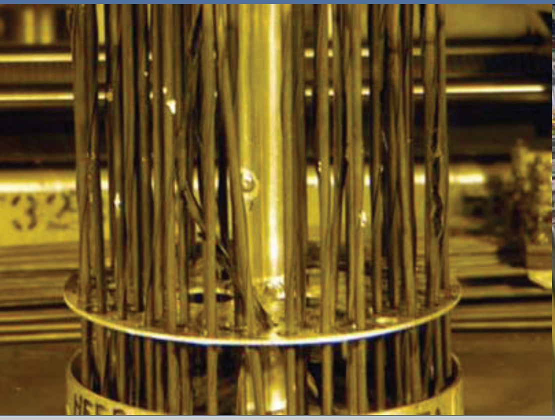
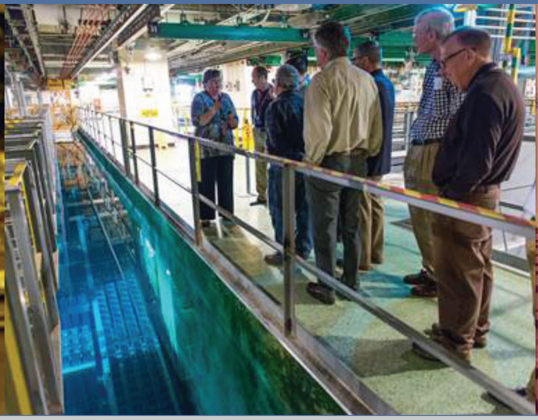
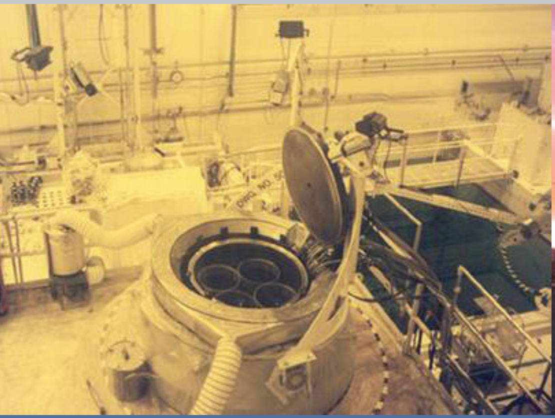
U.S. Nuclear Waste Technical Review Board


Management and Disposal of U.S. Department of Energy Spent Nuclear Fuel

A Report to the United States Congress and the Secretary of Energy



December 2017

U.S. Nuclear Waste Technical Review Board

MANAGEMENT AND DISPOSAL OF U.S. DEPARTMENT OF ENERGY SPENT NUCLEAR FUEL

Report to the United States Congress and the Secretary of Energy

December 2017

U.S. Nuclear Waste Technical Review Board

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December 2017

The Honorable Paul D. Ryan
Speaker
United States House of Representatives
Washington, DC 20515

The Honorable Orrin G. Hatch
President Pro Tempore
United States Senate
Washington, DC 20510

The Honorable Rick Perry
Secretary
U.S. Department of Energy
Washington, DC 20585

Dear Speaker Ryan, Senator Hatch, and Secretary Perry:

Congress created the U.S. Nuclear Waste Technical Review Board in the 1987 Nuclear Waste Policy Amendments Act (NWPAA) (Public Law 100-203) to evaluate the technical and scientific validity of activities undertaken by the Secretary of Energy to implement the Nuclear Waste Policy Act. In accordance with this mandate, the Board has undertaken a review of the Department of Energy's (DOE) efforts to manage the inventory of spent nuclear fuel (SNF) that is under its control at several facilities around the country. While disposal of spent nuclear fuel and high-level radioactive waste in a deep geologic repository remains the ultimate objective of the DOE nuclear waste management program, there is significant uncertainty about when such a repository will be constructed in the United States. Until disposal occurs, it is essential to manage SNF in a way that will facilitate its eventual disposal, and it is also important to improve understanding of processes related to packaging and storage of the SNF that could affect future transportation and disposal activities. The Board's review, which is a product of three years of effort, is presented in this *Report to Congress and the Secretary of Energy on Management and Disposal of U.S. Department of Energy Spent Nuclear Fuel*.

The report provides a summary of quantities and characteristics of DOE SNF by storage site. It also examines DOE packaging and storage activities and plans at each of the sites. Three main issue areas are highlighted in the report. First, the report identifies issues related to managing the aging of DOE SNF and the facilities used to store the SNF. Second, the report discusses issues related to packaging of stored non-naval DOE SNF into a standard canister. Third, the report discusses issues that would affect disposal of DOE SNF if DOE continues to evaluate a range of repository settings.

Based on the information and findings developed in the report, the Board makes six recommendations:

1. *The Board recommends that DOE develop and fully implement programs to manage degradation of SNF, the materials that contain SNF, and SNF facilities for additional multiple decades of storage operations at all storage facilities. Managing degradation includes assessing its potential of occurring and—when it is predicted to occur at unacceptable rates—monitoring storage conditions of the SNF and the materials in which it is stored to prevent degradation or to mitigate degradation effects. These programs should take into account five important considerations listed in Section 9.1.1.*

2. *The Board recommends that DOE include the capability for measuring and monitoring the conditions of the SNF in new DOE storage systems, such as the DOE standardized canister, and in new packaging and storage facilities to aid in establishing the condition of the SNF during subsequent operations and its acceptability for those operations.*

3. *The Board recommends that DOE conduct research and development activities to confirm that reactions between DOE SNF and any water remaining in any multi-purpose canister do not cause cumulative conditions inside the canister (*e.g.*, combustibility, pressurization, or corrosion) to exceed either the design specifications or applicable regulatory operational requirements. The period of interest extends over the duration of canister use, including the time spent in storage, in transportation, and at a repository, until DOE closes the repository. These research and development efforts should include the six activities listed in Section 9.1.3.*

4. *To minimize complications in developing and operating a packaging facility for DOE SNF at Idaho National Laboratory, the Board recommends that DOE complete research, development, and licensing-related activities for the DOE standardized canister—and any other canisters that may be used—prior to completing the facility's preliminary design. In particular, DOE should complete the seven tasks related to the DOE standardized canister listed in Section 9.1.4.*

5. *The Board recommends that the DOE Office of Nuclear Energy (DOE-NE) implement the existing Office of Civilian Radioactive Waste Management waste acceptance system requirements to increase the likelihood that SNF managed by DOE-NE and that waste forms resulting from electrochemical processing of sodium-bonded SNF will be acceptable for geologic disposal in a repository.*

6. *If DOE continues to conduct generic investigations of a range of potential repository environments, the Board recommends that DOE identify and prioritize its research efforts concerning DOE SNF degradation related to disposing of DOE SNF in each of the potential host-rock environments. As part of this effort, DOE should complete the two tasks listed in Section 9.1.6.*

The Board trusts that Congress and the Secretary will find the information in this report useful and looks forward to continuing its ongoing technical and scientific review of DOE activities related to nuclear waste management and disposal.

