Indian Reservation in Utah, but approvals for site access and leases are still under consideration within the U.S. Department of the Interior and other government agencies. However, if a deep geologic repository is licensed in the relatively near term or if the U.S. government decides to receive UNF for reprocessing in that time frame, there may be no need for a separate centralized storage facility.

If no disposal or reprocessing facility is operating in the next couple of decades—and if, at that time, none can be foreseen in the near future—decisions about when and how to store UNF will need to be made. Factors to be considered in those decisions include the following:

- safety and security, including environmental security
- equitable geographic distribution of risks and benefits associated with production of nuclear power and storage of the UNF
- management of the UNF stored at sites where the reactor has been decommissioned
- licensing and regulatory issues
- construction and operation costs for the storage facility or facilities
- cost to the federal government (i.e., taxpayers) and electricity consumers
- risk-benefit analysis by the host community and surrounding area
- support from the host community and surrounding area
- support from the general public
- federal or private management of the site
- national policy on UNF management.

Many of the factors listed above are interrelated. The last factor, national policy on UNF management, affects almost all of the others. For example, a long-term, stable policy would allow host communities and surrounding areas to conduct a risk-benefit analysis with some certainty. Removing uncertainty about national policy could also have an impact on the costs of the storage facilities, both near term and in the future.

Summary of Options for Ultimate Disposition of UNF

Three options for disposition of UNF are considered in the Report:

option 1: once-through fuel cycle with UNF assemblies directly and permanently disposed of underground

option 2: limited reprocessing and recycling of UNF into light water reactors (LWRs) with reprocessing wastes and used recycled fuel permanently disposed of underground

option 3: full recycling of UNF into fast reactors with reprocessing wastes permanently disposed of underground.

If the once-through fuel cycle is adopted, underground disposal in a centralized deep geologic repository like the one that was planned at Yucca Mountain is an option (option 1). Virtually all countries with commercial nuclear power programs currently plan to dispose of UNF or

reprocessing wastes in a centralized geologic repository. No country has built such a repository for UNF although the United States is operating a geologic repository for defense transuranic waste. An alternative to a deep geologic repository has been proposed and analyzed recently. It is proposed that UNF could be disposed of in boreholes 1.86 to 6.21 miles (3 to 10 km) deep drilled into the basement rock. Nuclear power plants are typically sited above thick, stable rock formations that would be suitable for boreholes. Both options for direct disposal have advantages and disadvantages that need to be explored. While the technical issues have been fairly straightforward, issues related to political considerations and public acceptance have been more complex and difficult to resolve.

In option 2, there is limited reprocessing, and mixed uranium-plutonium oxide (MOX) fuel is recycled into LWRs. Aqueous reprocessing methods are used to recover plutonium from UNF, and the plutonium is recycled in MOX, which is typically used only once in an LWR. Because it is used only once, MOX fuel is of limited value in LWRs; it is much more valuable in fast reactors where it can be recycled multiple times. Option 2 could, therefore, be considered as an interim step toward option 3, full recycling in fast reactors. It may be worthwhile to develop reprocessing capability and begin building an inventory of MOX fuel while the U.S. reactor fleet still consists primarily of LWRs—if it is clear that fast reactors will be coming on line in the future. The United States could also decide to pursue option 2 if providing UNF reprocessing services to other countries appears to be a way to avoid nuclear proliferation. Advanced aqueous reprocessing technologies have been under development, primarily motivated by the recovery of other minor actinides to reduce toxicity of the remaining waste and to enhance proliferation resistance.

If fast reactors are in place, there will be a strong incentive for option 3, reprocessing with full actinide recycling. UNF from fast reactors has as much or more fuel value than the fresh fuel put into the reactor, but it must be reprocessed to separate the useable fuel from the waste products. Two categories of reprocessing technologies are available: aqueous reprocessing, which was described in the previous paragraph, and pyroprocessing. Pyroprocessing was originally developed to reprocess metal uranium fuel. It recovers all of the actinides together so that plutonium is not isolated. Some research has been conducted on applying pyroprocessing to oxide fuel, but much work is yet to be done. Since option 3 requires the use of fast reactors, evaluation of this option must include consideration of capital costs associated with the development of fast reactors. A "cradle-to-grave" cost-benefit analysis would consider the total impacts of uranium enrichment, fuel fabrication, fuel recycling, reactor construction and operation, and waste disposal.

It is important to note that for both options 2 and 3, high-level waste (HLW) will be produced from reprocessing and recycling activities. A permanent disposal facility will still be required for this HLW. Numerous studies have been conducted on the impacts of reprocessing on repository performance. In general, as radiotoxicities of waste are reduced by reprocessing, the potential for releases from the repository and impacts on humans and the environment will be reduced.

Factors that need to be considered when deciding which treatment and permanent disposal option to adopt include the following:

- economics
- resource utilization

- environmental concerns and impacts on long-term performance of geologic repositories
- nonproliferation
- retrievability
- public acceptance
- ethical issues.

Bounding Scenarios and UNF Management Options

It is not possible to predict accurately the number and types of nuclear reactors that will be operating in the United States during the 21st century. It is, however, possible to identify bounding scenarios and examine the UNF management options for those scenarios. The two bounding scenarios for nuclear power utilization that the Committee considered are

1. no-growth scenario in which all existing nuclear power plants operate for 60 years and then shut down with no new nuclear plants being built

2. growth scenario in which half of the growth in electricity demand between 2010 and 2100 in the United States is supplied by nuclear power.

Any scenario between these two bounding scenarios will require the use of some combination of the UNF management methodologies and facilities discussed here.

For the no-growth scenario, the options for storage of UNF are simply to store it at the reactor or at an interim away-from-reactor storage facility. The away-from-reactor facility could be national or regional, and it could be at the site of the repository. Eventually, the UNF assemblies will need to be permanently disposed of in an underground repository. If a repository opens in the next decade or two, there will be no need to build a centralized away-from-reactor storage facility. Reprocessing is not justified for this scenario. For completeness, the Committee noted that the UNF could be moved to another country, but that is not a realistic option.

In the growth scenario, the Committee assumed that fast reactors will be introduced in mid-century to meet the increased demand for electricity. Under this scenario, demand for uranium will grow, UNF becomes an asset, and recycling will be justified. Short-term storage of UNF in the pool at the reactor will continue to be required. However, centralized or regional consolidated storage may be more cost-effective than storage at growing numbers of individual reactors. To minimize transportation, the centralized storage could be at the reprocessing facility. One or more reprocessing and recycling facilities would be justified, and methods for minimizing proliferation risks at the reprocessing facilities will be important. Regardless of the type of reprocessing done, a geologic repository will still be required for permanent disposal of HLW from reprocessing.

Concluding Remarks

Regardless of whether nuclear power utilization in the United States over the next century is similar to one of the bounding scenarios or something between them, three technical outcomes are inescapable. First, an interim storage facility, or facilities, will be needed to store the UNF until facilities for treatment and disposal are ready. Second, a deep geologic repository, or repositories, will be required for ultimate disposal of defense HLW and wastes from recycling and/or direct disposal of UNF. In addition, a transportation system will be required to move the UNF and wastes from the places they are generated to storage, treatment, and disposal facilities.

Whether the United States needs a used commercial nuclear fuel reprocessing and fuel fabrication (recycling) system depends on many factors including the U.S. policy with respect to international nonproliferation efforts.

Finally, one other feature essential for America's nuclear future, whether that future is the orderly closure of the current nuclear plants or expansion of the nation's nuclear capacity with advanced technologies, is a long-term, stable nuclear energy policy with clear short- and long-term objectives and milestones. In addition, creation of an independent entity to oversee UNF management has been endorsed by ANS [see Position Statement 22, "Creation of an Independent Entity to Manage U.S. Used Nuclear Fuel" (November 2009)].

INTRODUCTION

Most discussions of significant expansion of commercial nuclear power eventually get around to the question "What about the waste?" In early 2010, American Nuclear Society (ANS) President Tom Sanders formed the ANS President's Special Committee on Used Nuclear Fuel Management Options (the Committee) to explore the options for managing used nuclear fuel (UNF). The Committee produced "Report of the ANS President's Special Committee on Used Nuclear Fuel Management Options" (the Report).

The term "used nuclear fuel" was chosen for the Report, in preference to "waste," because it is a more accurate term. While fuel discharged from a reactor can be treated as waste, it does not have to be. In several nations with large commercial nuclear power industries, fuel discharged from a reactor is reprocessed, and >90% of the material from the UNF can be incorporated into new fuel for reactors. Since the Report discusses a range of options for managing fuel from nuclear reactors, "used nuclear fuel" is more appropriate.

The Report is divided into two parts. Part I, "Current Status and History of Used Nuclear Fuel Management," provides background information that is useful when assessing the options for UNF management, including a history of UNF management in the United States. Part II, "Options for Used Nuclear Fuel Management for the Next Century," summarizes options for storage of UNF until it is prepared for final disposition. It also presents options for treatment and final disposition of the UNF. These options are presented within the context of two bounding scenarios for the use of nuclear power in the United States between now and 2100.

The Committee members did not attempt to predict the future of nuclear power in the United States nor did they try to define a comprehensive suite of possible scenarios. Instead, the Committee identified two scenarios thought to be bounding. In the first scenario, nuclear power is phased out after the current nuclear power plants reach the ends of their lifetimes. In the second scenario, nuclear power continues to be utilized and is expanded to provide half of the increased demand for electricity in the United States over the next century. The UNF management options for those two scenarios are then defined. Fuel management options needed for any alternative scenario for the use of nuclear power would be included among those defined for the bounding scenarios considered by the Committee.

Finally, the Committee's findings are summarized in the section "Concluding Remarks."

PART I
CURRENT STATUS AND HISTORY OF USED NUCLEAR FUEL MANAGEMENT

1.0 INTRODUCTION

Part I of "Report of the ANS President's Special Committee on Used Nuclear Fuel Management Options" (the Report) provides background information on used nuclear fuel (UNF) management in the United States and a short overview of how other countries plan to deal with UNF. It begins with a description in Sec. 2.0 of nuclear fuel, what happens to it in the reactor, and the composition of the UNF that is discharged from the reactor. Section 3.0 provides information on the amount of UNF in the United States and where and how it is stored. Summary descriptions are provided of the rules governing UNF storage and the safety of that storage. Section 4.0 presents a history of UNF management in the United States and includes a short discussion of transportation of UNF, since transportation has been and continues to be an important consideration in UNF management. Finally, Sec. 5.0 summarizes UNF management policies and activities in other countries that use nuclear power.

An overview of the nuclear fuel cycle sets the stage for the other sections of Part I. Uranium dioxide is the fuel currently used in commercial nuclear reactors in the United States. Uranium ore is processed to extract the uranium (usually in the form of U_3O_8, called "yellowcake"), which is converted through a series of steps to uranium dioxide. The uranium dioxide is pressed into small cylinders [~0.5 in. (1.29 cm) long and 0.5 in. (1.29 cm) in diameter], which are stacked in metal tubes. These tubes are, in turn, placed in fuel assemblies, which go into the nuclear reactor.

Uranium was chosen as the fuel for reactors because one isotope, ^{235}U, fissions or splits, producing energy. Natural uranium contains <1% ^{235}U. The enrichment process concentrates the ^{235}U, and the resulting reactor fuel is a little more than 4% ^{235}U. After a fuel assembly has been in the reactor long enough for much of the ^{235}U to fission and for by-products of the fission process to build up, the fuel will no longer sustain the nuclear reaction, and the fuel assembly needs to be removed. The UNF removed from the reactor is highly radioactive. The radioactive decay of unstable nuclides produces heat, so fuel elements need to be cooled. Consequently, the fuel is stored initially in a deep pool of water at the reactor site to cool down and to allow some of the highly radioactive materials in the fuel to decay. After a few years, the UNF can be removed from the pool and stored on site in dry casks or transported elsewhere for storage, treatment, or disposal. More details on UNF and its management follow.

2.0 WHAT IS USED NUCLEAR FUEL?

Our discussion of UNF that comes out of the reactor begins with a description of the fresh fuel that goes into the reactor, followed by an explanation of what happens to that fuel in the reactor. Fresh nuclear fuel assemblies contain three main components: the actual fuel pellets,

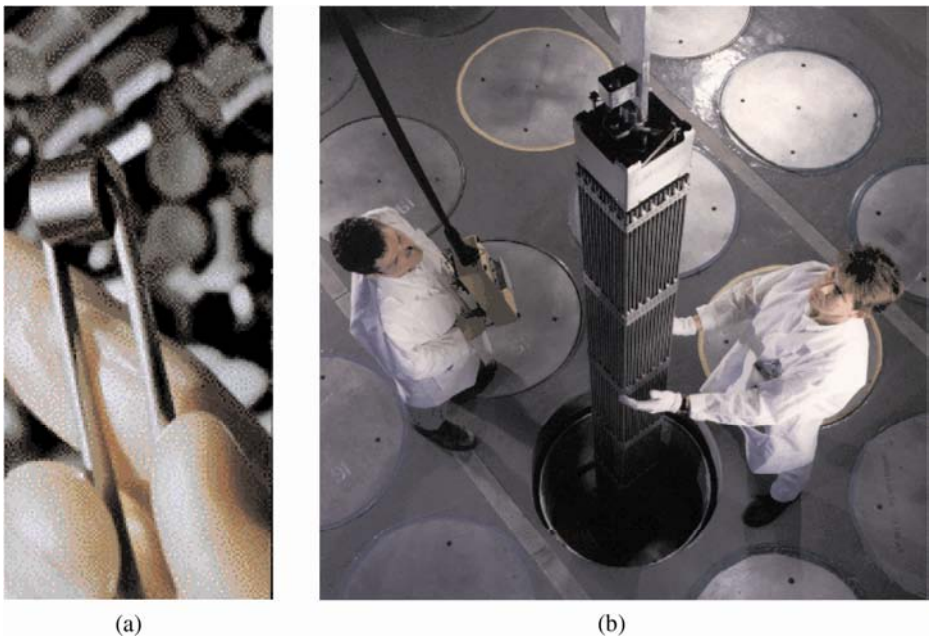


Fig. 1. Photographs of (a) fuel pellet and (b) fuel assembly. (Courtesy of U.S. Department of Energy)

the cladding or metal tube that contains a stack of the fuel pellets, and the structure that holds the tubes together to form a fuel assembly. In most water-cooled reactors, like the ones used in the United States, the fuel pellets are uranium dioxide enriched with the ^{235}U isotope. The pellets are contained within zirconium alloy tubes up to 14 ft (4.27 m) long. The tubes are collected into assemblies, as shown in Fig. 1. Assemblies are arrayed in the reactor core within a massive stainless steel support structure. The reactor containing the fuel assemblies is filled with water.

In a nuclear reactor, ^{235}U fissions when it is struck by a neutron, producing energy in the form of heat, two smaller nuclei called fission products, and two or three neutrons. The energy heats the surrounding coolant water. This heated water can be used to produce steam either directly or indirectly, and the steam is used to drive a conventional steam turbine generator as is done in a fossil fuel plant. This process converts the heat of nuclear fission into electricity. The neutrons produced by fission travel through the reactor colliding with atoms. Sometimes, a neutron simply bounces off of an atom, causing the neutron to slow down; sometimes, a neutron is absorbed by the atom it hits; and sometimes, a neutron strikes a ^{235}U atom, causing fission. The bottom of Fig. 2 illustrates fission. The top of Fig. 2 shows what happens when a neutron is absorbed by ^{238}U. When a neutron (which weighs ~1 atomic mass unit) is absorbed by ^{238}U, the isotope ^{239}U is formed. Uranium-239 is very unstable: An electron is emitted, and ^{239}U decays to form ^{239}Pu, which is itself a fissile isotope much like ^{235}U. Plutonium-239 can also absorb neutrons to produce higher isotopes of plutonium and other transuranic (TRU) isotopes.[1]

[1]Isotopes that can fission are either "fissile" or "fertile." Fissile isotopes readily fission in any type of reactor. The only fissile isotope in nature is ^{235}U, which is only 0.71% of natural uranium. Fertile isotopes fission only under certain conditions but may be converted to fissile isotopes if they absorb a neutron and then decay to other elements; e.g., ^{238}U absorbs a neutron and decays to ^{239}Pu.

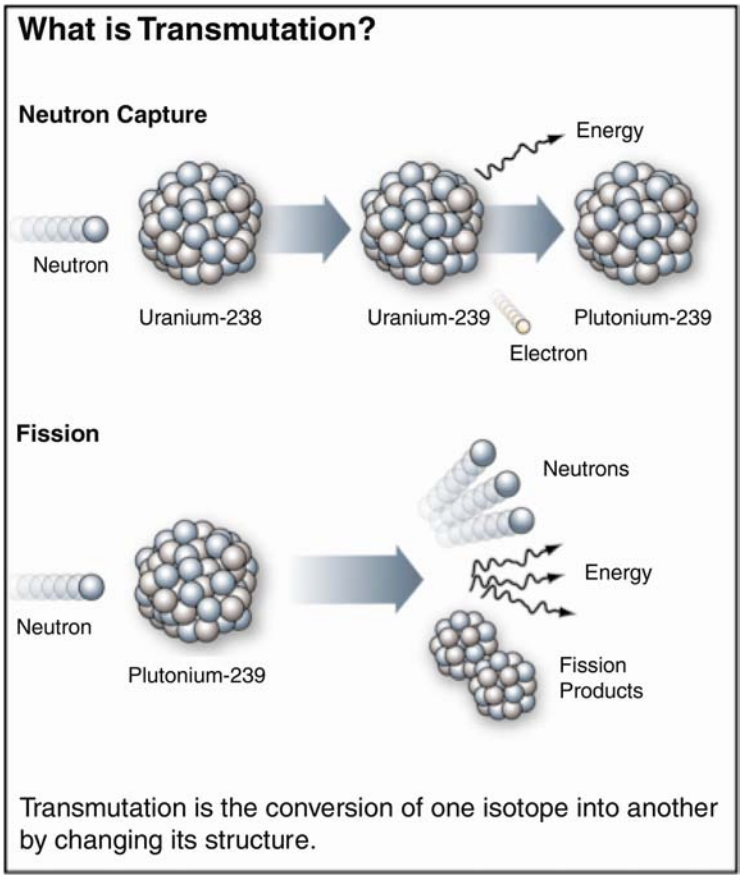


Fig. 2. The transmutation process.