Sincerely,

Jean M. Bahr
Chair

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Abbreviations and Acronyms

ALARA	as low as (is) reasonably achievable
ATR	Advanced Test Reactor
Board	U.S. Nuclear Waste Technical Review Board
CFR	Code of Federal Regulations
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOE-EM	U.S. Department of Energy Office of Environmental Management
DOE-NE	U.S. Department of Energy Office of Nuclear Energy
EBR-II	Experimental Breeder Reactor 2
EIS	environmental impact statement
FSV	Fort St. Vrain
GAO	U.S. Government Accountability Office
GWd	gigawatt-day
HLW	high-level radioactive waste
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
MCO	multi-canister overpack
MTHM	metric ton of heavy metal
MTU	metric ton of uranium
MWd	megawatt-day
NRC	U.S. Nuclear Regulatory Commission
NWTRB	U.S. Nuclear Waste Technical Review Board
OCRWM	U.S. Department of Energy Office of Civilian Radioactive Waste Management
RCRA	Resource Conservation and Recovery Act
SNF	spent nuclear fuel
SRS	Savannah River Site
TMI-2	Three Mile Island Unit 2
TRIGA®	Training, Research, Isotopes, General Atomics (a type of nuclear research reactor)

Executive Summary

Introduction

While disposal of spent nuclear fuel[1] (SNF) and high-level radioactive waste (HLW) in a deep geologic repository remains the ultimate objective of the U.S. Department of Energy (DOE) nuclear waste management program, there is significant uncertainty about when such a repository will be constructed in the United States. Until a viable disposal solution is found, it is necessary and important that DOE manage its SNF in a manner that does not impede its eventual disposal (Figure ES-1).

DOE's spent fuel inventory comprises a broad range of fuels, resulting primarily from defense-related activities (Figure ES-2). DOE is responsible for packaging, storing, transporting, and eventually disposing of the SNF that it manages.

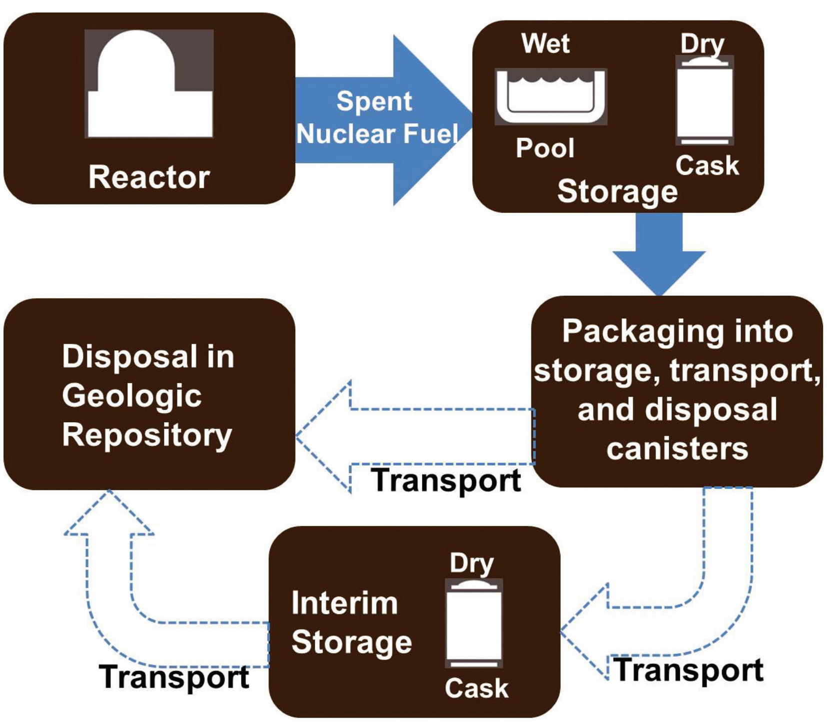

Figure ES-1. U.S. Department of Energy spent nuclear fuel management activities that lead to geologic disposal.
Once SNF is removed from a reactor, it is cooled and stored either in a pool (wet) or in variety of dry storage configurations, both indoors and outdoors, including casks, vaults, and other storage arrangements. Before the SNF can be stored, transported, or disposed of, it must be properly packaged to avoid any negative outcomes. For almost all of its SNF, DOE adopted a multi-purpose canister approach (appropriate for storage, transport, and disposal) to facilitate subsequent SNF management activities. Once packaged in a multi-purpose canister, DOE stores the SNF on site until it can be transported (dashed arrow indicates future activity) either directly to a geologic repository or to an off-site interim storage facility, and then transported again to a geologic repository.

[1] Underlined terms and phrases are explained in the Glossary (Chapter 11).

Properly managing SNF in the near term is particularly important because, in the absence of a permanent geologic disposal option, the SNF will need to be stored for decades longer than originally planned. Furthermore, the waste needs to be managed (*e.g.*, stored and packaged) in a way that will facilitate—not hinder—its eventual transport and disposal in a geologic repository. Because of the importance of the processes that could affect management and disposal of DOE SNF, the U.S. Nuclear Waste Technical Review Board (Board) has undertaken a review of the technical and scientific validity of DOE's SNF management activities. This report to Congress and the Secretary of Energy documents the Board's evaluation, findings, and recommendations.

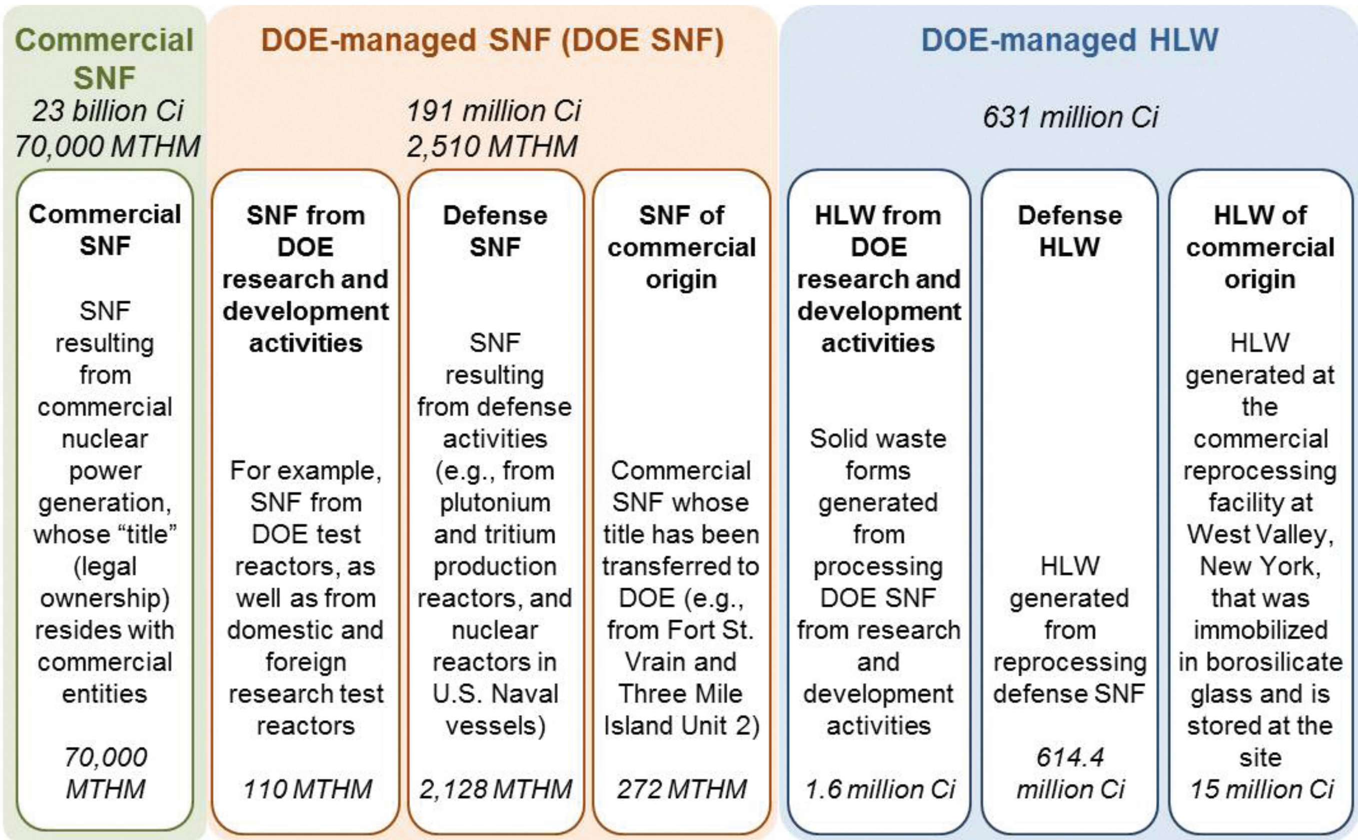

Figure ES-2. Wastes that require disposal in a geologic repository.
Categories of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) with relative radioactivity in curies (Ci) and mass in metric tons of heavy metal[2] (MTHM).

This report records the quantities and characteristics of DOE SNF by storage site and examines DOE's packaging and storage activities and plans related to DOE SNF. Figure ES-3 depicts the status of DOE management activities that lead to disposal of DOE SNF. The three main issues addressed in the report are aging management, packaging, and disposal of DOE SNF.

Quantities and Characteristics of Spent Nuclear Fuel

DOE currently manages about 2,500 MTHM of SNF, most of which is stored at four locations (Figure ES-3; Table ES-1): the Hanford Site in Washington State, the Idaho National Laboratory in Idaho, the Savannah River Site in South

[2] Metric ton of heavy metal is a commonly used measure of the mass of "heavy metal" initially present in nuclear fuel. Heavy metal refers to elements with an atomic number greater than 89 (*e.g.*, thorium, uranium, and plutonium). The mass of other constituents of the fuel, such as cladding, alloy materials, and structural materials, are not included. A metric ton is 1,000 kilograms, which is about 2,200 pounds.

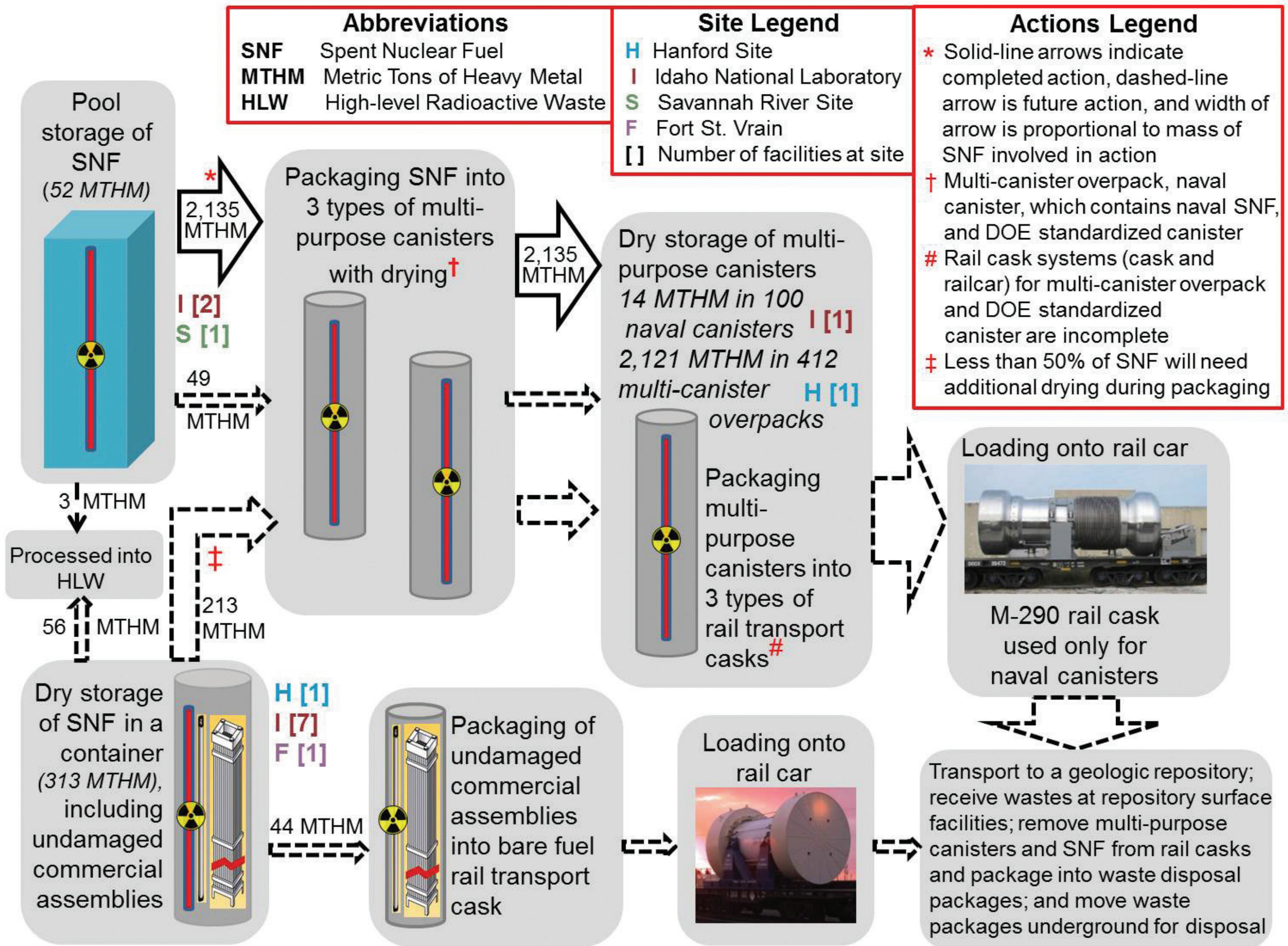

Figure ES-3. Status of activities that lead to disposal of U.S. Department of Energy spent nuclear fuel.
Simplified depiction of DOE SNF management activities at the Hanford Site, Idaho National Laboratory, Savannah River Site, and Fort St. Vrain independent spent fuel storage installation—from on-site storage of DOE SNF through disposal of SNF in a geologic repository. Mass of spent nuclear fuel in storage is depicted in *italics*. Status as of August 2014. Some stored SNF will be processed into HLW—56 MTHM of sodium-bonded SNF at Idaho National Laboratory and 3 MTHM of aluminum-based SNF at the Savannah River Site—and will not be disposed of as SNF. Damaged fuel of commercial origin will be packaged into the DOE standardized canister, a type of multi-purpose (storage, transportation, and disposal) canister.

Carolina, and the Fort St. Vrain independent spent fuel storage installation in Colorado. At these sites, DOE stores about 50 MTHM of SNF in storage pools—two located at Idaho National Laboratory and one at the Savannah River Site (Figure ES-3). The remaining inventory at the sites is stored dry in containers at 11 different dry storage facilities: two facilities at Hanford, eight facilities at Idaho National Laboratory, and one at Fort St. Vrain. At the time of writing, DOE is using six storage facilities, including two pools, beyond their 40-year design lifetimes.

Table ES-1. Mass and types of spent nuclear fuel stored at four locations

Storage Site	Mass of Stored Spent Nuclear Fuel Metric Tons of Heavy Metal	Number of Types of Spent Nuclear Fuel
Hanford	2,130	20
Idaho National Laboratory	325	250
Savannah River Site	30	60
Fort St. Vrain	15	1
Total	2,500	>250 (1)

Note: (1) Some types of spent nuclear fuel are stored at more than one location. In general, the complexity of spent nuclear fuel management activities correlates with the diversity of fuel types at a site.

The DOE SNF inventory consists of more than 250 types of SNF (Figure ES-4). The majority of DOE SNF—about 85% of the mass, in terms of MTHM—is from atomic energy defense activities. The defense-related inventory mostly comprises SNF from plutonium production reactors and nuclear reactors on U.S. Naval vessels. About 11% of the mass of DOE SNF is of commercial origin (Figure ES-2). This includes SNF from decommissioned commercial nuclear facilities such as the Fort St. Vrain nuclear power plant.