The typical constituents of UNF, excluding cladding and structural steel, after discharge from the reactor are shown in Fig. 3. The vast majority of the material in the UNF is uranium that is generally unchanged from the fuel that went into the reactor to produce energy. The TRU[2] elements of plutonium and the minor actinides—neptunium, americium, and curium—are the result of absorption of neutrons by ^{238}U atoms and subsequent absorption of neutrons by ^{239}Pu and so on. The TRU elements are generally radioactive with long half-lives and require long-term management.

The remaining elements in the UNF come from the fission process and are called fission products. Many fission products are stable and pose little concern. The radioactive fission products with short half-lives—primarily isotopes of cesium and strontium—decay in a few hundred years. There are also fission products that last for hundreds of thousands, or millions, of years that must be considered as well, notably the long-lived isotopes of iodine and technetium that can pose challenges in long-term management.

The composition of UNF depends, primarily, on how many ^{235}U atoms fissioned and how many neutrons were absorbed by ^{238}U and the heavier atoms formed. Burnup is the key parameter to

[2]Transuranics are man-made elements with atomic numbers greater than that of uranium (i.e., >92).

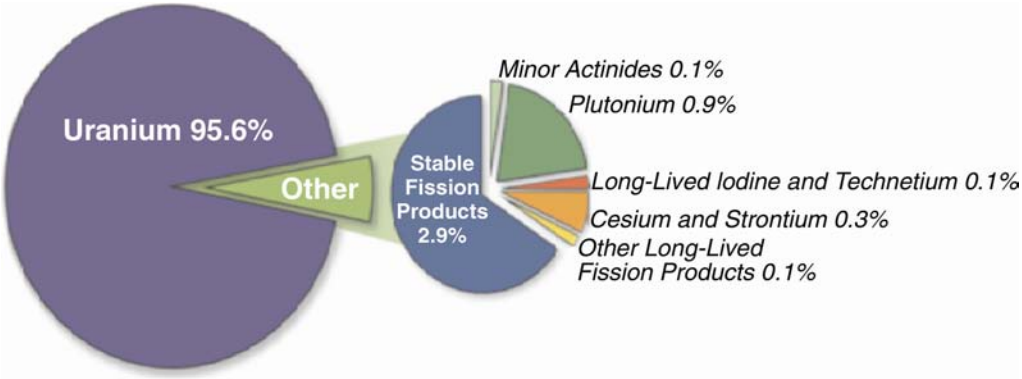


Fig. 3. Constituents of UNF.

describe how much of the nuclear fuel fissioned, with units of thermal energy produced per initial mass of fuel isotopes. The typical units of burnup are gigawatt(thermal)-day per tonne of the initial heavy metal (iHM). (All the fuel isotopes are heavy metals.) Thus, burnup indicates how much energy has been generated by fission per unit mass of fuel and correspondingly the fission products and TRU elements generated. Currently, typical U.S. burnup is ~50 GW(th)-day/tonne iHM.

If the nuclear fuel is not recycled, the burnup can be used to calculate how much UNF is produced each year as a function of power generated. In these calculations, thermal efficiency is assumed to be 34%, which is typical for nuclear plants. (Thermal efficiency of fossil-fired plants is about the same.) A nuclear power plant with uranium dioxide fuel [at 50 GW(th)-day/tonne] operating at full power 90% of the time (typical for U.S. reactors) will require 19.3 tonnes of uranium fuel per gigawatt(electric) of reactor capacity. The United States is generating ~92-GW(e) full-power years of electricity from nuclear per year, so the rate of UNF accumulation is ~2000 tonnes/year.

Achieving a burnup of 50 GW(th)-day/tonne iHM requires the fresh uranium fuel to be ~4.21% ^{235}U. Naturally occurring uranium is only 0.71% ^{235}U. A process called enrichment is used to increase the percentage of ^{235}U in the fuel. For example, if the enrichment process starts with 2 tons of natural uranium, and all of the ^{235}U from one ton is removed and added to the second ton, the concentration of ^{235}U in that second ton would be 1.42%. In practice, it is not possible to remove all of the ^{235}U from the first ton of uranium. Assuming the leftover material, called "tails," from enrichment has a ^{235}U concentration of 0.25%, 8.59 tonnes of natural uranium with 0.71% ^{235}U is required to make 1 tonne of enriched uranium in fuel. The United States is currently using ~17,000 tonnes of natural uranium per year.

2.1. Why is UNF Difficult to Manage?

Both the amount of UNF and the composition of that UNF must be taken into account when deciding how to store, treat, transport, and dispose of it. When it is discharged from the reactor, a UNF assembly is highly radioactive, and it generates heat. Each radioactive isotope in the UNF emits a characteristic type of radiation and has a characteristic rate of decay. Together, the type of radiation and the rate of decay determine the amount of heat generated and potential radiation dose to a human.

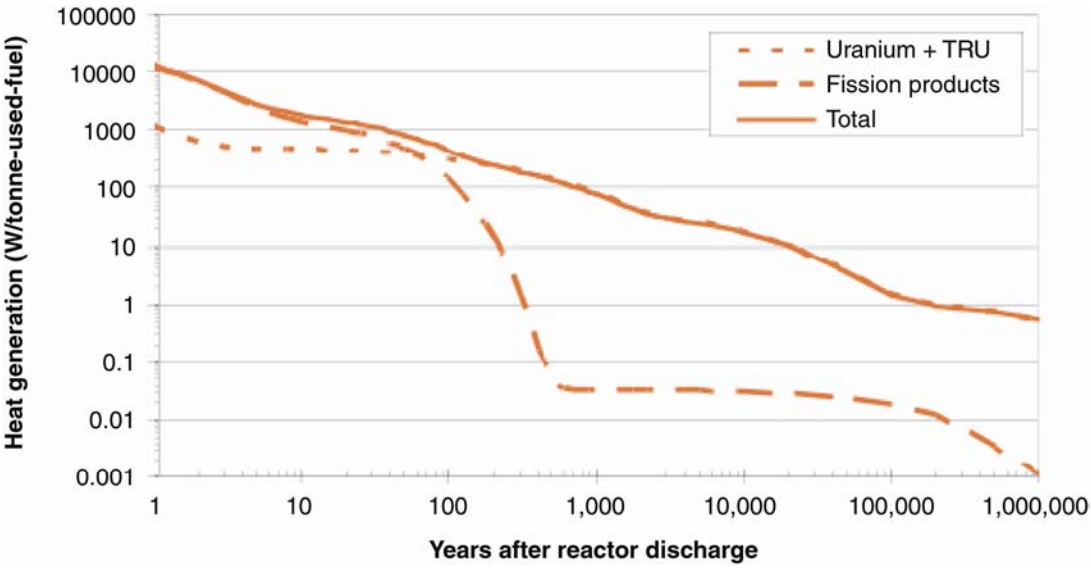


Fig. 4. Used uranium oxide fuel decay heat as a function of time.

Figure 4 shows the heat generation rate of the UNF constituents over time. The actinides dominate heat production after ~100 years, while during the first 50 years, the fission products are generating most of the heat. Though uranium constitutes the vast majority of the mass of UNF, the heat from uranium isotopes is small compared with the heat generated by other constituents of UNF.

Another important characteristic of UNF is the radiotoxicity. For purposes of the Report, the radiotoxicity is defined as the radiation dose to a human caused by a particular mass of isotopes if that mass were ingested or inhaled into the body. Figure 5 shows the radiotoxicity of UNF over time in comparison to the radiotoxicity due to natural uranium used to make the fuel. In Fig. 5, the horizontal line labeled "1" represents the radiotoxicity of natural uranium ore. Thus, the radiotoxicity of fission products is less than the radiotoxicity of natural uranium in ~250 years, while the total radiotoxicity of UNF does not fall below the radiotoxicity of natural uranium for >100,000 years.

The very long half-lives of some of the radionuclides from the UNF have become a central issue of UNF management. Permanent isolation of these radionuclides from humans and the environment has been the ultimate goal of the management.

The fission product isotopes dominating heat production are different from those that dominate radiotoxicity. As a result, it is theoretically possible to separate the fission product heat management problem from the fission product radiotoxicity problem by removing selected fission products from the UNF. Also, as illustrated in Fig. 5, by removing and recycling the TRU elements, the radiotoxicity of the remaining waste would be lower than that of the natural uranium ore from which it came in <1000 years.

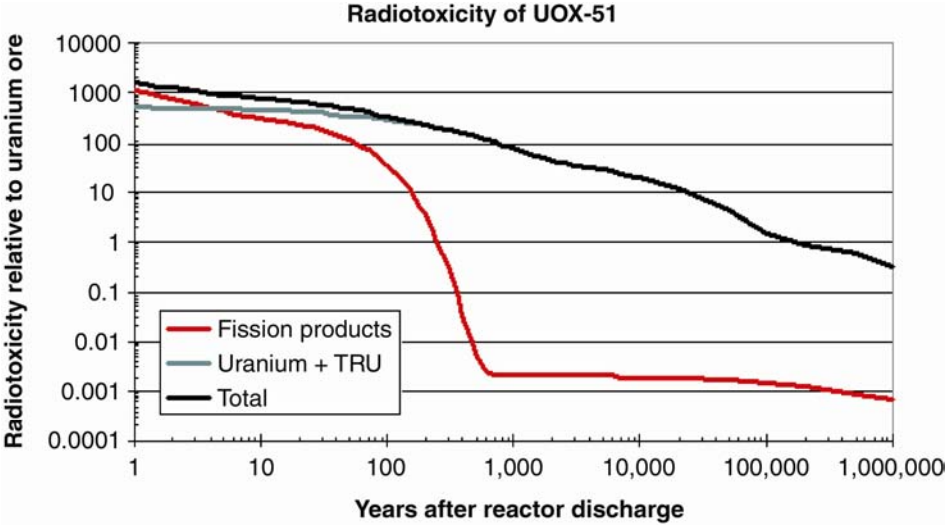


Fig. 5. Used uranium oxide fuel radiotoxicity as a function of time.

The United States currently practices the once-through fuel cycle, where UNF is stored for disposal without any recycling. However, as discussed previously, UNF still has a significant amount of valuable material that can be recycled to extract more of the energy content. UNF is being recycled in France and Japan. During reprocessing and recycling, plutonium is removed from UNF and fabricated into mixed uranium-plutonium oxide (MOX) fuel. Use of MOX extracts some of the energy content of the UNF but does not significantly reduce the long-term radiotoxicity and decay heat of the waste material. This is because every fission results in fission products, and some neutrons released during fission are absorbed by ^{238}U to form TRU materials. If all of the fission products and TRU materials are ultimately buried, the total heat and radiotoxicity of the buried material will be the same whether a once-through or MOX fuel cycle is used. It is, however, possible to fission the TRUs or transmute both the fission products and the TRUs. Transmutation is a process that converts the radioactive isotopes to elements that are not radioactive or ones that have very short half-lives. These nuclear processes have the potential to reduce the long-term decay heat and radiotoxicity of TRUs and fission products, thus reducing the magnitude of the long-term management of the material that is disposed. It should be noted, however, that transmutation is currently done on a very small scale and is expensive.

3.0 WHERE IS USED NUCLEAR FUEL NOW?

3.1. How Much UNF Exists?

There is an estimated 270,000 tons of UNF in storage worldwide (Ref. 1), much of it at reactor sites. Annual worldwide production of UNF is estimated at 12,000 tons, a quarter of which is recycled. About 2000 tonnes of UNF is produced each year in the United States (Ref. 2). Based on recent values published by the Energy Information Administration, the calculated amount of UNF stored in the United States in 2010 was just over 60,000 tonnes. To visualize this total amount of UNF produced by the U.S. nuclear energy industry in 50 years of operation (~62,500 tonnes), consider that those fuel assemblies stacked neatly would cover a football field to a depth of only ~7 yards (~6.4 m) (Ref. 3). By comparison, in

1 year U.S. coal-fired electric plants produce 100 million tonnes of inorganic coal combustion products (Ref. 4).

3.2. Where and How Is UNF Stored?

During the operation of a nuclear reactor, nuclear fuel needs to be unloaded and replaced with fresh fuel periodically. The UNF is stored in deep pools of water that are built into the reactor building (Fig. 6). The water is used to provide cooling and radiation shielding for the highly radioactive UNF that is freshly discharged from the reactor. After the radioactive isotopes in the UNF have decayed sufficiently, usually 5 or more years, UNF can be removed from the pool and stored in dry storage casks.

Originally, as described in Sec. 4.0, designers of nuclear power plants anticipated that after UNF had cooled in the pool, it would be reprocessed, with usable portions of the fuel being recycled and the residual waste disposed of in a deep geologic repository. However, commercial reprocessing of UNF never materialized in the United States, and the repository program has been repeatedly delayed in the last two decades. As a result, many of the UNF pools at nuclear power plants are nearing, or have reached, capacity. Furthermore, more than 60 nuclear power plants have received 20-year license extensions, and many others are in the process of seeking license extensions. These increased operating lives of existing nuclear power plants will require additional storage capacities.

Faced with the UNF storage capacity shortage, nuclear operating companies usually address the issue by "reracking" the UNF in the pool, that is, rearranging the fuel assemblies so that the same amount of pool space can hold more UNF. This has already been done—sometimes more than once—at most operating reactors in the United States. Higher storage densities can be achieved without the risk of nuclear chain reaction by adding neutron-adsorbing materials in the racks or in the water itself. Once the UNF storage pools are reracked to the maximum extent possible, nuclear operating companies store the fuel above ground in certified dry storage casks and canister-based systems outside the storage pool in independent spent fuel storage installations (ISFSIs).

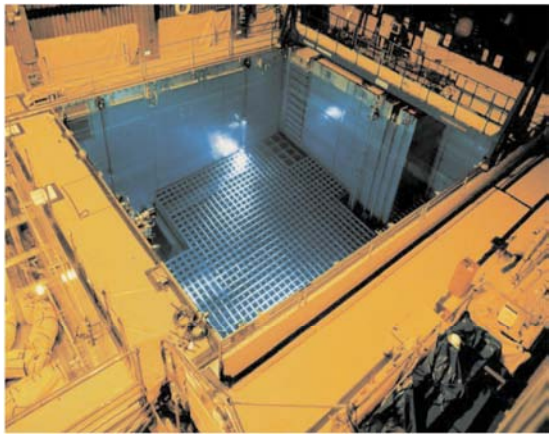


Fig. 6. Photograph of a UNF pool. (Courtesy of U.S. Nuclear Regulatory Commission)

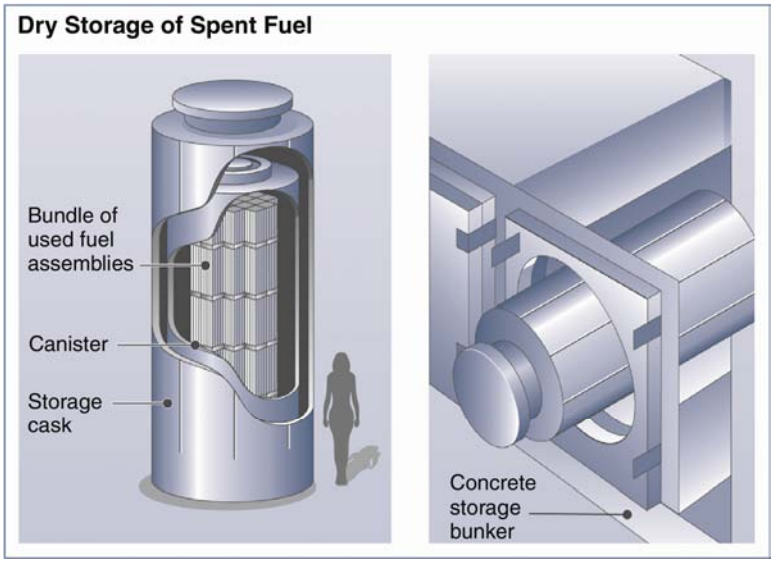


Fig. 7. Illustration of a dry cask storage system. Source: U.S. Nuclear Regulatory Commission Web site: www.nrc.gov/waste/spent-fuel-storage.html (current as of Jan. 2011).

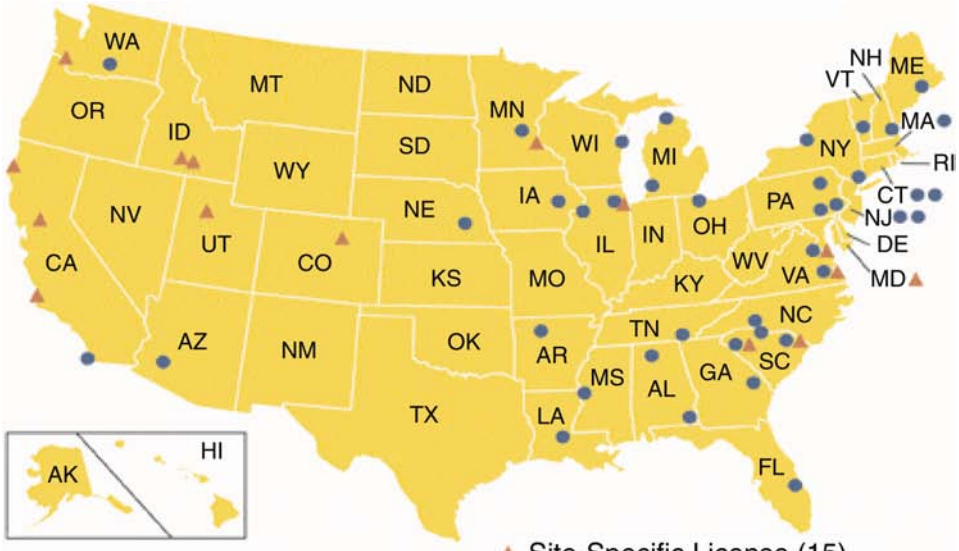
Dry storage of UNF differs from pool storage by making use of gas or air instead of water as the coolant and metal or concrete instead of water as the radiation barrier. In dry cask storage, UNF is surrounded by inert gas inside typically a steel cylinder that is either welded or bolted closed. The cylinder is surrounded by additional steel, concrete, or other material to provide radiation shielding. Each canister is designed to hold approximately 24 to 72 UNF assemblies, depending on the type of assembly. Figure 7 shows a typical dry storage cask. In some designs, casks are stored horizontally in concrete bunkers; in others, they are set vertically on a concrete pad.