The DOE SNF inventory other than that of defense or commercial origin (the remaining 4% by mass) includes SNF from DOE research and development activities, as well as from domestic and foreign research and test reactors. Both Idaho National Laboratory and the Savannah River Site receive small amounts of SNF from foreign and domestic research reactors. However, the pool facility at the Savannah River Site has limited space available to accommodate more fuel so DOE is removing some aluminum-based SNF from the pool and processing it to create HLW (Figure ES-3).

Idaho National Laboratory continues to receive and store SNF from naval vessels. The existing building and equipment for handling naval SNF are over 50 years old and are too small to handle the largest fuel-containing components. In response, DOE decided to build a new naval SNF handling facility at Idaho National Laboratory. With that new facility, DOE will be able to load all naval SNF into multi-purpose (storage, transport, and disposal) naval SNF canisters, transfer the canisters into or out of temporary dry storage, and load waste shipping containers for transport to a repository. The acceptability of such containers for disposal depends on the repository design and is presently unknown.

Unlike commercial SNF, which basically has two types, the characteristics of DOE SNF vary widely. The inventory includes more than 10 different fuel compounds including uranium metal, thorium-uranium carbide, and thorium-uranium oxide. The range of cladding composition for DOE fuel is greater than for commercial fuel, with some compositions that can degrade during storage. Other characteristics of DOE SNF also vary. DOE SNF has a wide concentration range of fissile material that, at the higher end of the range, increases the potential for nuclear criticality. DOE SNF is more damaged than commercial SNF. Compared with commercial SNF, there is also less knowledge about the present physical state of DOE SNF, including its degree of degradation, and the potential for further degradation. The total mass-averaged radioactivity of DOE SNF—mainly from fission products—is about eight times less than that of commercial SNF.

The diverse physical and chemical properties of DOE SNF, and the degraded condition of some of it, drive the technical challenges associated with DOE's SNF management activities. In general, these challenges are increasing with time because of deleterious aging effects on both the cladding and fuel. Requirements stipulated in legal agreements and regulations add to the challenges DOE faces. For example, DOE faces a 2035 deadline to remove SNF from the state of Idaho, which affects

SNF management at Idaho National Laboratory. Also, the U.S. Nuclear Regulatory Commission (NRC) regulations for storage, transport, and disposal—to varying degrees—limit DOE's use of multi-purpose canisters (*i.e.*, canisters used for storage, transportation, and disposal) in which most DOE SNF, by mass, currently resides or is planned to be packaged into (Figure ES-3). Degradation of individual DOE SNF types also varies depending on the disposal environment.

In this report, the Board examines technical issues concerning DOE SNF packaging and storage resulting from both technical and external constraints that might affect continued storage, transport, and final disposal of the fuel. In its analysis, the Board assumes that DOE will use the three types of multi-purpose canisters that it has proposed [multi-canister overpack (MCO), naval canister—both of which are in use—and a DOE standardized canister that has yet to be deployed] to package and store DOE SNF. For the purpose of evaluating the conditions under which the three-canister approach might work, the Board's analysis also assumes that DOE will not remove SNF from the multi-purpose canisters and repackage it prior to disposal.

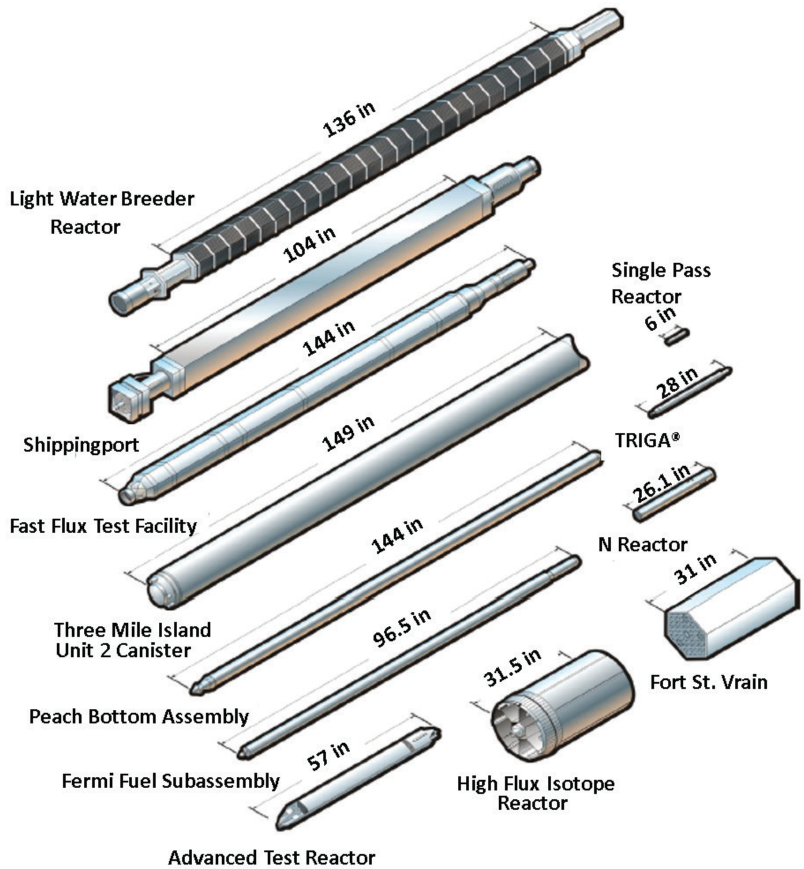

Figure ES-4. Some of the more than 250 spent nuclear fuel types and their sources.
The figure depicts a selection of the many types of DOE fuel and the reactors they came from. The small N Reactor SNF and Single Pass Reactor SNF, composed of uranium metal slugs, are types of defense SNF that were produced in plutonium production reactors at Hanford. Examples of commercial-origin SNF that DOE manages include Fort St. Vrain fuel, which is thorium-uranium carbide particles dispersed in graphite; Three Mile Island Unit 2 Canisters, which contain SNF debris, Light Water Breeder Reactor fuel, composed of thorium-uranium oxide pellets; and Shippingport SNF. High Flux Isotope Reactor and Advanced Test Reactor fuels, which have high fissile isotope concentrations and are aluminum-based, are examples of research reactor SNFs that are still being produced. (Source: INL 2007).

Aging Management Issues

As materials age, they can degrade. An aging management program manages degradation effects to ensure continued safe operations for extended periods of time. Different fuel compounds—and the cladding that surrounds the fuel—have different rates of degradation in storage (Figure ES-5) and the stability of an individual fuel compound or cladding material depends on the storage environment. For example, DOE's storage practices, particularly those of storing some aluminum-clad SNF in water pools, could adversely affect DOE's ability—decades in the future—to retrieve and package stored SNF into a canister (Figure ES-5A) for disposal.

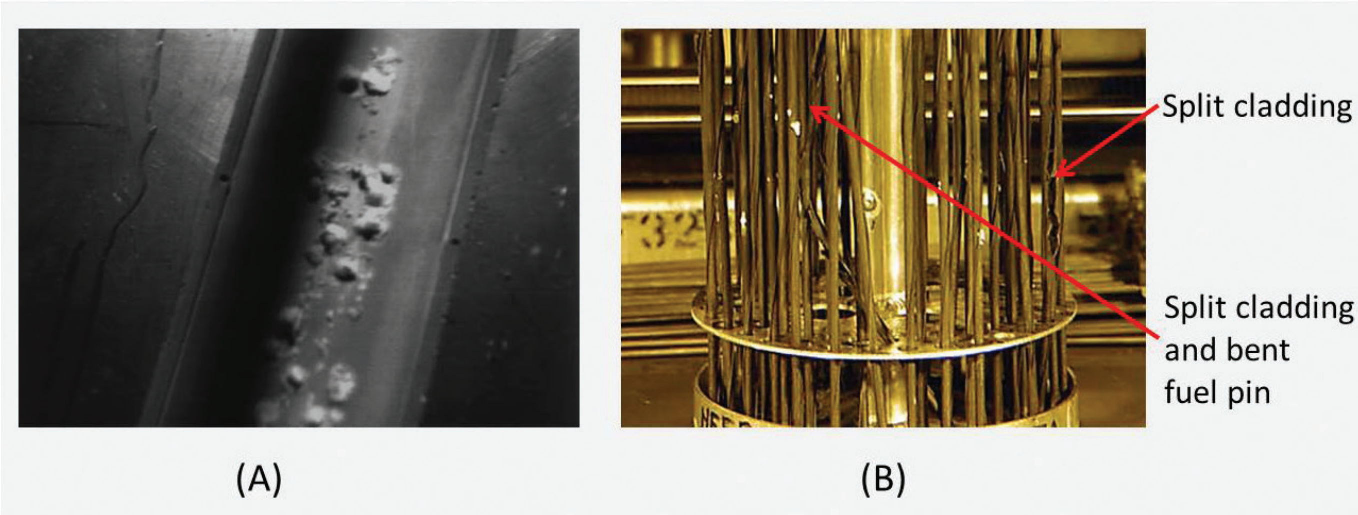

Figure ES-5. Examples of aging processes that have occurred during extended storage of U.S. Department of Energy spent nuclear fuel.
A. Pit corrosion damage on fuel plate cladding over fuel material region in an aluminum-based Materials Testing Reactor type–assembly (Source: Carlsen *et al.* 2005). The hydrated aluminum corrosion products complicate future drying of the fuel. B. Moisture in dry storage containers penetrated small holes—pinhole-sized—in stainless steel cladding surrounding the SNF from a reactor that used sodium for heat transfer (cooling) and reacted vigorously with metallic sodium inside the cladding, creating hydrogen and sodium hydroxide, which split the cladding. Hydrogen evolved and accumulated in the storage canisters due to the reaction of water with sodium. (Source: DOE 2006).

Different SNF storage container materials (*e.g.*, aluminum containers that hold aluminum-based fuel, stainless steel and carbon steel containers that hold a variety of SNF types, and concrete used for pools and dry storage facilities) also have different rates of degradation during storage that depend on the storage environment.

Some sodium-bonded SNF, which contains metallic sodium between the cladding and the fuel, has been stored in containers in a pool and in dry storage at Idaho National Laboratory. Under both wet and dry storage conditions, the SNF degraded when moisture entered either the storage container or the cladding of the fuel (Figure ES-5B). Because metallic sodium reacts with water to produce corrosive sodium hydroxide and hydrogen gas, DOE considers and treats sodium-bonded SNF as a hazardous waste. The DOE Office of Nuclear Energy (DOE-NE) is treating some sodium-bonded SNF in an electrochemical process that creates two new (other-than-glass) types of HLW. These new waste forms will need to be acceptable for disposal in a geologic repository.

Damaged metallic uranium SNF at Hanford corroded during storage in pools, which made DOE's retrieval and packaging process there more complex. DOE cleaned corrosion products (*e.g.*, loose corroded pieces of fuel and hydrated uranium and aluminum minerals) off the metallic SNF before packaging it into MCOs to minimize the amount of water that might be contained in the canister and to limit degradation of the SNF and canister during storage. The MCO design allows for monitoring of temperature, pressure, and gaseous constituents like hydrogen and oxygen—generated from interactions of radiation from the fuel with water remaining after drying and packaging—inside the MCOs during storage. DOE monitors representative MCOs, which include a range of contents from good undamaged fuel to baskets containing loose corroded pieces of SNF, to ensure MCO design limits (*e.g.*, gas pressurization) are not exceeded during storage.

Packaging Issues

Outstanding packaging issues primarily are related to the DOE standardized canister.[3] DOE has yet to finish research and development activities for the DOE standardized canister that will be needed to design and operate any packaging facility it develops. DOE still needs to develop both the remote welding techniques required to seal the canisters and the advanced neutron absorbers—metal sheets used to create baskets for the SNF—required to reduce the potential for criticality for canisters containing SNF with high fissile isotope concentrations. Finally, DOE also plans to add water-bearing pelletized supplemental neutron absorbers to hundreds of DOE standardized canisters, but DOE has not decided the final composition of material that will surround the absorbers.

Defining what is, and proving, suitable drying of the SNF and any water-bearing materials added during packaging of the DOE standardized canister is critical. Water remaining in the standardized canister after drying affects degradation within the canister and can create conditions (*e.g.*, generation of hydrogen) that impact the suitability for later canister transport. DOE needs NRC's approval before transporting the SNF from storage sites to either a centralized interim storage facility or a geologic repository. DOE model predictions for hydrogen concentrations inside the DOE standardized canister that it believes to be conservative show that hydrogen concentrations could exceed limits that NRC applies during transport package reviews. Similar models predict high hydrogen concentrations in stored MCOs. However, monitoring results for MCOs show that less hydrogen accumulates during storage than predicted.

Disposal Issues

The types of DOE SNF vary widely, are mostly different from commercial SNF, and will behave differently depending on the disposal environment. Since 2010, DOE's disposal research and development activities have focused on a range of geologic disposal options, including repositories in granite, clay/shale, salt, and deep boreholes. Earlier the focus had been on volcanic tuff. The variability in physical and chemical characteristics of the SNF affects processes that can occur in geologic repositories. If damaged, both uranium metal DOE SNF and thorium-uranium carbide DOE SNF can react with water and create gas. Understanding gas generation and migration is a key issue in the assessment of repository performance, especially for granite and clay/shale repositories. Some DOE SNF, such as uranium metal and aluminum-based SNF, will corrode after disposal and can create small particles (colloids) that affect the release of radionuclides from the waste package into the disposal environment.

The total radioactivity of DOE SNF is much less than commercial SNF (Figure ES-2). For a repository in which both commercial and DOE SNF are disposed of, the contribution of DOE SNF radioactivity to post-closure repository performance is generally unimportant. However, the total radioactivity from commercial and DOE SNF for some radionuclides, which can be important contributors to the post-closure repository performance, is dominated by a small mass (50 MTHM) of DOE thorium-uranium oxide SNF (roughly 2% of the total mass of DOE SNF). If DOE SNF is disposed of separately from commercial SNF (*e.g.*, a defense-only waste repository) the contribution of DOE SNF radioactivity to post-closure repository performance will be significant.

Findings and Recommendations

Based on the information developed in this report, the Board presents six principal findings and recommendations on managing and disposing of DOE SNF.

1. **Finding: DOE's aging management programs are not fully implemented.** Some DOE SNF storage facilities lack aging management programs to facilitate retrieving stored SNF and packaging it into multi-purpose canisters needed to

[3] The Board adopts DOE's nomenclature for this canister even though it is not standard by any conventional definition. The DOE standardized canister is a canister system that consists of four cylindrical stainless steel canisters with two different diameters (18 inches and 24 inches) and two different lengths (10 feet and 15 feet). The different sizes and eight internal basket designs of the multi-purpose canisters accommodate the wide dimensional variability of DOE SNF.

transport it to either a centralized interim storage facility or a permanent repository. Aging management programs also provide assurance that the SNF can continue to be safely stored and transported when required, and retrieved if necessary. For most of its SNF storage facilities, DOE has not completed an aging management assessment identifying the actions it should take now and in the future to facilitate retrieving stored SNF many decades from now. DOE does have an aging management assessment for the Savannah River Site pool facility, but it has yet to implement all the activities identified in the assessment. Furthermore, DOE has not completed aging management assessments that could facilitate continued use of the multi-purpose canisters at its existing storage facilities beyond 40 years and during subsequent transportation and geologic repository operations.