The first dry storage installation was licensed by the U.S. Nuclear Regulatory Commission (NRC) in 1986 at Dominion's Surry nuclear power plant in Virginia. As of June 2009, more than 50 sites in 33 states have ISFSIs (Fig. 8). More than 1000 dry storage packages containing more than 11,000 tonnes of UNF are currently in dry storage in the United States, with more being planned.

The U.S. Nuclear Regulatory Commission requires the UNF to be cooled in the pool for at least 5 years before being transferred to dry casks. NRC periodically inspects the design, fabrication, and use of dry storage casks, to ensure that licensees and vendors are performing tasks in accordance with radiation safety and security requirements. Dry cask storage systems are designed to ensure that fuel and cladding degradation will be avoided, accidental chain reaction (criticality) will be prevented, effective shielding will be provided, and radiation releases will be avoided. The system is also designed to resist floods, tornadoes, projectiles, temperature extremes, and other unusual scenarios.

3.3. What Rules Govern UNF Storage?

A plant's operating license includes storage and surveillance requirements for fuel storage and handling and is the governing document for fuel storage. When additional storage using an ISFSI is required to increase site storage capabilities, there are two ways an ISFSI may be licensed under 10 CFR 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater Than Class C Waste" (Ref. 5) as follows:



33 States have at least one ISFSI

▲ Site-Specific License (15)
● General License (39)

ALABAMA
- Browns Ferry
- Farley

ARIZONA
- Palo Verde

ARKANSAS
- Arkansas Nuclear

CALIFORNIA
- ▲ Diablo Canyon
- ▲ Rancho Seco
- San Onofre
- ▲ Humboldt Bay

COLORADO
- ▲ Fort St. Vrain

CONNECTICUT
- Haddam Neck
- Millstone

FLORIDA
- St. Lucie

GEORGIA
- Hatch

IDAHO
- ▲ DOE: TMI-2 (Fuel Debris)
- ▲ Idaho Spent Fuel Facility

ILLINOIS
- ▲ GE Morris (Wet)
- Dresden
- Quad Cities

IOWA
- Duane Arnold

LOUISIANA
- River Bend

MAINE
- Maine Yankee

MARYLAND
- ▲ Calvert Cliffs

MASSACHUSETTS
- Yankee Rowe

MICHIGAN
- Big Rock Point
- Palisades

MINNESOTA
- Monticello
- ▲ Prairie Island

MISSISSIPPI
- Grand Gulf

NEBRASKA
- Ft. Calhoun

NEW HAMPSHIRE
- Seabrook

NEW JERSEY
- Hope Creek/Salem
- Oyster Creek

NEW YORK
- Indian Point
- FitzPatrick

NORTH CAROLINA
- McGuire

OHIO
- Davis-Besse

OREGON
- ▲ Trojan

PENNSYLVANIA
- Limerick
- Susquehanna
- Peach Bottom

SOUTH CAROLINA
- ● ▲ Oconee
- ● ▲ Robinson
- Catawba

TENNESSEE
- Sequoyah

UTAH
- ▲ Private Fuel Storage

VERMONT
- Vermont Yankee

VIRGINIA
- ● ▲ Surry
- ● ▲ North Anna

WASHINGTON
- Columbia

WISCONSIN
- Point Beach

Note: Data are current as of June 2009
NRC-abbreviated unit names used
Source: U.S. Nuclear Regulatory Commission

Fig. 8. Map of location of ISFSIs in the United States.

1. A "site-specific license" authorizes operation of a storage facility at a nuclear power plant or elsewhere, subject to NRC's standard licensing requirements. To obtain a site-specific license, the utility submits a license application to NRC, and NRC performs a technical review of all the safety aspects of the proposed ISFSI. If the application is approved, NRC issues a license that is valid for 20 years. A spent-fuel storage license contains technical requirements and operating conditions (fuel specifications, cask leak testing, surveillance, and other requirements) for the ISFSI and specifies what the licensee is authorized to store at the site.

2. Alternatively, nuclear power plant operators may operate an ISFSI under a "general license." This licensing option authorizes a nuclear power plant licensee to store spent fuel in NRC-approved casks at a site that is licensed to operate a power reactor under 10 CFR 50, "Domestic Licensing of Production and Utilization Facilities" (Ref. 6). A licensee must demonstrate that the site is adequate for storing spent fuel in dry casks. The licensee must also review its security program, emergency plan, quality assurance program, training program, and radiation protection program and make any necessary changes to incorporate the ISFSI at its reactor site.

An NRC-approved cask is one that has undergone a technical review of its safety aspects and been found to be adequate to store spent fuel at a site that has been evaluated by the licensee to meet all of NRC's requirements in 10 CFR 72. NRC issues a Certificate of Compliance for a cask design to a cask vendor if the review of the design finds it technically adequate.

3.4. Is UNF Safe Where It Is—And If So, For How Long?

Used nuclear fuel storage facilities are designed to protect against sabotage, theft, and diversion. NRC sets the requirements and assesses compliance with the requirements; the licensees are responsible for providing the protection.

The U.S. Nuclear Regulatory Commission has a threat assessment program to maintain awareness of the capabilities of potential adversaries and threats to facilities, material, and activities. NRC's domestic safeguards program is focused on physically protecting and controlling UNF against sabotage, theft, and diversion. Key features of the physical protection programs for UNF storage facilities include the following:

- intrusion detection
- assessment of detection alarms to distinguish between false or nuisance alarms and actual intrusions
- response to intrusions
- off-site assistance, as necessary, from local, state, and federal agencies.

Although no studies to date have determined a required life for distributed local site storage in wet and dry storage, NRC updated (Ref. 7) its original Waste Confidence Decision.[3] On

[3] 10 CFR 51.23 [73 FR (1990)] (Ref. 8) Waste Confidence Rule sets forth the NRC policy on HLW.

September 15, 2010, NRC approved an updated waste confidence decision (Ref. 9), which states in part that "The Commission finds reasonable assurance that, if necessary, spent fuel generated in any reactor can be stored safely without significant environmental impacts for at least 60 years beyond the licensed life for operation (which may include the term of a revised or renewed license) of that reactor in a combination of storage in its spent fuel storage basin and either onsite or offsite independent spent fuel storage installations." The fuel storage can be a combination of storage in the UNF pool and dry cask storage in either on-site or off-site ISFSIs according to the updated position.

Over the last 20 years, there have been no radiation releases from UNF storage facilities that have affected public health and no known or suspected attempts to sabotage UNF casks or storage facilities within the United States.[4]

4.0 HISTORY OF USED NUCLEAR FUEL MANAGEMENT IN THE UNITED STATES

In the beginning of the nuclear age during World War II, the U.S. government operated nuclear power plants expressly for the purpose of reprocessing the UNF from the plants and isolating the plutonium for use in nuclear weapons. Highly radioactive liquid wastes were generated as a by-product of the production of plutonium for defense purposes. Shortly after the war, the United States embarked on the development of commercial nuclear power. At that time fissile materials (i.e., materials that fission, like ^{235}U) were thought to be scarce, and the nuclear community expected and assumed that fissile material in UNF from commercial nuclear power plants would be recycled.

President Eisenhower's Atoms for Peace Plan in 1953 and the creation of the Atomic Energy Commission (AEC) began the development of commercial nuclear power in earnest. Later, in the Atomic Energy Act of 1954,[5] commercial nuclear energy was made a high priority, and AEC was also assigned the responsibility for managing UNF from civilian reactors and high-level waste (HLW) resulting from the reprocessing of the UNF.

The Atomic Energy Commission pursued several paths in the development of nuclear power. Development of nuclear propulsion systems for the U.S. Navy resulted in the launch of nuclear submarines in the 1950s. As of 2010, almost all submarines and aircraft carriers in the U.S. Navy are nuclear powered. AEC also pursued breeder reactor development because of the widely shared belief that UNF from nuclear reactors should be reprocessed and the recovered plutonium should be used to fuel breeder reactors. Experimental Breeder Reactor I and Experimental Breeder Reactor II (EBR-II) were built in Idaho and started operations. Breeder reactors are designed to produce one or more ^{239}Pu atoms for each ^{235}U atom fissioned. Because ^{239}Pu is fissile and can act much like ^{235}U, breeder reactors produce more fissile material than they consume. Breeder reactors were expected to help build the inventory of fissile material needed to fuel reactors. A third path AEC followed was the development of light water reactors (LWRs), which were modeled after the successful Naval propulsion reactors. LWRs were the ones that prevailed, and almost all commercial reactors in nuclear power plants that have been

[4]Institute of Nuclear Power Operations Plant Information Center Search of Event History for all U.S. plants.
[5]Atomic Energy Act of 1954, 42 U.S.C. § 2011 et seq.

built in the United States are LWRs. An exception is the Fermi-I plant, which was a breeder reactor and sustained a fuel-damaging accident shortly after it went into operation (Ref. 10).

In anticipation of the large quantities of liquid HLW from defense activities, as well as the UNFs from civilian nuclear reactors, in 1955, AEC asked the National Academy of Sciences (NAS) to formulate the scientific basis for establishing a U.S. nuclear waste disposal program.

The National Academy of Sciences considered possibilities of disposal of HLW in various geologic formations within the United States, and in 1957, the NAS National Research Council reported "… that radioactive waste can be disposed of safely in a variety of ways and at a large number of sites in the United States." NAS also indicated that "…the most promising method of disposal of high-level waste…is in salt deposits" (Ref. 11).

Following the NAS report, AEC's efforts to identify a location for HLW disposal were directed toward U.S. salt deposits. Investigations of potential host rocks for disposal of radioactive waste between 1962 and 1972 eventually led to the selection of an abandoned salt mine in Lyons, Kansas. However, technical problems were later uncovered, namely, the discovery of old abandoned wells drilled through the deposit, which raised serious concerns about the potential safety of the site. In addition, there was intense local opposition to developing the abandoned mine as a geologic repository. These issues led to the cancellation of the project and led AEC to reevaluate its strategy for geologic disposal.

Between 1972 and 1974, AEC identified new concepts and began work on alternative methods of disposal. Various concepts were considered including deep geologic disposal on land in mined repositories or deep boreholes, under the ocean, in polar ice sheets, or in space. Another concept considered was transmutation, which is conversion of the radioactive wastes into materials that either are not radioactive or have short half-lives and will soon decay to material that is not radioactive. These concepts are summarized in Vol. 1 of the U.S. Department of Energy (DOE) "Final Environmental Impact Statement: Management of Commercially Generated Radioactive Waste" (Ref. 12). However, when this evaluation was completed, disposal in a mined geologic repository within the contiguous United States remained the preferred option.

The Atomic Energy Commission also proposed to develop a long-term (100-year) retrievable surface storage facility (RSSF) for HLW in 1972. This approach would have allowed the federal government to meet its obligation to accept commercial HLW (i.e., UNF) while allowing more time for work on a repository. The RSSF proposal was subsequently dropped by AEC's successor, the Energy Research and Development Administration (ERDA), in 1975, after environmental groups and the U.S. Environmental Protection Agency (EPA) objected that economic factors might turn the storage facility into a permanent repository. This social concern that long-term storage will become a de facto disposal facility has remained an objection to developing a federal interim storage facility before a permanent disposal system is available.

After abandoning the RSSF proposal, ERDA turned again to development of a permanent disposal system. ERDA initiated a process to find sites for geologic repositories for HLW in several states. However, local opposition in combination with technical issues stalled the process.

In parallel, studies of a bedded salt site in southeastern New Mexico for disposal of a different type of radioactive waste, TRU waste, progressed with strong local support. This site—the Waste Isolation Pilot Plant (WIPP)—was authorized by Congress in 1979 to dispose of defense-related TRU waste. Although TRU waste is not considered as hazardous as HLW, long-term isolation in a deep geologic repository is still required. WIPP was ultimately opened in 1999 and has been operating smoothly since then.

By the 1970s, commercial nuclear energy was expanding rapidly with the support of the U.S. government. The government assumed most financial liabilities for potential catastrophic nuclear accidents through the Price Anderson Act.[6] The federal government also was responsible for uranium enrichment, i.e., increasing the concentration of ^{235}U from the 0.71% found in nature to >3% needed for reactor fuel. The commercial nuclear industry was planning to reprocess and recycle UNF using the aqueous process employed by AEC in its plutonium production plants.

However, in 1974, India conducted a nuclear detonation that used plutonium from reprocessed fuel, which drastically changed the U.S. government's view on reprocessing. President Carter in 1977 banned commercial reprocessing in the United States and attempted to stop the development of breeder reactors (which was ultimately stopped by Congress in 1983). Although President Reagan reversed the no-reprocessing policy in 1981, the expense and political uncertainty of reprocessing prevented any significant commercial fuel reprocessing activity in the United States. The urgency of developing reprocessing capability was further reduced by the discovery of substantial and widespread uranium deposits.

Since the United States was not reprocessing commercial fuel, the expectations of the technical community about the form of wastes requiring disposal changed. It was originally anticipated that UNF would be reprocessed to recover plutonium and uranium for reuse, leaving only the residual wastes for disposal. Direct disposal of UNF now became the center of attention for waste management.

In 1974, AEC was divided into two separate agencies. The regulatory function became NRC, a separate and independent agency to regulate commercial nuclear facilities. The remainder of AEC was joined with parts of other federal departments and agencies responsible for different aspects of energy programs to create ERDA. In 1976, ERDA created the Nuclear Waste Terminal Storage (NWTS) program, which was the direct predecessor to the current HLW management program.

The NWTS program studied a variety of rock types and planned to develop six repositories, two in salt formations and four in other host rocks, e.g., shale, basalt, or crystalline rocks. The number of repositories was based on predictions of future growth of nuclear power and the desire to distribute the burden of disposal among several states. ERDA began investigations in a number of states and also began a search for potential sites on federal land, especially where previous activities had been conducted using radioactive materials, including the Nevada Test Site and the Hanford Reservation in Washington.

[6] PL 85-256 (42 U.S.C. 2012 et seq.)

To unify government activities related to energy, DOE was formed in 1977. The new department was formed from ERDA, the Federal Energy Administration, the Federal Power Commission, and several related programs from other government agencies.

In 1979, an Interagency Review Group recommended that the United States develop at least two repositories in different regions of the country. Candidate sites should be located in a variety of host rocks, and the development of repositories should proceed in a technically conservative step-by-step manner. Partly in response to this recommendation, the Office of Nuclear Waste Management of DOE and the U.S. Geological Survey of the U.S. Department of the Interior released jointly a draft plan for disposal of radioactive waste in a mined repository (Ref. 13). The plan was written by 17 scientists from five organizations and concluded that there was a need to direct research away from generic plans to characterize four or five specific sites.

In 1980, President Carter announced a comprehensive waste management program that included an effective role for state and local governments. Since the disposal facility for HLW would be a large, federally funded project with a potential for environmental impact, an Environmental Impact Statement (EIS) was required. In 1981, in its Record of Decision for the EIS, DOE selected geologic repositories as the preferred disposal method, based on the comparison of disposal alternatives in the 1980 DOE EIS (Ref. 12). During 1981 and 1982, DOE developed criteria for mined geologic repositories for disposing of nuclear waste consistent with the listed criteria then available from existing sources (Refs. 12 and 14 through 17).

The Nuclear Waste Policy Act of 1982 (NWPA)[7] established the current geologic disposal program including a comprehensive national policy for management and disposal of UNF and HLW. The NWPA remains, with amendments, the statutory framework for the U.S. HLW disposal program and partitioned the responsibility for waste disposal among DOE, NRC, and EPA. DOE was given the responsibility to implement the NWPA, NRC was to develop the implementing regulations, and EPA was to develop the standards that repositories must meet to ensure public and worker health and safety. The NWPA also created the Office of Civilian Radioactive Waste Management (OCRWM) within DOE to oversee disposal of UNF. Nuclear waste generators, i.e., nuclear power–producing utilities, are obligated to pay a fee ($0.001/kW·h) for which in return they were given a contract with a start date of 1998 for removal of their UNF for disposal.

The NWPA required the development of two repositories and limited the amount of waste to be disposed of in the first repository to an equivalent of 70,000 tonnes of heavy metal until the second repository started operation.

The NWPA prescribed a process for site selection, which required DOE to nominate at least five sites and screen down to three for actual site characterization. DOE OCRWM identified nine potentially acceptable sites, including Yucca Mountain. The nine sites had three different rock types: salt, basalt, and tuff.

In 1984, Draft Environmental Assessments were issued for all nine sites. In 1986, the U.S. Secretary of Energy nominated five sites as suitable for characterization for the first repository and recommended three of the sites to President Reagan for approval for site characterization.

[7]Nuclear Waste Policy Act, 42 U.S.C. 10101 et seq.

President Reagan approved the following sites: Yucca Mountain, Nevada; Deaf Smith County, Texas; and the Hanford Site, Washington. DOE concluded that this particular order of preference provided the maximum diversity of geological and hydrological settings. DOE also completed the Multi Attribute Performance Study, which ranked the technical aspects of the sites and concluded that all the sites had good scientific bases for being potential repository sites.

In 1985, DOE also began crystalline rock investigations to identify sites for a second repository. DOE pursued a consultation process with states and communities in the 17 states that had promising crystalline rock characteristics for a repository. Considerable public and political backlash resulted. In 1986, the U.S. Secretary of Energy recommended 12 potential areas in seven states for the second repository but postponed site-specific work for the second repository because of budget constraints and decreased estimates of the amount of UNF requiring disposal.

The NWPA also required DOE to explore and potentially recommend a monitored retrievable storage (MRS) facility for UNF. In 1986, DOE recommended to Congress the former Clinch River reactor site near Oak Ridge, Tennessee, for an MRS. However, there were state-level objections. Although the local community of Oak Ridge endorsed this recommendation (subject to conditions), the state government opposed it strongly.

Motivated in part by the state-level opposition to repository siting programs and in part by concern about rising program costs, Congress reassessed the NWPA and passed the Nuclear Waste Policy Amendments Act of 1987 (NWPAA).[8] Congress redirected the DOE to focus its site characterization activities only at Yucca Mountain, Nevada, and to report on the need for a second repository on or after January 1, 2007, but no later than January 1, 2010. The decision to abandon what was arguably a defensible site selection process in the NWPA had the predictable effect of spurring opposition from the State of Nevada.

In addition, DOE's proposal to locate an MRS facility at the Clinch River site in Oak Ridge, Tennessee, with two alternative sites in Tennessee, was nullified by the NWPAA, which authorized the MRS but added linkages that prevented the MRS from being constructed until construction of the first repository was authorized.[8] A nuclear waste negotiator was also authorized to find a volunteer state or American Indian tribe for a geologic repository or MRS site. The amended law provided funding for states or tribes that were willing to seriously explore the possibility of hosting an MRS or repository. The primary focus was on finding a volunteer MRS host in the hope that with a willing volunteer, restrictive linkages could be relaxed. Some thought this was the only way that DOE could meet its contractual obligation for system operations by 1998. No volunteer states came forward for grants to study possible MRS sites, and only three American Indian tribes applied for the funding. Unfortunately, Congress in 1994 terminated this effort by deleting DOE funding for it. At this point, it became obvious that DOE could not meet its contractual obligation to nuclear utilities to remove UNF from their sites by 1998, thus setting up the multi-billion-dollar legal liabilities that exist today. These liabilities result from nuclear utilities having to pay for the storage of UNF at their plant sites even though, collectively, they have already paid billions of dollars into the Nuclear Waste Fund to pay for DOE's program to dispose of UNF.

[8]Nuclear Waste Policy Amendments Act of 1987, 42 U.S.C. 10172 et seq.

Fig. 9. Entrance to the research facility at Yucca Mountain. (Courtesy of U.S. Nuclear Regulatory Commission)

On February 14, 2002, the U.S. Secretary of Energy recommended the Yucca Mountain site to President Bush as suitable for further development. Following the process laid out in the NWPA, the State of Nevada disapproved the site, and Congress then voted in July 2002 to approve the Yucca Mountain site for development as the nation's first deep geologic repository for UNF and HLW. The recommendation was soon followed by President Bush's approval.

Although there were delays, in June 2008 DOE finally submitted the license application to NRC for the construction of a repository at Yucca Mountain. The application was accepted by NRC for review in September 2008. Figure 9 is a photograph of the entrance to the research facility at Yucca Mountain.

Soon after taking office in January 2009, the Administration of President Obama indicated that it would end the Yucca Mountain project, as a matter of policy, and announced that a blue ribbon commission would be convened to perform a comprehensive review of policies for managing UNF and HLW. On January 29, 2010, the 15-member Blue Ribbon Commission on America's Nuclear Future (BRC) was established to conduct the review, including all alternatives for the storage, processing, and disposal of civilian and defense UNF and HLW. Furthermore, the BRC was asked to evaluate advanced fuel cycle technologies that would optimize energy recovery, resource utilization, and the minimization of materials derived from nuclear activities in a manner consistent with U.S. nonproliferation goals. The BRC is directed to provide an interim report to the U.S. Secretary of Energy by August 2011 and the final report by February 2012.

In March 2010, DOE notified NRC of its intent to withdraw its license application for Yucca Mountain with prejudice (i.e., it will not be resubmitted in the future) and has since notified DOE program staff and contractors to terminate the work. The states of Washington and South Carolina have sued to stop the termination in federal court, and an expedited hearing has been granted. Meanwhile, NRC's Atomic Safety Licensing Board has ruled that the license application cannot be withdrawn with prejudice since the NWPAA requires the license application for a deep geologic repository at Yucca Mountain if the site is recommended and accepted.

At the time the Report was prepared, the fate of the Yucca Mountain repository was uncertain.

While it was managing programs to locate and build facilities to first store and then permanently dispose of UNF and HLW, DOE was also pursuing programs that would reduce the volume and toxicity of the waste to be disposed of. Those programs had the additional goal of reducing

proliferation of material that could be used in nuclear weapons. The first such program was the Advanced Fuel Cycle Initiative (AFCI), which began under President Clinton.

Under the AFCI program, a suite of aqueous separation processes based on uranium extraction (UREX) was developed. UREX consists of a family of processes where specific groups of radionuclides that would contribute to the heat load or radiotoxicity of HLW are separated and removed. In addition, in UREX, pure plutonium that could be attractive to terrorists is never isolated from other elements. Rather, plutonium is separated as a group with other minor actinides. The UREX process is a modification of the plutoniun-uranium extraction (PUREX) process, which was developed more than 50 years ago by AEC to reprocess UNF from government-owned reactors to isolate plutonium. The PUREX process is used in France and a few other countries to reprocess UNF from commercial nuclear power plants and make MOX fuel.

In addition to the aqueous processes, DOE researchers studied pyroprocessing, a nonaqueous process conducted in molten chloride salts that make use of electrochemical dissolution. Pyroprocessing is currently not used commercially but has been the subject of much research and development. Pyroprocessing technology was initially used as a demonstration project to treat the sodium-bonded UNF from EBR-II. Pyroprocessing is most suitable for metallic UNF but can also process oxide fuel if additional chemical steps are included.

New fuel made from reprocessed uranium and plutonium—so-called MOX fuels—can be recycled in existing commercial LWRs, which is being done in France. The recycled fuels are put back into a reactor to generate more electricity rather than being sent to a repository. After the fuel has been recycled once, however, the buildup of undesirable isotopes makes further recycling less attractive.

For multiple recycling of UNF, various options have been evaluated by DOE, including recycling in high-burnup, gas-cooled reactors; reactors fueled by thorium and plutonium; and fast reactors. Fast reactors are different from LWRs in that they are designed to transmute some of the undesirable isotopes into fissile material while generating electricity from the fissile material originally in the fuel. The term "fast" refers to the speed of the neutrons in the reactor. Neutrons produced during fission are very fast. LWRs are designed to slow the neutrons down; fast reactors are not. Fast neutrons are needed for transmutation.

The goal of recycling is to remove the uranium, plutonium, and a few other selected long-lived radionuclides to be put back into a reactor for reuse after each cycle, thus minimizing the volume and toxicity of waste sent to the repository. However, with current technology, long-lived radionuclides such as ^{129}I and ^{99}Tc are very difficult to remove and cannot practically be recycled in reactors. Thus, for the foreseeable future there will be residual nuclear wastes that will need to be permanently disposed of in a repository.

In 2006, during the Administration of President Bush, a program to expand nuclear energy globally while preventing nuclear proliferation was initiated by DOE. The program was called the Global Nuclear Energy Partnership (GNEP) and built upon the AFCI. Under GNEP, the United States worked with more than 20 countries to build a system by which countries with current nuclear fuel enrichment and reprocessing capability would provide those services to other countries that wanted to use nuclear power but could not afford to develop the expensive supporting fuel cycle

facilities. Keeping the fuel cycle facilities in countries that already have enrichment and reprocessing capabilities also helps to limit proliferation of nuclear weapons materials.

4.1. Transportation of UNF

Transportation of UNF has been an integral part of the UNF management system throughout the history of the nuclear industry. In the United States and worldwide, there has been significant experience with moving UNF and other radioactive wastes from the place they were generated to a storage, treatment, or disposal facility.

Transportation of UNF and other highly radioactive materials has been safely performed worldwide for >60 years. Thousands of tons of UNF and other similar highly radioactive waste have been safely transported by rail, truck, and ship over tens of millions of miles without any accident that has breached or leaked radioactive material from the highly sophisticated packaging. For example, DOE's WIPP has safely transported by truck more than 8,000 shipments with a total distance traveled of more than 10 million miles. Transportation of UNF to the La Hague reprocessing facility in France and Sellafield Ltd's reprocessing facility in the United Kingdom has a similar safety record. Within the United States, more than 3,000 shipments of UNF have traveled safely more than 1.7 million miles without release of the radioactive cargo. The shipping containers for UNF are constructed of many layers of steel and lead and are designed to withstand severe accident conditions involving crashes, fires, and submersion. Numerous scientific studies have evaluated safety of UNF transport and have confirmed that public health and safety are well protected (Refs. 18 through 21).

Used nuclear fuel transportation systems are required to take substantial security and safeguards precautions to ensure that all shipments are properly protected by very robust container designs, by security escorts, and other classified security precautions. Comprehensive international and NRC regulations are the basis for the integration of protections provided by the shipping cask design, transport method, and private and governmental security forces. Extensive protection plans coupled with sophisticated communications and advanced planning with federal, state, and local agencies provide substantial assurance that public health and environmental protections are provided for under all plausible circumstances.

Although the safety and security aspects of UNF transportation are well documented (Ref. 22), the public is generally unaware of them. A substantial effort to inform local officials and the public about the transportation of radioactive materials was made prior to radioactive shipments to WIPP, and similar efforts should be made prior to initiating a new major UNF shipping program.

5.0 USED NUCLEAR FUEL MANAGEMENT POLICIES IN OTHER COUNTRIES

Outside the United States, the nations with one or more currently operating nuclear power plants have taken different paths to nuclear waste management and are at various stages of development. France, Japan, Russia, and the United Kingdom have constructed and operate commercial-scale nuclear fuel reprocessing facilities both to manage their domestic UNF stream and to provide nuclear fuel cycle services to other customer nations. India, China, and South Korea have publicly announced their intention to pursue nuclear fuel reprocessing but have not

yet constructed commercial-scale facilities. Other nations are considering reprocessing but have not made a final decision at this time. These include Taiwan, Brazil, and South Africa.

Other than a few countries (e.g., Iran) that have agreed to transport their UNF to a nation with reprocessing capabilities, nations with nuclear plants must assume responsibility for disposal of their UNF. Among these nations, whether reprocessing or a once-through fuel cycle is employed, a general consensus has emerged that deep geologic repositories are the safest, most desirable method to dispose of UNF or the HLW resulting from reprocessing of UNF.

Sweden is perhaps furthest along in its efforts to develop a repository and could serve as a case study for repository siting best practices. The Swedish Nuclear Fuel and Waste Management Company (SKB), which was created by the nation's utilities, conducted a competition between two volunteer communities, Forsmark and Oskarshamn, to host the repository. Each community was guaranteed a specific level of investment by SKB, regardless of whether it was ultimately chosen as the repository site. The decision-making process was based solely on the favorability of the local geology; politics did not play a role. In 2009, Forsmark was chosen as the host community; the decision was based primarily on the quality of its subsurface bedrock. At the time of SKB's selection, public support for the proposed repository in both candidate towns exceeded 80%. Construction on the repository is slated to begin in 2016 with operations commencing sometime between 2022 and 2024.

In addition to Sweden, Finland and France both have "characterization facilities" or "laboratories" that are widely understood by the local public to be the precursors to an HLW repository. Construction on operating repositories at these locations is slated to begin in this decade, with start-up occurring by 2030.

Elsewhere in Europe, 14 countries, including Austria (which has no nuclear plants), Italy (which has no operating nuclear plants), the Czech Republic, and Ireland (which has no nuclear plants) have established a working group to consider the creation of a European Repository Development Organisation that would build a multinational facility to store UNF or HLW.

Given the technical, political, and cultural context in which each nation's HLW policies are developed and implemented, it is difficult to draw overarching conclusions about the elements of success or failure. Table I shows the plans for UNF management in most of the nations using nuclear power.

TABLE I

HLW Management Strategies Around the Globe

Country	Policy	Facilities and Progress Toward Final Repositories
Belgium	Reprocessing	• Central waste storage at Dessel • Underground laboratory established 1984 at Mol • Construction of repository to begin about 2035
Canada	Direct disposal	• Nuclear Waste Management Organisation set up 2002 • Deep geological repository confirmed as policy, retrievable • Repository site search from 2009, planned for use 2025
China	Reprocessing	• Central UNF storage at LanZhou • Repository site selection to be completed by 2020 • Underground research laboratory from 2020, disposal from 2050
Finland	Direct disposal	• Program start 1983, two UNF storages in operation • Posiva Oy set up 1995 to implement deep geological disposal • Underground research laboratory Onkalo under construction • Repository planned from this, near Olkiluoto, open in 2020
France	Reprocessing	• Underground rock laboratories in clay and granite • Parliamentary confirmation in 2006 of deep geological disposal, containers to be retrievable and policy "reversible" • Bure clay deposit is likely repository site to be licensed 2015, operating 2025
Germany	Reprocessing but moving to direct disposal	• Repository planning started 1973 • UNF storage at Ahaus and Gorleben salt dome • Geological repository may be operational at Gorleben after 2025
India	Reprocessing	• Research on deep geological disposal for HLW
Japan	Reprocessing	• Underground laboratory at Mizunami in granite since 1996 • HLW storage facility at Rokkasho since 1995 • HLW storage approved for Mutsu from 2010 • NUMO set up 2000, site selection for deep geological repository under way to 2025, operation from 2035, retrievable

(Continued)

Table I (Continued)

Country	Policy	Facilities and Progress Toward Final Repositories
Russia	Reprocessing	• Underground laboratory in granite or gneiss in Krasnoyarsk region from 2015, may evolve into repository • Sites for final repository under investigation on Kola peninsula • Various interim storage facilities in operation
South Korea	Direct disposal	• Waste program confirmed 1998 • Central interim storage planned from 2016
Spain	Direct disposal	• ENRESA established 1984, its plan accepted 1999 • Central interim storage probably at Trillo from 2010 • Research on deep geological disposal, decision after 2010
Sweden	Direct disposal	• Central UNF storage facility – CLAB – in operation since 1985 • Underground research laboratory at Aspo for HLW repository • Forsmark site selected for repository (volunteered location)
Switzerland	Reprocessing	• Central interim storage for HLW at Zwilag since 2001 • Central LLW and ILW storages operating since 1993[1] • Underground research laboratory for HLW repository at Grimsel since 1983 • Deep repository by 2020, containers to be retrievable
United Kingdom	Reprocessing	• LLW repository in operation since 1959 • HLW from reprocessing is vitrified and stored at Sellafield • Repository location to be on basis of community agreement • New NDA subsidiary to progress geological disposal
United States	Direct disposal but reconsidering	• DOE responsible for UNF from 1998, $32 billion waste fund • Considerable research and development on repository in welded tuffs at Yucca Mountain, Nevada • 2002 decision that geological repository be at Yucca Mountain was countered politically in 2009

[1]LLW: low-level waste; ILW: intermediate-level waste.
Source: World Nuclear Association.

PART II
OPTIONS FOR USED NUCLEAR FUEL MANAGEMENT FOR THE NEXT CENTURY

1.0 INTRODUCTION

Part II of "Report of the ANS President's Special Committee on Used Nuclear Fuel Management Options" (the Report) discusses the management options for used nuclear fuel (UNF) over the next century. Section 2.0 provides a summary of the UNF storage options for the coming century, including those currently in use. "Storage" refers to where the UNF is kept prior to final disposal, in the case of the once-through fuel cycle, or prior to reprocessing. Section 2.0 also discusses the factors that should be taken into account when selecting storage options. These factors are numerous and include technical, economic, environmental, social, and political considerations. Section 3.0 describes the options for the disposal of UNF, which are essentially direct disposal of the UNF or reprocessing/recycling with disposal of the remaining high-level waste (HLW). The section will provide a brief description of the various reprocessing methods being considered. In addition, Sec. 3.0 identifies factors that are likely to be important when deciding which disposal option to select.

The bulk of Part II is devoted to a discussion of two bounding scenarios for nuclear power in the United States over the next century and the associated UNF management options. Scenario 1, the no-growth scenario, presumes that the nuclear power plants currently operating in the United States will continue to run until their licenses expire at which time they will be shut down, and no new nuclear power plants will be built. Scenario 2, the growth scenario, presumes that nuclear power provides one-half of the increased demand for electricity in the United States between 2010 and 2100. These scenarios are described in Sec. 4.0. For each scenario, the options for management of UNF will be discussed. While the role nuclear power will play in generating electricity for the United States over the rest of the 21st century cannot be predicted with certainty, it will almost certainly lie between the two bounding scenarios, and it is not likely to require UNF management options in addition to those identified for the two scenarios.

2.0 OPTIONS FOR STORAGE OF USED NUCLEAR FUEL

2.1. Description of Options for Storage of UNF

When most U.S. commercial nuclear power plants were designed and constructed, in the 1960s and 1970s, plans for storage of UNF were thought to be complete. Each plant had a storage pool for its UNF. The pools were not designed to store all of the UNF nuclear power plants would discharge over their 40-year lifetimes. It was expected that the UNF would be cooled for several years in the on-site storage pools and then sent to a reprocessing facility where the uranium and plutonium would be recycled. In 1976, reprocessing was suspended, and in 1977, it was banned. Although that decision was overturned in 1981 and reprocessing is now allowed, the U.S. government has adopted a once-through fuel cycle with direct disposal of UNF. This policy was

codified into law with the passage of the Nuclear Waste Policy Act of 1982 (NWPA) as amended in the Nuclear Waste Policy Amendments Act of 1987.

The NWPA tasked the U.S. Department of Energy (DOE) with the design, license, and construction of a geologic repository at Yucca Mountain in Nevada for the direct disposal of UNF. It also required DOE to begin taking UNF from U.S. utilities in 1998. For a number of reasons, the project was delayed, and in 1995, DOE announced that it would not be able to open the Yucca Mountain disposal facility in 1998. By the late 1990s, some utilities had already exceeded the capacity of their UNF pools and had begun using casks to store UNF at their reactor sites. The UNF storage pools and the casks used to store UNF on site are described in Part I of the Report, "Current Status and History of Used Nuclear Fuel Management." Both storage options will be available and are likely to be widely used over the coming century. However, they are not likely to be the only options.

As the Yucca Mountain project was delayed, utilities began exploring additional options for storage of UNF including expanding on-site storage capabilities and developing interim consolidated UNF storage capabilities away from the reactor sites. In the future, there could be one centralized UNF storage facility or several regional facilities. A consolidated UNF storage facility would be likely to accommodate UNF from several nuclear power plants in dry storage casks.

The most developed interim consolidated UNF storage project is Private Fuel Storage, LLC (PFS), which proposed to build a storage site on the Goshute Indian Reservation in Utah. PFS obtained a 20-year license from the U.S. Nuclear Regulatory Commission (NRC) on February 21, 2006, for temporary aboveground storage of up to 44,000 tons of UNF from U.S. commercial nuclear power plants. NRC placed several conditions on the construction authorization. It required PFS to arrange for adequate funding and obtain the necessary approvals from other agencies, including the Bureau of Land Management, the Bureau of Indian Affairs, and the Surface Transportation Board. PFS has so far been unable to obtain the necessary permits and approvals from the other agencies to transport UNF to the Goshute Indian Reservation.