***Recommendation**: The Board recommends that DOE develop and fully implement programs to manage degradation of SNF, the materials that contain SNF, and SNF facilities for additional multiple decades of storage operations at all storage facilities. Managing degradation includes assessing its potential of occurring, and—when it is predicted to occur at unacceptable rates—monitoring storage conditions of the SNF and the materials in which it is stored to prevent degradation or to mitigate degradation effects. These programs should take into account five important considerations listed in Section 9.1.1.*

2. **Finding: Measuring and monitoring conditions of the SNF during dry storage is important.** The ability to measure and monitor conditions of the SNF in the storage facility during future dry storage (*e.g.*, monitoring gas composition in a multi-purpose canister like that being done for the MCOs) is important to the design, development, and deployment of new DOE storage systems. Although DOE has considered including monitoring capability for new storage systems, it has not done so in its baseline design for the DOE standardized canister.

   ***Recommendation:** The Board recommends that DOE include the capability for measuring and monitoring the conditions of the SNF in new DOE storage systems, such as the DOE standardized canister, and in new packaging and storage facilities to aid in establishing the condition of the SNF during subsequent operations and its acceptability for those operations.*

3. **Finding: An improved technical basis is needed for proposed drying procedures for DOE SNF before packaging it in multi-purpose canisters.** A better understanding of how much water remains in sealed multi-purpose canisters and the cumulative conditions inside the canisters adds confidence that proposed drying procedures for DOE SNF will be satisfactory. DOE assessed physical and chemical processes that could occur inside sealed DOE standardized canisters over a 50-year storage period. DOE proposed drying procedures for aluminum-based SNF, but it did not consider all the sources of water that could be in the canisters. It also did not account for how long the sealed multi-purpose canisters may serve as a radionuclide containment barrier. Using the expected amount of residual water, including chemisorbed water associated with supplemental neutron absorbers and hydrated SNF corrosion products, can improve DOE's understanding and technical basis for drying SNF. An understanding of gas composition and pressure in multi-purpose canisters can inform the technical and regulatory considerations for following storage, transport, and disposal operations. Predicting—and monitoring—gas composition and pressure of sealed multi-purpose canisters (see Recommendation #2) can confirm DOE's understanding of and the basis for its conclusion that proposed SNF drying procedures are adequate.

   ***Recommendation:** The Board recommends that DOE conduct research and development activities to confirm that reactions between DOE SNF and any water remaining in any multi-purpose canister do not cause cumulative conditions inside the canister (*e.g.,* combustibility, pressurization, or corrosion) to exceed either the design specifications or applicable regulatory operational requirements. The period of interest extends over the duration of canister use, including the time spent in storage, in transportation, and at a repository, until DOE closes the repository. These research and development efforts should include the six activities listed in Section 9.1.3.*

4. **Finding: Technical and regulatory uncertainties complicate planning for packaging facilities.** A key step in DOE's SNF management plans is developing packaging facilities at Idaho National Laboratory, Hanford, and Savannah River

Site for DOE SNF that still needs to be placed into about 3,500 DOE standardized canisters. DOE has not completed all the research and development activities for the standardized canister that will define the full capabilities required for a packaging facility. DOE does not know whether the packaging facility would be licensed by NRC, or which NRC licensing regulation(s) would apply if NRC regulated the facility. NRC will also need to approve the canister for transport years hence, and any conditions associated with NRC's approval could affect the design for the canister and packaging facility. These technical and regulatory uncertainties complicate planning for these packaging facilities, the first of which is planned for Idaho National Laboratory.

Recommendation: *To minimize complications in developing and operating a packaging facility for DOE SNF at Idaho National Laboratory, the Board recommends that DOE complete research, development, and licensing-related activities for the DOE standardized canister—and any other canisters that may be used—prior to completing the facility's preliminary design. In particular, DOE should complete the seven tasks related to the DOE standardized canister listed in Section 9.1.4.*

5. **Finding: Waste acceptance system requirements affect the disposition of DOE SNF and DOE-NE is not subject to the requirements.** Both the DOE Office of Environmental Management (DOE-EM) and the naval nuclear propulsion program are waste custodians and have signed agreements with the DOE Office of Civilian Radioactive Waste Management (OCRWM) to accept their SNF for disposal. These agreements require waste custodians to use waste acceptance system requirements, which apply to all SNF and HLW that will be disposed of in a repository, in order for the DOE organization responsible for waste disposal (at that time the agreements were signed it was OCRWM) to accept the waste for disposal. Both DOE-EM and the naval nuclear propulsion program continue to manage their waste according to the waste acceptance system requirements ("Civilian Radioactive Waste Management System Waste Acceptance System Requirements Document," Revision 5, ICN 01, DOE/RW-0351). DOE-NE manages some SNF and is treating sodium-bonded SNF to yield two HLW forms, both of which will need to be shown to be acceptable for geologic disposal. Previously, DOE-NE transferred some of its SNF from the Advanced Test Reactor to DOE-EM. DOE-NE is not a "waste custodian" and does not have a waste acceptance agreement with OCRWM.

   Recommendation: *The Board recommends that DOE-NE implement the existing OCRWM waste acceptance system requirements to increase the likelihood that SNF managed by DOE-NE and that waste forms resulting from electrochemical processing of sodium-bonded SNF will be acceptable for geologic disposal in a repository.*

6. **Finding: The diversity of DOE SNF combined with differences in physical and chemical characteristics of potential repository environments complicates the potential disposal of DOE SNF.** Since 2010, DOE has focused on alternative geologic disposal options, including generic environments other than tuff and deep borehole disposal of some types of wastes. The diversity of DOE SNF in terms of chemical composition and radionuclide content, combined with the diverse physical and chemical environments that can occur in repositories located in generic environments such as granite, clay/shale, and salt, complicates potential disposal of DOE SNF. Understanding processes that may adversely affect the isolation properties of the repository, such as gas generation, is a key issue in the assessment of repository performance. Evaluations of repository post-closure performance depend on the mass and radionuclides content of SNF in a specific package and the number of packages. The diversity of chemical and physical characteristics of DOE SNF leads to widely variable masses of SNF and radionuclides in each package, depending of the specific fuel type and the design of engineered barrier systems. DOE identified and prioritized its research on these different disposal environments based on disposing of commercial SNF without thoroughly considering the need to dispose of DOE SNF that has a wide variety of compositions and conditions.

   Recommendation: *If DOE continues to conduct generic investigations of a range of potential repository environments, the Board recommends that DOE identify and prioritize its research efforts concerning DOE SNF degradation related to disposing of DOE SNF in each of the potential host-rock environments. As part of this effort, DOE should complete the two tasks listed in Section 9.1.6.*

1. Introduction

The Nuclear Waste Policy Amendments Act of 1987 directs the U.S. Nuclear Waste Technical Review Board (Board) to "… evaluate the technical and scientific validity of activities undertaken by the Secretary [of Energy] … including activities relating to the packaging or transportation of high-level radioactive waste or spent nuclear fuel" (U.S. Congress 1987). The purpose of this report is to present the Board's review and evaluation of the U.S. Department of Energy's (DOE's) activities related to management and disposal of DOE spent nuclear fuel (SNF),[4] the simplified stages of which are depicted in Figure 1-1.