2.2 Factors to Be Considered When Selecting Storage Options

This section identifies factors that are likely to be considered when developing UNF storage systems over the next century. It should be noted that these factors are often interrelated and cannot be considered independent of each other, thus complicating the selection of a storage option.

2.2.A. Safety and Security, Including Environmental Safety

It is probably easier to protect one site from a terrorist attack than it is to protect many smaller sites. On the other hand, storage facilities at reactors are smaller and perhaps less attractive targets. It would be logical to locate the consolidated interim storage (CIS) site in an area of low population and not beside a major water supply. (Nuclear power plants are near water supplies to provide cooling.) Therefore, consolidating from existing reactor locations to the new CIS location would reduce the number of Americans living within close proximity [50 miles (80.47 km)] to UNF and reduce the risk to large water supplies. It is also more economical to monitor and secure one large facility rather than multiple smaller ones unless the cost of monitoring and

protecting the UNF storage on site is an integral part of the cost of monitoring and protecting the nuclear power plant. As the amount of UNF stored at reactor sites increases, the balance between the options of on-site storage and consolidated storage may shift. In addition, safety and security associated with transporting the UNF from the reactor site to CIS would need to be considered. Other countries have used CIS sites, and information about safety and security arrangements for those sites may be useful when making decisions about storage options in the United States.

2.2.B. National Parity

It may be necessary to establish multiple regional CIS facilities at the same time to share responsibility for storing UNF. For example, one could envision having three CIS facilities in the general geographic regions of Southeast, Northeast, and West. Having three CIS facilities in regions where nuclear power plants are located would also minimize the distance UNF would need to be transported to a CIS facility.

2.2.C. Stranded Sites

One of the more urgent needs is to address sites where reactors have been shut down and decommissioned but UNF remains. When UNF is on a site with an operating reactor, there is a trained security force as well as nearby emergency responders. It is very costly to maintain a robust level of safety and security oversight if there is no ongoing business at the site.

2.2.D. Licensing and Regulatory Issues

A CIS facility would be designed, licensed, constructed, and operated in accordance with the NRC's site-specific licensing provisions as provided in 10 CFR 72 (Ref. 5).

Under current regulations [10 CFR 72.42 (Ref. 23)], the initial license term for an independent spent fuel storage installation (ISFSI) with a general license may not exceed 20 years. The license may be renewed.

A one-step licensing process is utilized in 10 CFR 72. The application for a site-specific license must contain general and financial information about the applicant, proposed technical specifications, a Safety Analysis Report (SAR), an emergency plan, an ISFSI decommissioning plan, a security plan, and an Environmental Report. The SAR presents a description and safety assessment of the proposed site and ISFSI structures, a plan for the conduct of operation, general design criteria, an emergency plan, a description of the quality assurance program, a description of a detailed physical protection plan, and a description of the decommissioning plan. After NRC reviews a license application for completeness, notice of the proposed action and opportunity for public hearing is published in the Federal Register.

2.2.E. Construction and Operation Costs

Based on a May 2009 Electric Power Research Institute (EPRI) study (Ref. 24), a 40,000-tonne CIS facility with capacity for 4000 storage casks would cost approximately $490 million, with a decommissioning cost of $230 million.

Staffing costs are estimated to be $8 million/year during periods of loading or unloading, with a staff of 85 full-time employees (FTEs), and $3.7 million/year during caretaker periods, with a staff of 40 FTEs. The differences in staffing are related primarily to the cask throughput for the facility. This throughput will drive the number of maintenance and equipment operations staff as well as the number of staff needed to support at-reactor loading.

Any cost savings that would result from removing storage casks from the nuclear power plant site have not been estimated but would need to be considered. In addition, the cost of transporting the UNF to the CIS facility would have to be considered.

2.2.F. Cost to the Federal Government and the Taxpayer

Today, the U.S. government is in partial breach of contract with many U.S. utilities for failure to perform under the Spent Nuclear Fuel Standard Contracts and consistent with the NWPA, which required DOE to begin taking possession of commercial UNF in January 1998. The District of Columbia Circuit Court ruled in favor of utilities and directed the U.S. government to compensate utilities. Payments for the incremental storage costs by utilities (e.g., reracking and dry cask storage) resulting from DOE's failure to perform are funded from the U.S. Treasury Judgment Fund, not the Nuclear Waste Fund.

The U.S. Department of Energy estimated the potential U.S. government liability for failure to perform under the standard contracts to be $12.3 billion, if DOE were able to start receiving UNF in 2020 and receive it at a rate that ramps to 3,000 tonnes/year (Ref. 25).

2.2.G. Risk-Benefits Analysis by the Host Community and Surrounding Area

The host community and surrounding area are likely to demand assurances that an interim storage site will not become a de facto permanent storage site. They may want to see substantial progress on recycling and permanent disposal facilities before the CIS facility is constructed. In addition, the community will want assurances about the CIS's safety. In some cases, training, equipment, and facilities for first responders and medical personnel may be requested. Increased truck traffic could be a concern and might have to be addressed by providing funds for traffic management systems and road construction and maintenance. Other factors that will be important in the risk-benefits analysis are jobs and economic benefits to the community such as payments in lieu of taxes and/or fees.

For many communities, jobs will be very important. As is noted above, a CIS facility does not create a large number of jobs. A proposal to package the CIS facility with a related project requiring more employees, such as a recycling facility and/or a large research and development facility, might be offered.

2.2.H. Host State and Community Support

State and local support for a UNF storage facility is critical if the facility is to be constructed in a timely manner and operated without interruption. That support is important for continued on-site storage at an existing power plant or a new consolidated storage facility. It is important whether the storage site location is mandated by law or selected from a group of volunteer sites. Key to establishing and maintaining local, regional, and state support for a

site are effective communications and interaction with the public, local government, regional institutions, and state government to demonstrate respect, and to build trust and confidence. Building a partnership with local and regional institutions typically includes providing resources to enhance first-responder capability, roads, and other infrastructure that could be required to support the CIS facility. It is important that the local communities, surrounding regions, and states receive a substantial share of the monetary and noneconomic benefits provided to host a CIS facility. If benefits are not shared, support from the host community may be negated by opposition from the surrounding regions, which is important, in part, because the UNF must be transported through those regions to reach the storage facility.

2.2.I. Support from the General Public

While support for a storage facility from the host community and surrounding region is widely recognized as being a factor in selection of a storage location, the level of support from the public for the general approach to storage is also a consideration. Management of UNF is a national issue. If the general public does not support the overall approach to UNF storage, it is likely to be more difficult to build a storage facility.

2.2.J. Federal or Private Management

It is important that the storage facilities and transportation system be managed as efficiently as possible. In the past, DOE has sought private management of those systems with oversight by federal agencies. If the systems are operated by a private corporation, the financial arrangements among the federal, state, and local governments and the private corporation will have to be defined as will the federal government's responsibility for overseeing the operations. Congress may consider whether federal or private management is preferred when it addresses UNF management options.

In Position Statement 22, "Creation of an Independent Entity to Manage U.S. Used Nuclear Fuel," issued in November 2009, the American Nuclear Society stated that an independent entity overseeing UNF management "should possess the following characteristics:

- access to nuclear waste fees, not subject to annual congressional appropriations;
- governance that promotes long-range planning and continuity of leadership;
- authority to provide consolidated interim storage, nuclear fuel recycling, and geologic disposal consistent with laws, policies, and regulations;
- authority to support U.S. national security and nonproliferation objectives on a full-cost reimbursement basis;
- fully subject to U.S. Nuclear Regulatory Commission and U.S. Environmental Protection Agency regulations."

2.2.K. National Policy on UNF Management

A long-term, stable national policy on UNF management will be critical for timely decisions about UNF storage options. If the policy related to storage facilities and transportation, treatment, and disposal of UNF is perceived to be in a state of flux, potential host communities and states will be reluctant to commit to accept a storage facility. Further, without a stable national policy, industry and financial institutions will be hesitant to invest in UNF management facilities.

3.0. SUMMARY OF OPTIONS FOR ULTIMATE DISPOSITION OF USED NUCLEAR FUEL

3.1. Introduction

Three options for ultimate disposition of UNF are considered in this section:

option 1: the once-through fuel cycle in which UNF from the reactor is permanently disposed of underground

option 2: limited reprocessing and recycling of UNF into light water reactors (LWRs), the type of reactor currently operated in the United States

option 3: full recycling of UNF into fast reactors, which have been built on an experimental basis and could be ready for large-scale deployment in the mid-21st century.

Options 2 and 3 both include the permanent disposal of reprocessing wastes.

3.2. Option 1: Once-Through Fuel Cycle and Direct Disposal of UNF

In the once-through fuel cycle, after the fuel is used in a nuclear reactor, it is discharged from the reactor and cooled for a few years in the UNF pool on site; then, it is supposed to be disposed of permanently. Deep geologic disposal has been the proposed method of permanent disposal in the United States and internationally. Two different types of geologic disposal facility—central repositories and local boreholes—are currently considered as options for permanent disposal of UNF. These options are discussed further below. Other direct disposal options may be considered in the future, but the general consensus of countries with nuclear power programs around the world is that direct disposal will be in an underground facility.

3.2.A. Central Geologic Repositories

In 1956, the National Academy of Sciences (NAS) performed a study on permanent disposal of HLW and concluded that a mined geologic repository would be the most suitable method to isolate the waste. Other countries agree. However, up to this point, not a single country has succeeded in building such a facility for UNF or HLW. It should be noted that the United States has built and operates a geologic repository for transuranic (TRU) waste and that several countries have built underground laboratories to conduct research related to repositories.

It is important to be able to predict the performance of a repository (i.e., its ability to confine the radioactive materials) over long periods of time. The performance assessment requires evaluation of all components of the repository under future conditions and events that might allow radioactive material to be released into the environment. In the current U.S. Environmental Protection Agency (EPA) environmental standard, the performance assessment needs to be calculated for up to one million years after repository closure.

An enormous number of scientific and engineering studies on geologic repositories have been conducted in the United States and internationally. The geologic media most frequently studied include the following:

- unsaturated tuff, i.e., Yucca Mountain
- salt, i.e., Waste Isolation Pilot Plant
- granite, i.e., Forsmark in Sweden
- clay, i.e., France.

In addition to site characteristics and engineered barriers in a repository, in general, the following waste-related factors/measures are important in predicting the performance of a geologic repository for the disposal of HLW or UNF:

1. radiotoxicity of disposed materials, which reflects the inherent radiological hazard of the materials to be disposed of
2. inventory (mass and volume) of materials to be disposed of
3. heat-generating characteristics of the material. Degradation rate of materials and uncertainties of predictability usually increase with temperature; therefore, this is mainly an engineering issue that provides a measure of the repository space required.

The design and performance assessment of the Yucca Mountain repository has been based on the characteristics of UNF that was expected to be buried there. The results of the analyses presented in the license application of Yucca Mountain show that the radionuclides that dominate the annual doses typically have a combination of characteristics such as (a) large initial inventory in the waste, (b) moderate to high solubility, (c) long half-life (>10^5 years), and (d) low sorption in the transport paths. The radionuclides that are shown to be key risk contributors are ^{99}Tc, ^{14}C, ^{239}Pu, ^{129}I, ^{36}Cl, ^{230}Pu, and ^{237}Np for the first 10,000 years. Between 10,000 years and one million years, the key risk contributors are ^{242}Pu, ^{237}Np, ^{226}Ra, ^{129}I, and ^{99}Tc. These results demonstrated that the long-term risks are dominated by long-lived fission products (^{99}Tc and ^{129}I) and a few TRU materials (plutonium and neptunium).

For unprocessed UNF, the initial heat is dominated by the fission products ^{90}Sr and ^{137}Cs, and later on by ^{241}Pu and its decay product ^{241}Am. For the Yucca Mountain repository, thermal management of temperatures within and between waste emplacement drifts became a severe design constraint.

3.2.B. Local Disposal

Discussions of the permanent disposal of UNF and nuclear wastes have focused almost exclusively on large facilities located in settings of favorable geology that would accumulate and permanently isolate UNF from national or, at least, regional nuclear power plants. Challenges associated with the identification and characterization of sites for centralized facilities and the transportation of UNF and nuclear wastes to the facilities are well known.

There is, however, an alternative to centralized UNF repositories. UNF could be disposed of in deep holes bored 1.86 to 6.21 miles (3 to 10 km) into the stable basement rock below or near each nuclear power plant where the nuclear fuel has been used. This "deep borehole" waste disposal concept was suggested first in the 1970s (Ref. 26). It continues to be considered (Refs. 27 and 28). The concept has the following obvious attractions:

- It greatly reduces the need to transport UNF long distances through populated areas across multiple political and regulatory boundaries.

- The UNF is displaced from the biosphere much farther than would ever be considered in a mined repository such as the Yucca Mountain repository.

Boreholes ranging from <1.64 ft (<0.5 m) to as large as 3.94 ft (1.2 m) in diameter are drilled 1.86 to 6.21 miles (3 to 10 km) into crystalline rock. The technology to drill the smaller-diameter holes this deep now exists and has been demonstrated. Crystalline rocks at the depth of the borehole have been stable for millions of years. Nearly all currently operating nuclear power plants are thought to be located over suitable basement rocks. The depth of placement of the nuclear waste or UNF in a deep borehole makes inadvertent intrusion quite unlikely. Intentional, clandestine intrusion with the intent of absconding with the waste would be very difficult.

As with centralized UNF repositories, there are technical issues with the deep borehole waste disposal strategy. The emplacement of nuclear waste causes thermal stresses in the basement rock, but those stresses can be ameliorated by increasing the distance between adjacent boreholes. Sealing the borehole to prevent the escape of long-lived, volatile radionuclides such as ^{129}I is being investigated. Using "gettering" materials (i.e., materials that adsorb radionuclides that are leached from the buried fuel) in the backfill of the hole and fusing the rock above the waste are promising alternatives. Casement of the boreholes of the anticipated depth and packaging of the waste need to be considered. The requirements for packaging may be minimal. In contrast to mined repositories, elaborate engineered barriers to protect the UNF or nuclear waste are not thought to be required. The host crystalline rock provides the isolation of the waste. Similarly, casement of the borehole in the vicinity of the waste may not be needed or desirable since gaps between the casing and the borehole wall could provide transport pathways. Casement of the borehole in regions where it passes through sedimentary overburden may be needed.

Economics of the deep borehole strategy have not been thoroughly explored. It appears that up to ten boreholes would be necessary for UNF generated during the operational lifetime of a typical, modern LWR. The cost to drill a sufficiently deep borehole is estimated to be about $20 million (Ref. 29). Costs associated with site characterization, waste packages, and regulatory

processes have not been adequately explored. It appears, however, that the cost of deep borehole waste disposal may be substantially less than the cost of a centralized, mined repository per unit of UNF.

Public acceptance of the local disposition of UNF into deep boreholes has not been explored. The public acceptance of dry cask storage of UNF on nuclear power plant sites has been quite high, but it is not clear whether this public confidence might extend to the deep borehole concept.

3.3. Option 2: Reprocessing and Limited Recycling in LWRs

In this case, the UNF from an LWR is reprocessed to recover plutonium and uranium. The fission products and other minor actinides (neptunium, americium, curium, etc.) are encapsulated into a glass waste form for permanent disposal. Since most of the fissile material (^{235}U) in the UNF has been fissioned, the reprocessed uranium from UNF has the equivalent of only ~15% of the energy value of the original fuel. It also contains undesirable ^{236}U and a minute amount of ^{232}U isotopes. Therefore, the reprocessed uranium is typically put in interim storage until a higher uranium price can justify its use.

The recovered plutonium is typically recycled as mixed uranium-plutonium oxide (MOX) fuel. Plutonium is not quite as good a fuel as ^{235}U in LWRs, and the MOX fuel is typically used only once since the plutonium that does not fission is converted into higher-mass actinides, which are even less likely to fission. The used MOX fuel is stored and can be reprocessed later for use in fast reactors.

The reprocessing with MOX recycle in the LWR fuel cycle was the reference fuel cycle through the mid-1970s, when a very large number of commercial fast reactors were envisioned by the year 2000, and a large commercial-scale reprocessing plant was under construction at Barnwell in South Carolina. Reprocessing and MOX recycling in LWRs were abandoned following President Carter's decision to prohibit reprocessing in 1977. The fast reactor commercialization efforts were also halted around the world as more uranium reserves were found and the nuclear orders were canceled following the Three Mile Island accident.

MOX recycle in LWRs was always considered as an interim step toward building the industrial base for ultimate recycling in fast reactors. Although the interest in fast reactors has been revived as evidenced by the construction projects in India, China, and Russia, the nuclear renaissance in the United States will have to be based on advanced LWR types in the next decade or two or longer since fast reactor designs for use in the United States are not yet complete. If the United States decides to pursue fast reactor technology, commercial fast reactors are likely to follow the advanced LWRs in the 2040–2050 time frame at the earliest. Therefore, the reprocessing decision is not as straightforward as it was in the 1970s when fast reactors were expected to be built soon. Simply turning the clock back 30 years and restarting the reprocessing may not be the best approach.

France, the United Kingdom, and Japan have maintained commercial reprocessing, although the plans for the commercial fast reactors have been delayed substantially. In such cases, utilizing the existing commercial reprocessing and MOX fabrication facilities for reprocessing of the LWR

UNF and partial MOX recycle in LWRs would be a viable option. However, if such infrastructure does not exist, as in the United States, the factors discussed in Sec. 3.5 have to be evaluated carefully. The reprocessing and recycling decision, if based solely on its impact on the nuclear fuel cycle, is intimately tied with the fast reactor deployment and cannot be made as a separate decision by itself.

3.4. Option 3: Full Actinide Recycling

In this fuel cycle option, the LWRs are operated on a once-through fuel cycle, but their UNF is not disposed of in a permanent repository. Instead, the reprocessing of their UNF is delayed until fast reactors become available or until there is a firm plan to deploy fast reactors. In the LWR once-through fuel cycle, ~85% of the original ^{235}U is fissioned. However, the stockpile of plutonium from reprocessed LWR fuel can be used as the start-up fissile material for fast reactors. Once fast reactors are in place, there will be a strong incentive for reprocessing and recycling. The UNF from fast reactors has as much or more fuel value than the fresh fuel that was originally placed in the reactor. As a result, reprocessing and recycling UNF from fast reactors have the effect of increasing the available nuclear fuel supply. It must be noted, however, that even with this fuel cycle option, there will be HLW from the reprocessing, and the HLW will need to be disposed of permanently.

Several reprocessing technologies have been developed and studied over the past 50 years. A short description of those technologies and experience with them is presented here.

3.4.A. PUREX

The current commercial reprocessing of LWR UNF is based on the plutonium-uranium extraction (PUREX) process, which recovers plutonium and uranium in separate product streams. A slight variation of it is the co-extraction (COEX) process, which co-extracts equal amounts of plutonium and uranium in one product stream and the remaining uranium in another stream. The COEX process was proposed in response to the proliferation-resistant requirement of no separated plutonium product stream, but in essence it is not much different from mixing the pure plutonium and uranium products at the end of the process as proposed at the Rokkasho reprocessing plant in Japan.

3.4.B. Advanced Aqueous Reprocessing Technologies

In the last decade or so, advanced aqueous reprocessing technologies have been developed, primarily motivated to recover other minor actinides for full waste management benefits and to enhance proliferation resistance. In the United States a suite of uranium extraction+ (UREX+) processes is being developed for various combinations of product streams, as summarized in Table II.

In France, diamide extraction-selective actinide extraction (DIAMEX-SANEX) processes have been under development for recovery of americium and curium following the PUREX or COEX processes. For the long-term, the group actinide extraction (GANEX) process is being developed for a homogeneous recycling of actinides in fast reactors. In Japan, a new extraction system for TRU recovery (NEXT) process is being developed for recovery of bulk uranium followed by co-extraction of remaining uranium, plutonium, and neptunium, and then extraction of americium and curium.

TABLE II

Suite of UREX+ Processes*

Process	Prod 1	Prod 2	Prod 3	Prod 4	Prod 5	Prod 6	Prod 7
UREX+1	Uranium	Technetium	Cesium/ strontium	TRU[a] + Ln[b]	FP[c]		
UREX+1a	Uranium	Technetium	Cesium/ strontium	TRU	All FP		
UREX+2	Uranium	Technetium	Cesium/ strontium	Plutonium + neptunium	Americium + curium + Ln	FP	
UREX+3	Uranium	Technetium	Cesium/ strontium	Plutonium + neptunium	Americium + curium	All FP	
UREX+4	Uranium	Technetium	Cesium/ strontium	Plutonium + neptunium	Americium	Curium	All FP

*Prod 1 through Prod 7: product stream number 1 through product stream number 7, respectively.
[a]TRU: transuranic, i.e., man-made elements with atomic numbers greater than that of uranium (i.e., >92).
[b]Ln: lanthanides, i.e., elements with atomic numbers 59 to 70.
[c]FP: fission products.

A common thread of the advanced aqueous reprocessing technologies is a coprecipitation of plutonium with neptunium or other minor actinides and extraction of all minor actinides in addition to plutonium. The recovery of all actinide elements is aimed at reducing the long-term radiological toxicity of the waste stream. The recovered actinides then have to be transmuted in the reactor. However, thermal spectrum reactors, such as LWRs, are not ideally suited for actinide transmutation. The actinides can be transmuted effectively only in fast reactors. Furthermore, the fabrication of MOX containing minor actinides is a challenge in terms of technical feasibility and economics for recycling in LWRs.

3.4.C. Pyroprocessing

The Integral Fast Reactor (IFR) program under DOE, which was terminated in 1994, was developed to demonstrate the use of metal fuel and pyroprocessing technology. Pyroprocessing of metal fuel was, in fact, utilized in the Experimental Breeder Reactor II (EBR-II) fuel recycling demonstrations during 1964 to 1969. About 30,000 fuel pins were recycled based on melt-refining and injection-casting fabrication with a typical turnaround time of 2 months. The entire core was recycled up to five times. However, melt-refining could not remove noble metal fission products nor recover plutonium from the blanket. Hence, in the IFR program, electrorefining-based pyroprocessing was adopted. The original EBR-II Fuel Cycle Facility was refurbished with the new pyroprocessing process equipment systems and started operation in 1996 to treat the EBR-II UNF for disposal. Engineering-scale demonstration of pyroprocessing, including waste treatment processes, has been successful

through the EBR-II UNF treatment program, although the actinide recovery process has yet to be demonstrated.

In pyroprocessing, all actinide elements are recovered in a single product stream along with some uranium and trace amounts of rare earth fission products. Fabrication of fuel containing actinides with injection-casting was demonstrated for remote operation in the 1960s, and prototypic actinide-containing test pins had been successfully irradiated during the IFR program. The metal fuel and pyroprocessing for fast reactor actinide recycling application may be viable, but much work remains.

The application of pyroprocessing for LWR UNF processing is a different matter since LWR fuel is an oxide. The oxide-to-metal conversion process is required as a front-end step, and the electrorefining capacity would have to be scaled up by a factor of ~20 from fast reactor fuel with a high plutonium content to accommodate LWR UNF with a low plutonium content. It has been demonstrated that the electrolytic reduction process can be effective for the oxide-to-metal conversion and a planar electrode arrangement can increase the throughput rate substantially in a given refiner vessel size (Ref. 30). Therefore, applying pyroprocessing to the LWR UNF may be feasible, although the technology base is not as well established compared to the aqueous reprocessing variants.

3.5. Factors That Affect the Choice of Disposal Options

3.5.A. Economics

Economics is an important factor, but accurate cost estimates for various disposal options are not well established. A reference point to start is the 1 mill/kW·h nuclear waste management fee levied in accordance with the NWPA. The NWPA also mandated DOE to assess the adequacy of this fee for disposing of the UNF. The periodic fee adequacy assessments validated the 1 mill/kW·h fee, which translates to $200 to $400/kg HM. The lower fee is for the case of 25,000 MWd/tonne burnup, and the upper fee is for 50,000 MWd/tonne burnup. Therefore, we will assume that the average value of $300/kg HM represents a direct disposal cost without getting into the specifics of alternative disposal options. The direct disposal cost is then only ~15 to 20% of the total fuel cycle cost.

The direct disposal cost is expected to be very low, and the alternative reprocessing/recycling scenarios cannot compete with direct disposal solely based on the economics. Reprocessing costs have been assumed by the ANS President's Special Committee on Used Nuclear Fuel Management Options (the Committee) to be approximately $1000/kg HM for planning purposes (Ref. 2). The future cost may be lower in existing commercial facilities with their initial capital costs amortized or higher in newer facilities. Even with reprocessing, a repository is still required to dispose of the remaining actinides and fission products. Any savings in the repository due to reduced radiological toxicity or decay heat will be only a fraction of the already small disposal cost.

Therefore, the rationale for reprocessing and recycling options has to be based on factors other than economics.

3.5.B. Resource Utilization

Light water reactor UNF still contains valuable fissile materials that can be recovered by reprocessing and recycling. The residual uranium contains ~15% of the initial natural uranium equivalent value. However, the reuse of the reprocessed uranium is not straightforward. If reprocessed uranium is used as feedstock in the reenrichment process, ^{236}U will build up to the point that the ^{235}U enrichment has to be raised by ~15% over the fresh uranium because of the reactivity penalty caused by the absorption cross section of ^{236}U. More serious is the problem of ^{232}U in reprocessed uranium. The ^{232}U buildup is only a trace amount: 0.5 to 5 parts per billion depending on the burnup level. However, ^{232}U undergoes a series of decay steps that produce high-energy, penetrating gamma rays. If reprocessed material containing ^{232}U is introduced into enrichment plants and the fabrication lines, it will contaminate those facilities with material that gives off penetrating gamma rays and will require that heavy shielding be installed in the facilities. Because of the cost of the shielding, recycling of reprocessed uranium is not likely to happen until uranium prices rise substantially.

Although reprocessed uranium is not routinely recycled, some plutonium is recycled in selected reactors as MOX fuel. However, the reactivity worth of plutonium in the thermal spectrum of an LWR is only about half that of ^{235}U. Full plutonium recycling saves a natural uranium equivalent of only 10 to 15%. Since the cost of MOX fabrication is high (about five times more expensive than uranium fuel fabrication), the economic value of MOX as a fuel for LWRs is limited.

In the LWR once-through fuel cycle, the uranium utilization is only ~0.6% of the natural uranium, and the balance is discarded as depleted uranium in enrichment tailings and UNF. Even if both reprocessed uranium and plutonium are recycled, the uranium utilization is increased from 0.6 to 0.8%. Therefore, from both economics and resource utilization points of view, there is very little incentive to reprocess and recycle in LWRs, unless the reprocessing and MOX fabrication infrastructure already exists like in France and Japan.

A real incentive for uranium resource utilization comes from the use of fast reactors. As compared to <1% uranium utilization in the current commercial reactors, a factor of 100 improvement can be achieved in fast reactors by continuous recycling. Actinide elements are excellent fuel in fast reactors, and essentially all uranium can be used as fuel through breeding. However, it must be noted that only a limited number of fast reactors have been built, and a substantial technical and regulatory effort will be required to design and license fast reactors for widespread commercial use.

3.5.C. Environmental Concerns/Impacts on Long-Term Performance of Geologic Repositories

Reactor fuel assemblies are designed to produce energy and facilitate heat removal, but they are not designed as optimized waste forms. From the environmental point of view, not only the radiotoxicity and decay heat in the UNF have to be considered but also the physical form of the final waste package.

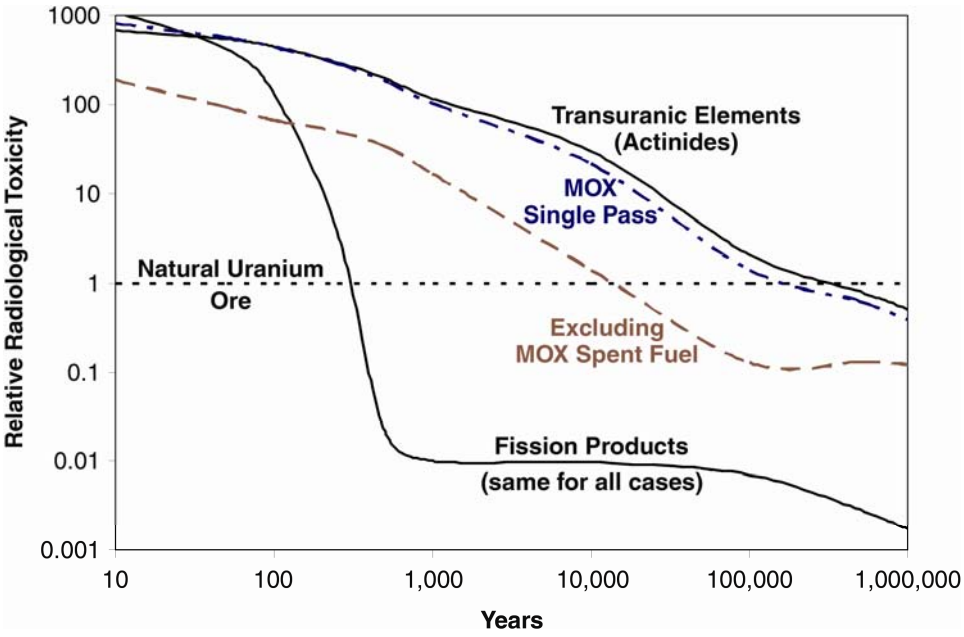


Fig. 10. Relative radiological toxicity of UNF constituents.

The radiological toxicity of typical LWR UNF as a function of time is illustrated in Fig. 10. Radiological toxicity here is a relative measure of the cancer risk if ingested or inhaled, which has been normalized to that of the natural uranium ore. As mined, the ore contains uranium along with its radioactive decay products that have accumulated over the millennia. If the radiological toxicity of the buried waste drops below the toxicity of natural uranium ore, then buried nuclear wastes leave the environment in no worse condition than it was when the uranium was mined. The place at which the radiological toxicity curve crosses the natural uranium line then can be loosely defined as an effective lifetime of the waste components.

The radiological toxicity due to fission products decays with a 30-year half-life, which is expected from the dominance of strontium and cesium whose half-lives are ~30 years. It drops below the natural uranium ore level in ~300 years and becomes two orders of magnitude less toxic in <1000 years.

On the other hand, the toxicity level associated with the actinides stays far above natural uranium ore and remains at least three orders of magnitude higher than fission products for hundreds of thousands of years. If 99.9% of actinides was removed from the waste, recycled into fuel, and transmuted in a reactor, then the radiological toxicity of the remaining 0.1% actinides in the waste stays below the natural uranium ore at all times, and the effective lifetime of the waste is dictated by the fission products.

Also shown in Fig. 10 is the effect of single-pass MOX recycling in LWRs. In today's commercial reprocessing based on PUREX, only uranium and plutonium are recovered. The minor actinides are disposed of as waste along with fission products. The recovered plutonium is recycled as MOX fuel only once, and the used MOX fuel is then stored for future reprocessing and use in fast reactors. In single-pass MOX recycle, about one-third of fissile plutonium can be fissioned, but the fertile plutonium isotopes (^{238}Pu, ^{240}Pu, and ^{242}Pu) evolve into even higher actinides, such as americium, curium, and neptunium. As a result, the radiological toxicity is almost unaffected by MOX recycle, as shown in Fig. 10. The radiological toxicity is basically transferred from the

original UNF to the MOX UNF. However, the effect of MOX recycle is sometimes presented to achieve a factor of 10 reduction in radiological toxicity and in effective radiological lifetime by excluding the actinides now contained in the MOX UNF. This case, excluding the MOX UNF, is also illustrated in Fig. 10. This reduction of toxicity can only be achieved if the MOX UNF can be ultimately recycled in fast reactors.

The performance of a geologic repository is usually measured in terms of the peak dose to a human from the releases of radionuclides from the repository into the environment. Performance assessments for deep geologic repositories have been conducted for the disposal of UNF and HLW in the United States, Sweden, and other countries in a variety of geologic formations and conditions. These calculations are based on specific characteristics of the waste, plus the complex interactions of the waste and the geologic environment.

Reprocessing can remove much of the actinides from UNF, thereby reducing the toxicity of the final waste destined for disposal. Furthermore, modification to the waste form from UNF to vitrified waste forms following reprocessing will, in general, increase the durability of the waste, reducing the releases of radionuclides from the waste in a repository. However, long-lived fission products (e.g., iodine and technetium) may outlive the most durable waste forms and could become transportable by groundwater, creating off-site dose risks that may require design features to ensure compliance with EPA dose standards in the long term. Finally, thermal output of the waste will impact the repository design and the associated costs of disposal but will have little impact on the repository's long-term performance.

3.5.D. Nonproliferation

As nuclear power expands, so does the amount of plutonium. All power plants produce plutonium, and some of the plutonium that is produced (or bred) in the fuel fissions while the fuel is still in the reactor. In fact, almost half of the energy comes from fissioning of plutonium bred in situ. Not all bred plutonium fissions, and the plutonium remaining in UNF amounts to ~1% of the heavy metal. The total amount of plutonium contained in the UNF accumulated to date in the United States is ~600,000 kg, growing at a rate of an additional 20,000 kg/year. Since the United States has about one-quarter of the world's reactors, worldwide inventory would be three to four times the U.S. inventory. Although the LWR once-through fuel cycle is commonly perceived as the most proliferation-resistant fuel cycle, one can argue that the ever-growing plutonium stockpile is prone to diversion and that it would be better from a nonproliferation point of view to recover plutonium along with other minor actinides and burn them in fast reactors at the same time eliminating the long-term radiological toxicity of UNF materials sent to permanent repositories.

Recycling of actinides in fast reactors implies reprocessing of the LWR UNF. The current commercial reprocessing is based on PUREX, which was originally developed for the purpose of cleanly separating pure plutonium for weapons. In recent years, advanced aqueous reprocessing technologies have been proposed and are being developed or demonstrated in order to recover minor actinides in addition to plutonium and also to avoid producing pure plutonium.

On a theoretical basis, pyroprocessing based on electrorefining is thought to be incapable of separating pure plutonium directly usable for weapons production. The underlying principle is that the free energies of chloride formation for plutonium, neptunium, americium, and curium are all in a fairly narrow range, causing them to deposit largely as a group. Element-by-element

separation in practical electrorefining at any reasonable rate is not practical and would make the production of pure plutonium difficult. However, recent work on assessment of proliferation resistance has found that "co-extracting Np with Pu does not alter the Attractiveness Level of the recycled material" (Ref. 31).

3.5.E. Retrievability

Under the NWPA, the repository was to be designed to allow UNF to be retrieved for 50 years after it had been emplaced. The provision for retrieval of the UNF provided flexibility in the selection of a disposal option. The United States could begin permanent disposal operations in support of the once-through fuel cycle but allow the UNF to be retrieved for reprocessing should national policy shift to reprocessing/recycling in the next 50 years. When the United States selects a disposal option in the future, it will need to consider whether retrievability should be a requirement.

3.5.F. Public Acceptance

Whatever UNF disposition path is ultimately selected, public acceptance is an important consideration. The specifics of the ultimate disposition path may not be important to the public as long as there exists a technical consensus on the chosen path and transparency in the decision-making process. In addition, having a clearly established plan for disposition of UNF may be essential for the public acceptance of nuclear power.

3.5.G. Ethical Considerations

Nuclear power plants provide 20% of the electricity generated in the United States. The current generation of Americans has benefitted significantly from this electricity, and many believe this generation has an obligation to dispose of the resulting waste as opposed to leaving it for later generations. On the other hand, the rapid advance of scientific technology may result in safer, more cost-effective methods for dealing with UNF in a few years. If that is the case, it may be to the advantage of both current and future generations to leave the UNF in a stable storage configuration while the new technologies are being developed.