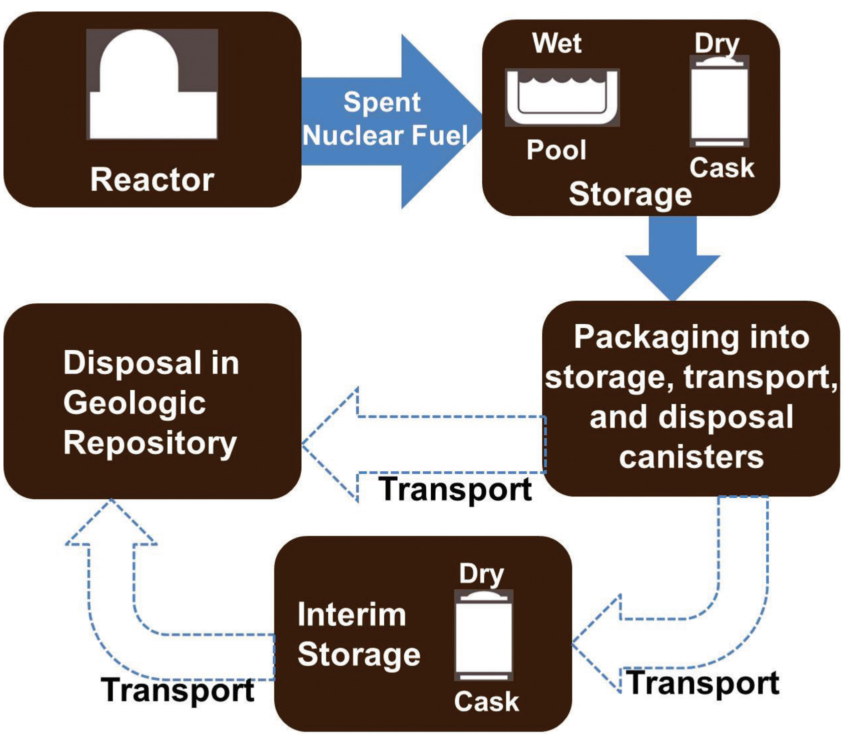

Figure 1-1. U.S. Department of Energy spent nuclear fuel management activities that lead to geologic disposal.
Once SNF is removed from a reactor, it is cooled and stored either in a pool (wet) or in variety of dry storage configurations, both indoors and outdoors, including casks, vaults, and other storage arrangements. Before the SNF can be stored, transported, or disposed of, it must be properly packaged to avoid any negative outcomes. For almost all of its SNF, DOE adopted a multi-purpose canister approach (appropriate for storage, transport, and disposal) to facilitate subsequent SNF management activities. Once packaged in a multi-purpose canister, DOE stores the SNF on site until it can be transported (dashed arrow indicates future activity) either directly to a geologic repository or to an off-site interim storage facility, and then transported again to a geologic repository. The complexities of DOE SNF, storage facilities, and each stage are addressed in Chapters 2–7 of the report and underpin the Board's evaluation of DOE's activities in Chapter 8.

[4] SNF is nuclear fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing. Upon first use in this chapter, underlined terms and phrases are explained in the Glossary (Chapter 11) and abbreviations are introduced.

The Board's review of DOE's SNF activities occurred over a timeframe in which DOE's disposal policies were changing and while DOE investigated different disposal options. The DOE disposal program evolved from the Federal Government pursuing a single proposed geologic repository at Yucca Mountain, Nevada, to the Obama Administration's decision to terminate the Yucca Mountain repository program. Following that decision, DOE began conducting non-site-specific repository studies and investigating disposal of some waste in deep boreholes. During the Board's review, DOE's program also changed from disposal of all SNF and high-level radioactive waste (HLW)[5] together in a single geologic repository to pursuing a separate defense waste geologic repository in addition to a geologic repository for other wastes (Figure 1-2). As of July 2017, DOE is no longer investigating deep borehole disposal or a separate defense waste repository.

Because of the ongoing uncertainty in disposal alternatives,[6] the Board's report focuses on continued storage of DOE SNF at the surface followed by some type of geologic disposal in a repository. Both continued storage and packaging of DOE SNF into disposal containers are necessary precursors to disposal (Figure 1-1); however, the choice of disposal options (*e.g.*, disposal rock type, and single or multiple repositories) is not strongly dependent on precursor steps. The Board takes no position on the disposal options but provides an analysis that can inform policy makers as they consider the nation's path for disposal of DOE SNF irrespective of the path(s) that are pursued.

DOE is responsible for transporting and disposing of SNF and HLW generated by both DOE and the commercial sector. Of these two types, this report focuses exclusively on managing and disposing of SNF under DOE's purview. This report does not consider management of commercial SNF owned by utilities or any HLW except as those wastes affect DOE's management of its SNF.

DOE SNF primarily includes material from defense-related activities (Figure 1-2). This material comes from programs that produce nuclear materials for nuclear weapons and other sources such as naval reactors (naval SNF). DOE SNF also comes from non-defense-related activities such as DOE research and development activities, commercial SNF that DOE took title to for testing and examination, and some SNF from decommissioned commercial nuclear facilities (*e.g.*, Fort St. Vrain nuclear power plant). In total, DOE is managing approximately 2,510 metric tons of heavy metal (MTHM) of DOE SNF.

DOE manages its SNF by handling, storing, and packaging it into multi-purpose canisters that can be used for storage, transport, and disposal (Figure 1-1). DOE SNF is currently stored either in wet (*i.e.*, water) or dry storage. As described in Chapter 2, characteristics of DOE SNF, such as chemical reactivity with water, require different handling, storage, and packaging options for different types of DOE SNF. DOE also "conditions"[7] the SNF (*e.g.*, by drying it) to make the SNF acceptable for dry storage, transportation, and disposal. In some cases, DOE SNF is not acceptable for disposal in its current form because it could be subject to regulation as hazardous waste under the Resource Conservation and Recovery Act of 1976 (U.S. Congress 1976). At one DOE storage site, there is insufficient capacity to continue to receive new SNF, and some of the existing stored SNF is vulnerable to corrosion under even well-maintained storage pool conditions. In these cases, DOE treats SNF by processing, which converts the SNF into HLW forms, such as glass logs and metallic waste. Currently, DOE does not separate any plutonium when it treats SNF, but instead will dispose of the plutonium as HLW. Thus, DOE uses the term processing, and this term is adopted in this report, for clarity, to describe any of DOE's SNF treatment processes that create HLW.

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[5] High-level radioactive waste is the highly radioactive material that results from SNF reprocessing. Historically, reprocessing also separated the fissile material for reuse. All defense-related domestic HLW is owned and managed by DOE. Some of the liquid HLW from reprocessing has been converted to solid form, *e.g.*, by vitrification and calcination, but most HLW created from reprocessing is in tanks in the form of liquid, salt cake, or sludge. The solid waste forms created from the tank wastes is also HLW. Treatment to convert the HLW into a solid form is necessary to meet transportation and disposal requirements.

[6] Although the President's budget request for fiscal year 2018 requests funding for the Yucca Mountain repository program, the Senate is considering, as of August 1, 2017, continuing used nuclear fuel disposition research and development activities instead.

[7] DOE defines conditioning as any process that prepares or treats SNF or HLW for transportation or disposal in accordance with regulatory requirements. The regulatory requirements, as well as legal agreements and records of decisions, which influence DOE's SNF management activities, are described in Chapter 3 of the report. Chapter 3 also describes how DOE's overall SNF management program addresses these constraints.