4.0. BOUNDING SCENARIOS

4.1. Scenario 1: No-Growth Scenario—Description and UNF Management Options

4.1.A. Scenario Description

The Committee considered a no-growth scenario for nuclear power as the lower bound for a nuclear power future and its impact on the UNF inventory that must be considered for eventual disposition. In this scenario, current operating plants remain in operation for a 60-year operating life (40-year initial license plus a 20-year license renewal) and then shut down. As of the end of 2010, 59 plants already have 20-year license renewals (Ref. 32) approved by NRC and will likely operate through 60 years. An additional 40 plants are either already being considered for a 20-year renewal, or their owners plan to request a license renewal. Some plants will not seek renewal, while others can and likely will seek a second 20-year license extension for a total operating life of 80 years. Finally, there will continue to be power uprates for existing plants, which will increase the annual inventory of UNF, and there will be improvements in the nuclear

fuel cycle operations, such as higher-burnup fuel, that will reduce the annual inventory of UNF. But, these are considered to be second-order effects. Thus, this no-growth scenario is considered to be a reasonable lower bound for the volume of UNF requiring disposal.

The current inventory of UNF is >60,000 tonnes of heavy metal equivalent, which is close to the statutory limit of 70,000 tonnes (63,000 tonnes of UNF and 7,000 tonnes of defense HLW) for the first HLW repository from the NWPA. Based on the expected annual output from currently operating plants and with the scenario described above, one estimates that the total UNF inventory would be ~140,000 tonnes of heavy metal equivalent when all the current plants reach their 60-year life before 2050. That is, the inventory of UNF even under the no-growth scenario would exceed by a factor of 2 the statutory limit for the first waste repository. Figure 11 shows the amount of UNF expected to accumulate under a variety of scenarios.

Given this inventory, let us consider the likely technical options for UNF management and disposition for the remainder of this century under the no-growth scenario.

4.1.B. Used Nuclear Fuel Management Options

4.1.B.1. Keep UNF at Reactor Sites

The first technical option is to keep the UNF at the reactor sites where it currently exists either in storage pools or ISFSIs (wet or dry). There are no substantial technical difficulties in continuing to store the inventories at these locations, but there are potential policy issues that depend on the individual sites and local and state governmental agreements. The main technical issues involve how long such storage provides adequate safety and security protection. In 2010 NRC Chairman Jaczko was supported by Commissioners Ostendorff and Svinicki in proposing that the NRC staff proceed with a waste confidence determination rulemaking based on the information at hand and that it also initiate a longer-term evaluation of the consequences of storing UNF for >100 years. (Note that current regulations allow UNF inventories to remain at power plant sites for up to 60 years after decommissioning; this would result in potential on-site storage at some sites through 2100.) Chairman Jaczko said in supplemental comments released in July 2010 that while he is confident the United States will be able to dispose of UNF in a safe and environmentally sound manner in <100 years, he believes it would be prudent "to direct the staff to consider any consequences of storing spent fuel longer than 100 years."

Used nuclear fuel is currently stored at 83 locations throughout the United States, including reactor storage pools, ISFSIs, national laboratories, and defense weapons sites. Additional sites include university research and training reactors. The 104 commercial nuclear generating units licensed to operate in 31 states discharge ~2000 tonnes of UNF annually. The total inventory was approaching the limit of 63,000 tonnes HM for one repository specified in the NWPA by the end of 2010.

There is dry storage at ISFSIs located at 40 sites with general licenses and 15 sites with site-specific licenses. The map in Fig. 8 in Part I of the Report shows the current ISFSI locations.

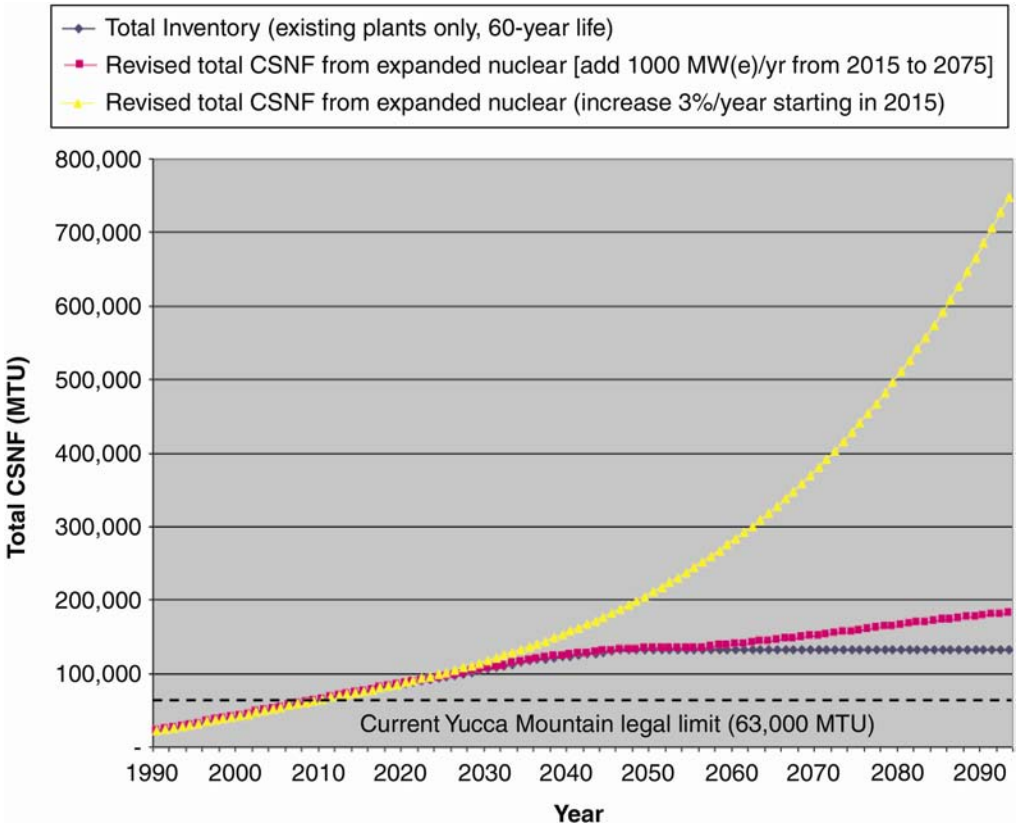


Fig. 11. EPRI estimate of UNF inventory (Ref. 33).

Today, there are also 11 shutdown commercial facilities in nine states that have stand-alone nuclear fuel storage sites. These isolated sites contain ~3000 tonnes of fuel. Some policymakers feel that UNF should be removed as soon as practicable from these sites to provide an empirical demonstration of site cleanup and waste confidence. These sites are as follows (Refs. 34 and 35):

1. Maine Yankee in Wiscasset, Maine, on the Atlantic Ocean: 542 tonnes U in 60 casks
2. Yankee Rowe in Franklin County, Massachusetts, on the Deerfield River: 127 tonnes U in 15 casks
3. Connecticut Yankee in Haddam Neck, Connecticut, on the Connecticut River: 412 tonnes U in 41 casks
4. Zion in Zion, Illinois, on Lake Michigan: 1019 tonnes U in pool storage
5. La Crosse BWR in Genoa, Wisconsin, on the Mississippi River: 38 tonnes U in pool to be transferred to five casks
6. Big Rock Point in Charlevoix, Michigan, on Lake Michigan: 58 tonnes U in seven casks
7. Fort Saint Vrain in Platteville, Colorado, on the Platt River: 14.7 tonnes U in dry vault (DOE managed, was formerly CPS commercial reactor)

8. Trojan in Ranier, Oregon, on the Columbia River: 359 tonnes U in 34 casks
9. Humboldt Bay in Eureka, California, on the Pacific Ocean: 29 tonnes U in five casks
10. Ranch Seco in Herald, California, near the Sacramento River: 228 tonnes U in 21 casks
11. GE Former Planned Reprocessing Plant in Morris, Illinois: 674 tonnes U pool storage.

4.1.B.2. Keep UNF at Interim Storage Sites Away from Reactors

Interim, centralized, engineered dry cask storage facilities for UNF could be built to offer more options for nuclear fuel storage. Such storage facilities would be licensed for a relatively short period of time in comparison to their expected ability to store UNF.

The "away-from-reactor" storage option would be of particular interest for decommissioned reactor sites where operating reactors have been shut down or are in some stage of being decommissioned. The goal of decommissioning is to return the land to unrestricted use, and the stored UNF is a major obstacle to meeting that goal.

4.1.B.3. Move UNF to a Geologic Repository (Before or After Current Nuclear Power Plant Licenses Expire)

The NWPA provides a plan and a process for DOE to develop a mined geologic repository for the disposal of UNF and HLW for commercial and defense activities. The repository would have to meet NRC and EPA safety and environmental protection requirements. In 1987, Congress directed DOE to pursue a site characterization study of one of the sites: Yucca Mountain. Originally, Yucca Mountain was to begin accepting UNF from commercial sites in 1998, and DOE has been incurring liability for the UNF since that time. DOE submitted a license application to NRC for the repository in 2008. However, the Administration of President Obama proclaimed in 2009 that Yucca Mountain as a geologic repository is "off the table."

4.1.B.4. Send UNF to Another Country for Disposal

Acceptance of UNF is a politically contentious topic. According to the World Nuclear Association, "At present there is clear and unequivocal understanding that each country is ethically and legally responsible for its own wastes, therefore the default position is that all nuclear wastes will be disposed of in each of the 40 or so countries concerned" (Ref. 36). From a *purely technical* point of view, an international repository system is the most efficient approach because not all countries have the appropriate geological characteristics required for safe and secure UNF disposal and many countries cannot afford the infrastructure required for geologic disposal. The International Atomic Energy Agency (IAEA) produced a report in 1980 on waste management and disposal, "International Nuclear Fuel Cycle Evaluation—INFCE," recommending that proposals "for establishing multinational and international repositories should be elaborated" because of their nonproliferation advantages. "Centralised facilities for disposal of spent fuel and/or vitrified high-level wastes ... would reduce the diversion risk" and be more economical (Ref. 37).

However, any international waste repository has implications under the Nuclear Non-Proliferation Treaty, further complicating any forward progress. Thus, the reality is that sending

UNF from the country of origin to another country for disposal, while technically feasible, is likely to be tangled politically for many years. This is not an option the Committee considered.

4.2. Scenario 2: Growth Scenario: Description and UNF Management Options

4.2.A. Scenario 2 Description

In the past few years, there has been a growth trend in nuclear power on a global scale. According to IAEA, nuclear power capacity could double by 2030 because of the growing global demand for energy (Ref. 38). For example, China plans at least to quadruple its nuclear capacity by 2020 and to quadruple it again from 2020 to 2050.

For the growth scenario discussed here, nuclear energy is assumed to contribute one-half of the future growth in electricity production in the United States between 2010 and 2100. The current annual electricity consumption is ~4000 TW·h. If the electricity demand grows at the recent historical rate of ~1%/year, then the electricity consumption rate would be ~6000 TW·h in 2050. If one-half of the new demand is to be met by nuclear, ~130 GW(e) of new nuclear generating capacity will have to be installed by 2050. After 2050, if the electricity demand continues to grow at 1%/year and nuclear power contributes one-half of the new production, then an additional 240 GW(e) of nuclear generating capacity would have to be installed between 2050 and 2100.

Combined with the existing capacity of ~100 GW(e), the resulting nuclear capacity on-line will be ~230 GW(e) in 2050 and ~470 GW(e) in 2100. Construction of a total capacity of 470 GW(e) in 90 years is a little more than 5 GW(e)/year, which is commensurate with the average nuclear capacity growth in the 1970s and 1980s. Therefore, this scenario is feasible.

In this scenario, the near-term deployment is assumed to be largely based on LWRs at least through the 2030s and 2040s. Whether these near-term deployments are based on large reactors or small modular reactors (SMRs) is irrelevant insofar as the UNF management issues are concerned. The amount of UNF in terms of heavy metal, its radioactivity, and its decay heat are dictated primarily by the amount of electricity generated rather than by reactor type or size. A higher discharge burnup can reduce the amount of heavy metal discharged per year but not the radioactivity nor the decay heat contents, which are important for the UNF management options.

If the nuclear capacity is more than doubled by 2050 and continues to grow, the introduction of fast reactors may be justified. Wide-scale deployment of fast reactors will depend on many factors including satisfactory demonstration of technologies, uranium prices, degree of benefits to the geologic repository program, reactor economics, and national policies/ incentives. If a government-supported fast reactor demonstration project is launched in the near future, a full-scale deployment of commercial fast reactors can be envisioned starting around 2050. However, an earlier deployment of fast reactors, as early as 2040, can be envisioned if technology conditions warrant.

Fast reactors could become economically viable if the uranium prices significantly escalate due to, for example, large-scale deployment of nuclear reactors around the world. Or, introduction

could be viewed as being in the best interest of the nation in terms of energy security issues, as an integral part of the UNF strategy, or as a hedge against the uranium price escalation.

In summary, the Committee's growth scenario assumes the following:

1. Between 2010 and 2050, nuclear capacity reaches 230 GW(e) mostly from LWRs.

2. Between 2050 and 2100, additional growth reaches 470 GW(e) of nuclear capacity from a mixture of LWRs and fast reactors.

4.2.A.1. Description of the Fuel Cycles Considered In Scenario 2

As discussed earlier, with only LWRs, there are currently two options for the back-end of the fuel cycle: once-through and partial recycling. The once-through fuel cycle has been the reference fuel cycle in the United States, where the UNF is destined for direct disposal in a repository. In Europe and Japan, the UNF is reprocessed to recover plutonium and unused uranium, and the plutonium is recycled back into the reactor as MOX fuel. Both of these fuel cycle options are depicted in Fig. 12.

The fresh fuel for LWRs has low fissile content, and ~85% of the initial fissile content is used in the reactor; therefore, the remaining fuel only has marginal value for reuse. In contrast, the fresh fuel for fast reactors requires much higher fissile content, and the UNF also contains as much fissile content because of a higher internal conversion ratio, which produces fissile plutonium. Therefore, recycling is usually an integral part of the fast reactor fuel cycle.

The initial start-up fuel for fast reactors can be any fissile material including enriched uranium, but utilizing the TRU elements (or actinides) reprocessed from the LWR UNF is also viable. About 10 tons of actinides (recovered from reprocessing 700 tons of LWR UNF) would be sufficient to provide the initial inventory and two to three reloads until self-generated recycle is established for a 1000-MW(e) fast reactor.

The fast reactor fuel cycle is depicted in Fig. 13, where the initial inventory is provided by reprocessing the LWR UNF. In Fig. 13, LWRs are assumed to operate on once-through mode until fast reactors become available. However, a hybrid cycle is also possible, where the MOX recycle in LWRs is carried out as an interim step before fast reactors become available. In this case, the used MOX fuel can be reprocessed to provide the initial inventory for the fast reactors.

The LWR MOX recycle is only an interim step because actinides are not a good fuel material in the thermal neutron spectrum found in LWRs, and actinides can be transmuted effectively only in a fast neutron spectrum. A complete transmutation of actinides is important in order to reduce the long-term radiological source terms in the repository.

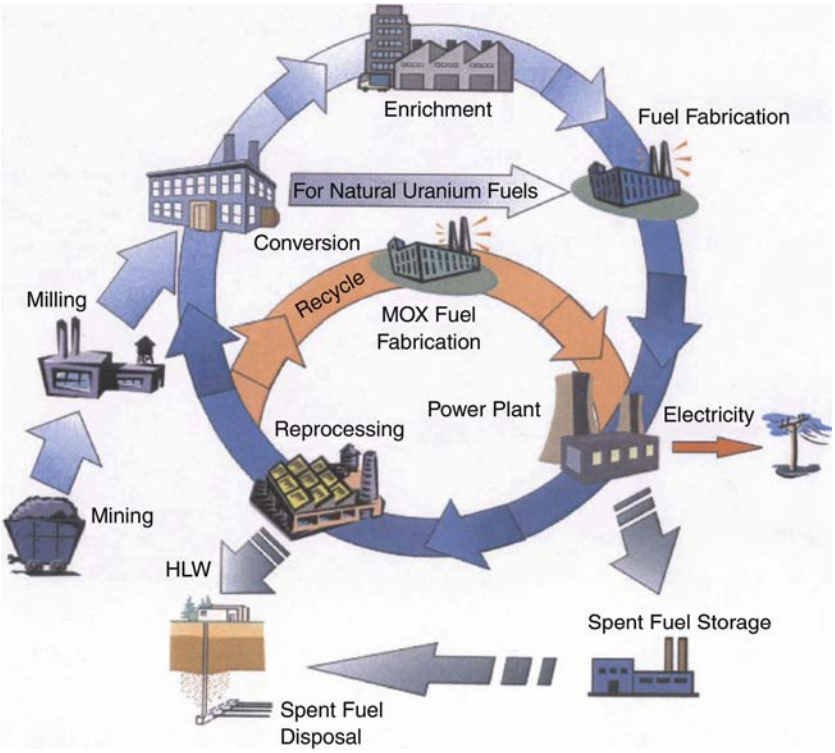


Fig. 12. LWR fuel cycle options: once-through and partial recycling.

4.2.B. Used Nuclear Fuel Management Options for Scenario 2

As the nuclear capacity is more than doubled by 2050 and continues to grow, UNF should probably be considered an asset rather than a waste. It is possible that demand for uranium will be much higher in the future. Under that circumstance, it is reasonable to make use of ^{238}U, which is >99% of naturally occurring uranium; ^{238}U does not fission and thus does not generate appreciable energy in LWRs. However, ^{238}U is converted to ^{239}Pu, which can be used efficiently in fast reactors.

If the entire nuclear capacity in this scenario were based on LWRs operating on the once-through fuel cycle, the UNF would accumulate to ~190,000 tons by 2050, continuing to increase to ~542,000 tons by 2100. Such magnitude would necessitate multiple repositories and extensive interim storage capacities. Reprocessing of UNF would appear to be a prudent option to limit the UNF accumulation. In addition, recycling offers the benefit of reducing the radiotoxicity of the final wastes that require permanent disposal. Furthermore, fast reactors offer the potential to further reduce the radiotoxicity of nuclear wastes by transmuting actinides.

4.2.B.1. Storage of UNF

Regardless of which scenario one assumes, the fact remains that both wet pool storage and on-site dry storage will be an integral part of the nation's UNF strategy for a very long time.

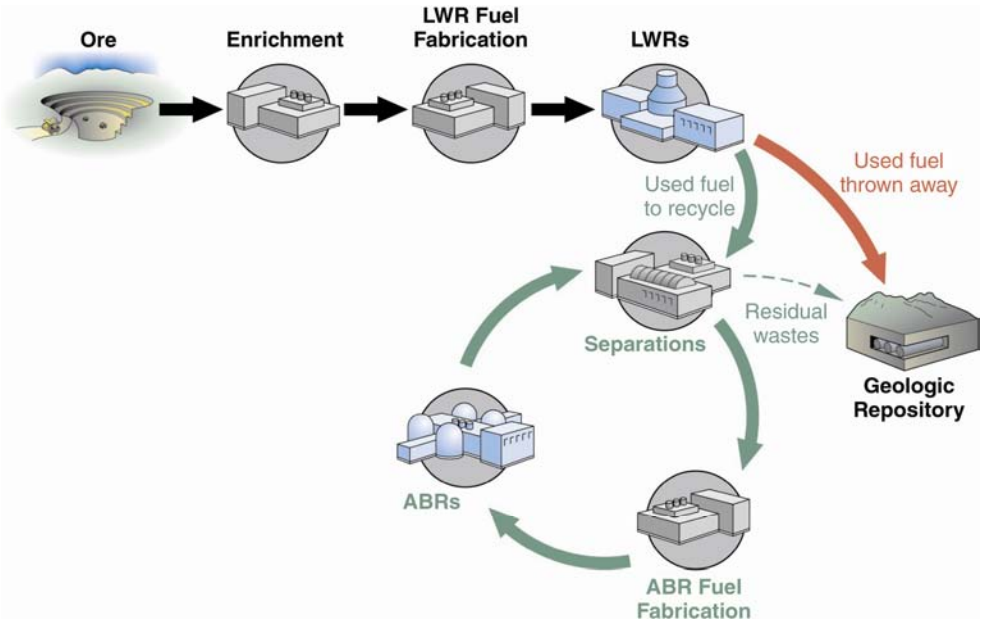


Fig. 13. LWR–fast reactor fuel cycle [note that Advanced Burner Reactors (ABRs) are fast reactors].

While new reactor designs generally contemplate the need for both wet and dry on-site UNF storage capabilities, currently the Utilities Requirements Document that most designs use as a reference for their design requirements requires only 10-years' worth of wet UNF pool capacity. While many of the new designs are increasing the pool capacity to >10 years of storage capacity, the fact is that whether a design has 10 or 40 years of capacity, on-site dry UNF storage capacity is likely to be needed for all new reactors deployed under the growth scenario. By 2050 and beyond, with the existing accumulated UNF inventory plus the additional generated UNF inventory, it is expected that a much greater long-term storage capacity will be needed. As discussed earlier, UNF inventory may be capped at 190,000 tons if fast reactors could be available in 2050 and if reprocessing capacity is available to reprocess 4000 tons/year. This UNF inventory is about three times the current UNF inventory, and if fast reactors are not available by 2050, the UNF inventory under this scenario could be significantly higher.

Many factors will influence future options for UNF storage: cost, safety, security, perceived terrorism threat, community support, and of course national energy policy. On-site storage will always remain as part of the interim UNF storage options. As UNF inventory grows and/or if reprocessing is determined to be an acceptable option, regional consolidated interim storage facilities may become more attractive. Regional consolidated storage facilities may be more cost-effective as compared to interim on-site storage since maintenance, physical security, and safeguarding can be centralized and standardized. Furthermore, if consolidated storage facilities are used, transportation issues and long-term transportation costs may be minimized by co-locating those facilities with the reprocessing facility and/or the permanent disposal facility.

4.2.B.2. Disposal

In the growth scenario, no matter what type of recycling, if any, is deployed, HLW will exist either in UNFs that may be directly disposed of or in solid HLW forms from reprocessing/recycling plants. Recycling UNF is not a solution to the nuclear waste disposal

problem, but it is a tool to make nuclear waste less hazardous, and as a side benefit, it generates products that can be reused as fuel to offset a portion of the costs of recycling. These wastes, in whatever forms they may be, need to be permanently, passively disposed of, and currently, the only known practicable method is in a geologic disposal facility.

The need for a geologic disposal facility has been studied for decades, and NAS in its 2001 report concluded the following: "After four decades of study, geological disposal remains the only scientifically and technically credible long-term solution available to meet the need for safety without reliance on active management" (Ref. 39). Thus, regardless of the decision made about recycling, one or more permanent geologic disposal repositories will be required.

As discussed in Part I, in addition to wastes from nuclear energy production, there is legacy HLW remaining from the cleanup of national defense nuclear facilities. Thousands of canisters of borosilicate glass containing HLW are currently being manufactured at the Savannah River facility, and plans are well underway to package similar wastes at the Richland and Idaho Sites. Also, there are large canisters of spent Naval reactor fuels and other UNFs owned by DOE awaiting direct disposal. These wastes have no economic values and are ready for geologic disposal now.

There are many different geologic media and engineered designs that could be used for a geologic repository. Mined geologic repository facilities have had the most study, but deep-sea disposal and deep [multifoot (multikilometer)-deep] boreholes are also options. There is no overall optimum, however, as there are positive and negative attributes of all the various geologic media and designs. Bedded and domed salts provide good sealing. However, retrievability/reversibility concerns, potential for brine migration, potential future resource recovery, and inadvertent intrusion are challenging. Unsaturated rock formations can provide good isolation and reversibility/retrievability, but the chemistry may not be as favorable as in other media. Hard rock granites can provide good isolation and reducing chemistry conditions, but fracture water flow predictions into the future can be challenging. Shale and clay formations hold some promise, but these also have drawbacks.

In summary, no matter what type of recycling may be employed in the growth scenario, a geologic repository is still required. Vitrified glass defense wastes, Fort Saint Vrain UNF, and other materials with no value all require geologic disposal. It is important to make progress to dispose of such wastes in the near term. There may be more than one disposal repository required for the growth scenario, and the experience gained from the first repository will be an important data source for future repository design refinements as well as a confidence-builder that demonstrates the United States can resolve the back-end nuclear issues.

4.2.B.3. Reprocessing/Recycling

In this growth scenario, if the reprocessing capacity were available to process 4000 tons/year by 2040, LWR UNF accumulation could be capped at <190,000 tons, provided fast reactors could be built for new capacity demands starting in 2050. The 4000 tons/year reprocessing will produce enough actinides to start up the needed fast reactors. As with the nuclear capacity assumptions, we are presenting the 4000 tons/year as an illustrative case rather than as a forecast or a requirement. If a larger capacity is assumed, the UNF inventory would decline faster. On the other hand, if a smaller capacity is assumed, the UNF inventory will continue to build up in time.

The 4000 tons/year reprocessing capacity in this example does not have to be built in a single facility (current average reprocessing capacity is 800 tons/year in facilities in other countries). It can be distributed to multiple facilities. In fact, there are some merits in constructing multiple facilities spread in time so that the operating experience of the first facility can be utilized to improve the design of the next, and so on. Also, the multiple facilities could be distributed geographically to minimize the transportation needs.

An early availability of reprocessing capability has the potential advantage of alleviating the UNF interim storage challenge. Currently, LWR UNF can be reprocessed using aqueous reprocessing, and MOX fuel can be manufactured. However, since the reprocessing facilities would most likely be available in a similar time frame as the start-up of fast reactors, the incentives to do interim MOX recycling in LWRs are diminished because of unfavorable economics and very little impact on waste management, as discussed in Sec. 3.0. If recycling is delayed until fast reactors are available, there is no need to establish the MOX fabrication facilities, which would be used only in the interim. As discussed in Sec. 3.0, if a technology such as pyroprocessing is used to reprocess fast reactor fuels, the MOX infrastructure would appear to have little future utilization in a fast reactor economy.

It has been widely shown in literature that there are three waste characteristics that are important to the performance of permanent disposal: (a) radionuclide composition, (b) heat generation, and (c) physical and chemical characteristics of waste forms. It has been demonstrated (Ref. 40) that removal of actinides that contribute most to the radiotoxicity of the waste (i.e., isotopes of plutonium, americium, neptunium, and curium) could result in improvement of performance of repositories located in oxidizing environments, while the removal will have much less impact in reducing environments. If reprocessing can reduce or separate long-lived fission products (e.g., ^{99}Tc and ^{129}I) from the final waste, it will, in general, improve the performance of the repositories. Reduction of volume and the thermal output of final waste will also improve the operation and design of the repository. Finally, a more durable physical and chemical waste form that resists the waste degradation will improve the repository performance. Therefore, in the growth scenario where reprocessing is a likely option, impacts on repositories will mostly be positive.

4.2.C. Proliferation Risk

An expanded use of nuclear energy to between two and three times the current level raises the issue of proliferation risk. It is generally recognized that diversion of nuclear materials and the fabrication of a nuclear weapon require strong motivation, material, technology to manipulate the material, and expertise. The motivation to divert material for weapons use is not addressed in the Report. However, it is recognized that other factors that affect proliferation risk could be expected to change with the expanded use of nuclear energy. Certainly, the amount of nuclear material in the country would grow in rough proportion to the expanded use of nuclear methods for electricity generation. The population with expertise in nuclear materials and capable of aiding an effort to divert and misuse nuclear materials would certainly grow. The technology for manipulating nuclear materials is assumed here to be fixed and widely known. Access to this technology for misuse would, presumably, grow with increased use of nuclear energy.

Equipment and expertise required to manipulate purloined nuclear materials would be reduced on the whole by extensive use of fuel reprocessing since material with substantially reduced radioactivity and contamination would be available. Extensive use of reprocessing would

increase the number of nuclear material shipments in the country and the opportunities for theft or diversion of nuclear materials.

Measures to safeguard and secure nuclear materials now in place for large nuclear power plants appear adequate so far. These measures would be reproduced at a minimum or enhanced at any new, large nuclear installation. To a significant level of approximation, the costs of these safeguard and security measures are independent of reactor size. For SMRs, when the number of modules on a particular site is small, the safeguard and security costs have to be amortized over a smaller amount of energy generation. Manpower costs rather than capital costs appear to be most limiting. Presumably, some innovations would be required for SMRs to have similar levels of safeguards and security but still remain economically competitive.

In this growth scenario, the overall proliferation risk is difficult to determine now. As fast reactors are deployed, the requirements for uranium enrichment will decrease, thus decreasing the proliferation risk. However, a fast reactor uses fuels with substantial quantities of plutonium and requiring reprocessing. Clearly, proliferation risks associated with reprocessing will depend on the ultimate designs of reprocessing technologies. Finally, if the United States develops reprocessing/recycling capabilities and chooses to provide those services to nations who want nuclear power but do not want enrichment or reprocessing facilities, there would be an effect on proliferation risk—somewhat increased proliferation risk due to larger volumes of reprocessed fuel in the U.S. facilities but decreased risk since other countries are not building their own enrichment and reprocessing facilities.

CONCLUDING REMARKS

"Report of the ANS President's Special Committee on Used Nuclear Fuel Management Options" has provided an overview of the use of nuclear power in the United States and the factors important to consider when deciding how to manage used nuclear fuel (UNF). It has described two bounding scenarios for use of nuclear power in the United States over the next century. Rather than attempting to present numerous possible scenarios for the amount of installed nuclear capacity, and thus UNF types and amounts, the approach taken was to concentrate on the development of two bounding scenarios. These two scenarios provide an opportunity to discuss the many options that the United States might consider for UNF management. In one scenario, the current nuclear power plants run until their licenses expire, assuming that the majority of the current operating units receive one 20-year license extension and no additional nuclear plants are built. In the other scenario, nuclear power meets 50% of the increased demand for electricity in the United States through 2100.

Regardless of whether the future proves to be similar to one of these bounding scenarios or somewhere in between, three technical outcomes are inescapable. First, an interim storage facility, or facilities, will be needed to store the UNF until facilities for treatment and disposal of the fuel are ready. The interim storage facilities could be at existing reactor sites, regional, or national, but they will be needed. If long-term—several decades or more—storage is necessary, safety, security, and safeguards requirements and implications need to be considered carefully. Second, regardless of the interim storage option selected, a deep geologic repository, or repositories, will be required for ultimate disposal of defense high-level waste and wastes from recycling and/or direct disposal of UNF. In addition, a transportation system will be required to move the UNF and wastes from the place they are generated to storage, treatment, and/or disposal facilities. All three of these technical outcomes must be combined with a siting process acceptable to the public.

Whether the United States needs a used commercial nuclear fuel reprocessing and fuel fabrication (recycling) system that can accommodate mixed uranium-plutonium oxide (MOX) fuel or actinide-bearing fuel depends on many factors including the U.S. policy with respect to international nonproliferation efforts. Availability and cost of uranium, costs and risks associated with reprocessing, and the effect of reprocessing on the toxicity and volume of the wastes sent to a repository will influence decisions related to repository type, size, and cost. Our scenario analyses indicate that recycling makes less economic and technical sense if nuclear energy is not expected to be expanded in the future. On the other hand, if nuclear energy is expected to become a major energy source in the future, a holistic approach should be developed that includes a closed fuel system with facilities, for example, fast reactors, to extend the utilization of uranium resources substantially and reduce radiological toxicity of nuclear wastes by transmuting long-lived actinides. In addition, as other nations begin to use nuclear power to meet their growing electricity demands without increasing CO_2 emissions, the United States should consider whether or not a UNF recycling capability in the United States provides nonproliferation benefits by enabling the United States to offer "cradle-to-grave" nuclear fuel services, removing the incentive for other countries to build their own reprocessing facilities, thus reducing the chances for proliferation of nuclear materials.

Finally, one other feature essential for the U.S. nuclear future, whether that future is the orderly closure of the current nuclear plants or expansion of the nation's nuclear capacity with advanced technologies, is a long-term, stable nuclear energy policy with clear short- and long-term objectives and milestones. Critical to the success of any national UNF policy is a predictable and sufficient funding mechanism to support its implementation. In addition, creation of an independent entity to oversee UNF management has been endorsed by the American Nuclear Society. Having such a policy and funding mechanism, along with a clearly defined and dedicated management structure, will help focus research, development, and regulatory efforts on a common set of objectives. Finally, meeting early milestones on UNF management will help to build public confidence in the policy and may make it easier to implement subsequent policy objectives.

ACRONYMS AND DEFINITIONS

ABR	Advanced Burner Reactor
actinides	group of 15 chemical elements that have increasing atomic numbers, from actinium (atomic number 89) to lawrencium (atomic number 103); all have similar chemical properties; also known as transuranics
AEC	Atomic Energy Commission
AFCI	Advanced Fuel Cycle Initiative
ANS	American Nuclear Society
BRC	Blue Ribbon Commission on America's Nuclear Future
CIS	consolidated interim storage
COEX	co-extraction
(the) Committee	ANS President's Special Committee on Used Nuclear Fuel Management Options
CSNF	commercial spent nuclear fuel
DIAMEX-SANEX	diamide extraction-selective actinide extraction
DOE	U.S. Department of Energy
EBR-II	Experimental Breeder Reactor II
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration
fissile material	material that fissions
fission	the splitting of a nucleus into at least two other nuclei and the release of a relatively large amount of energy
fission products	atomic fragments left after a large atomic nucleus fissions
FTE	full-time employee
GANEX	Group Actinide Extraction
GNEP	Global Nuclear Energy Partnership
GW(e)	gigawatt(electric)
GW(th)	gigawatt(thermal)
GW(th)-day	gigawatt(thermal)-day
half-life	the time in which one-half of the atoms of a radioactive isotope disintegrates into another nuclear form; half-lives vary from billionths of a billionth of a second to billions of years
HLW	high-level waste
HM	heavy metal; in nuclear fuel "heavy metal" typically refers to the actinides, any of the elements number 89 or higher
IAEA	International Atomic Energy Agency
IFR	Integral Fast Reactor
iHM	initial heavy metal
ILW	intermediate-level waste
ISFSI	independent spent fuel storage installation

isotope	nuclide of a particular element having the same number of protons as the element but a different number of neutrons
kW·h	kilowatt hour
lanthanides	group of 15 elements that have increasing atomic numbers, from lanthanum (atomic number 57) to lutetium (atomic number 71); all have similar chemical properties
LLW	low-level waste
long-lived fission product	radioactive material with long half-life (>200,000 years)
LWR	light water reactor
minor actinides	actinide elements in UNF other than plutonium and uranium (which are the major actinides). Neptunium, americium, and curium are the minor actinides of concern for UNF because of their radiotoxicity and heat generation in UNF.
MOX	mixed uranium-plutonium oxide
MOX fuel	a mixture of uranium oxide and plutonium oxide
MOX fuel cycle	reprocessing and recycling process whereby a mixture of MOX is extracted from UNF for further use
MRS	monitored retrievable storage
MTU	metric tons of uranium
MWd	megawatt day
MW(e)	megawatt(electric)
NAS	National Academy of Sciences
NEXT	new extraction system for TRU recovery
noble metal fission product	When the nucleus of a fissile atom splits, typically two lighter nuclei are formed. When one of these nuclei is a noble metal (ruthenium, rhodium, palladium, silver, osmium, iridium, platinum, or gold), it is called a noble metal fission product.
NRC	U.S. Nuclear Regulatory Commission
nuclide	a general term applicable to all atomic forms of an element
NWPA	Nuclear Waste Policy Act of 1982
NWPAA	Nuclear Waste Policy Amendments Act of 1987
NWTS	Nuclear Waste Terminal Storage (program)
OCRWM	Office of Civilian Radioactive Waste Management
once-through fuel cycle	UNF is stored for disposal without any recycling; current U.S. practice
PFS	Private Fuel Storage, LLC
PUREX	plutonium-uranium extraction
radioactive decay	the decrease in the amount of any radioactive isotope with the passage of time due to the spontaneous emission of radiation from the atomic nuclei
radionuclide	unstable (i.e., radioactive) form of a nuclide
rare earth fission product	When the nucleus of a fissile atom splits, typically two lighter nuclei are formed. When one of these nuclei is a rare earth element (one of 15 lanthanides or scandium or yttrium), it is called a rare earth fission product.
(the) Report	"Report of the ANS President's Special Committee on Used Nuclear Fuel Management Options"
RSSF	retrievable surface storage facility

SAR	Safety Analysis Report
SKB	Swedish Nuclear Fuel and Waste Management Company
SMR	small modular reactor
transmutation	a process that converts the radioactive isotopes to elements that are not radioactive or ones that have very short half-lives
TRU	transuranic
TW·h	terawatt hour
UNF	used nuclear fuel
UREX	uranium extraction
WIPP	Waste Isolation Pilot Plant

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