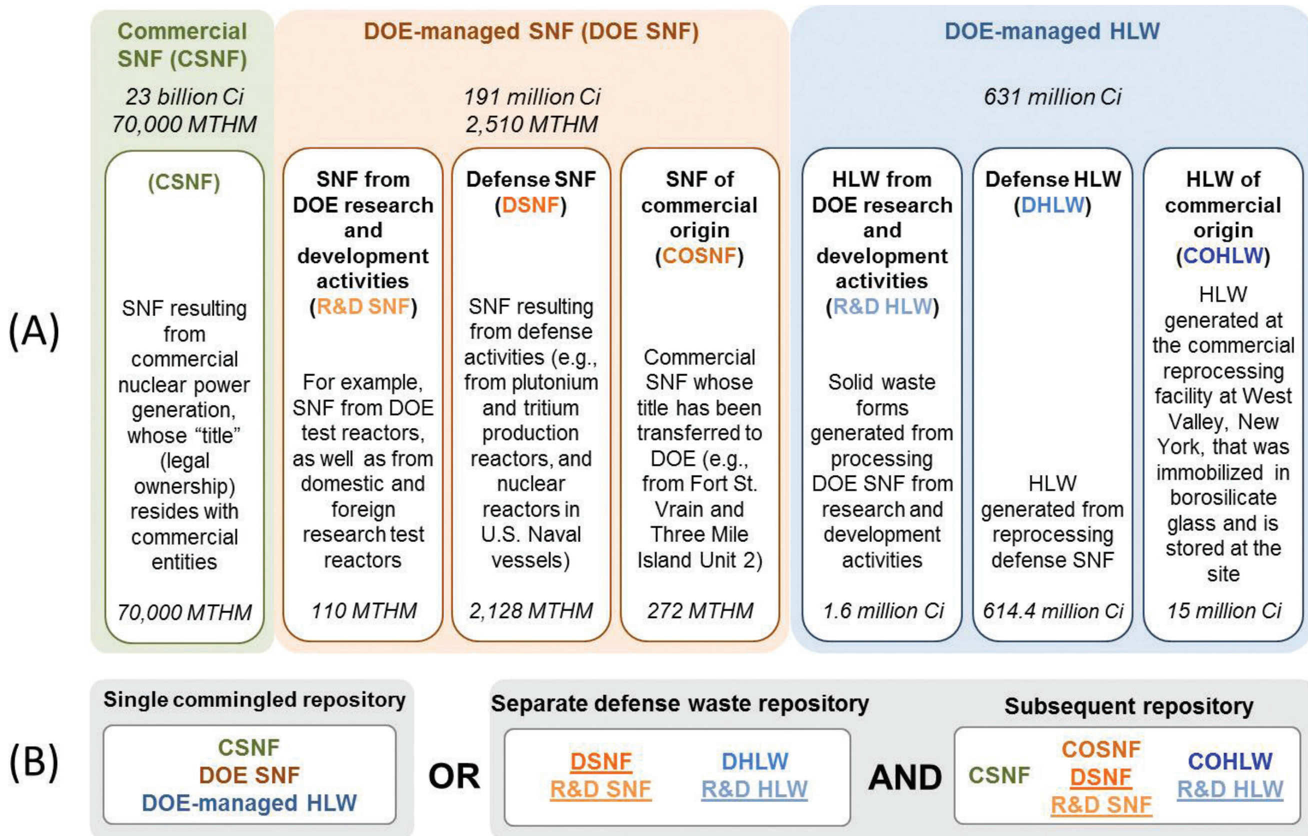

Figure 1-2. Wastes that require disposal in a geologic repository and their potential disposal options.
A. Categories of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) with relative radioactivity in curies (Ci) and mass in metric tons of heavy metal (MTHM) from Appendix 2 (see notes in Figure A2-6). B. Disposal options. Bold plain text categories (e.g., **CSNF** and **DHLW**) indicate disposal is required and underlined categories (e.g., **DSNF**) indicate that disposal is allowed and that some fraction of the category could be disposed in that repository.

The Administration's decision in 2010 (DOE 2010a) to stop work on the Yucca Mountain repository left DOE without a path to dispose of its SNF and HLW, and uncertainty in the requirements that would apply to disposal at another repository site. In 2010, DOE closed its Office of Civilian Radioactive Waste Management, which was responsible for transporting and disposing of SNF and HLW in a geologic repository. DOE reassigned some of that office's responsibilities to a number of other DOE offices, including the Office of Environmental Management and the Office of Nuclear Energy (DOE 2010b).

Shortly after DOE stopped work on the Yucca Mountain repository, President Obama directed the Secretary of Energy to establish a Blue Ribbon Commission on America's Nuclear Future to comprehensively review "policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense used nuclear fuel and nuclear waste" (Obama 2010). The Blue Ribbon Commission on America's Nuclear Future issued its final report on January 26, 2012 (BRC 2012). DOE responded to the report a year later with a strategy document (DOE 2013a). The strategy document "serves as a statement of Administration policy regarding the importance of addressing the disposition of used nuclear fuel and high-level radioactive waste; it lays out the overall design of a system to address that issue; and it outlines the reforms needed to implement such a system," and "presents the Administration's response to the final report and recommendations made by the Blue Ribbon Commission on America's Nuclear Future" (DOE 2013a). Although the DOE strategy mentions DOE SNF, it focuses primarily on commercial SNF.

The key goals and milestones in the DOE strategy relevant to managing and disposing of SNF are to

1. begin operating a pilot interim storage facility by 2021;
2. begin operating a larger interim storage facility by 2025;
3. have a geologic repository sited by 2026;
4. design and license the geologic repository by 2042; and
5. begin operating the geologic repository by 2048.

The pilot interim storage facility would be developed principally for SNF currently stored at shut-down commercial reactors and the larger interim storage facility would also, at least initially, be focused on commercial SNF. However, in the strategy document, DOE states that the feasibility of accepting "government-owned and managed used nuclear fuel and high-level radioactive waste" at interim storage facilities will be considered (DOE 2013a). DOE's strategy for all SNF and HLW management and disposal provides a framework for managing DOE SNF, but it would require legislative changes for implementation (DOE 2013a).

At the time its strategy was released in 2013, DOE's policy, in accordance with a 1985 Presidential finding (Reagan 1985), was to use a single repository for disposing of commercial and DOE SNF and HLW together (commingling). The DOE strategy document (DOE 2013a) indicated that the issue of commingling would be "subject to analysis" moving forward.

In October 2014, DOE completed an assessment of disposal options for DOE-managed HLW and SNF (DOE 2014) that considered using separate repositories for different types of SNF and HLW (Figure 1-2). The report recommended that DOE pursue different options for disposal of DOE-managed HLW from defense activities and some thermally cooler DOE-managed SNF, potentially including cooler naval SNF, separately from disposal of commercial SNF and HLW[8] (DOE 2014). The report also stated that other DOE-managed HLW and SNF, including HLW and SNF of commercial origin and naval SNF with relatively higher heat output, would be disposed of with commercial SNF and HLW. The report also recommended that DOE retain the flexibility to consider options for disposal of smaller DOE-managed waste forms in deep boreholes rather than in a mined geologic repository. DOE (2014) recommended a stepwise approach to disposing of the nation's HLW and SNF; such an approach could focus first on a repository for DOE-managed HLW and cooler DOE-managed SNF. DOE's recommendations were based on technical and programmatic considerations and did not include an evaluation of relevant regulatory and legal considerations (*e.g.*, the Nuclear Waste Policy Act–required evaluation).

In a document released in March 2015, DOE (2015a) evaluated the six factors identified in the Nuclear Waste Policy Act (U.S. Congress 1982) that are to be taken into consideration when making a Presidential evaluation about whether the development of a repository specifically for disposal of HLW resulting from atomic energy defense activities is "required." Based on the DOE (2015a) analysis, on March 24, 2015, President Obama recorded his finding that a separate repository for defense HLW is "required" (Obama 2015).

The categories of waste that require geologic disposal and their potential repository disposal options are described in Figure 1-2.[9] The Nuclear Waste Policy Act "prohibits the emplacement in the first repository of a quantity of SNF containing in excess of 70,000 MTHM or a quantity of solidified high-level radioactive waste resulting from the reprocessing of such a quantity of spent fuel until such time as a second repository is in operation" (U.S. Congress 1982). For the proposed geologic repository at Yucca Mountain, Nevada, DOE (2009a) allocated for emplacement 63,000 MTHM for commercial SNF,

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[8] Under the terms of the Nuclear Waste Policy Act (U.S. Congress 1982), commercial-origin SNF and HLW are not candidates for disposal in a separate repository for DOE-managed wastes that is sited and developed under the 1954 Atomic Energy Act. DOE retains the authority under the 1954 Atomic Energy Act to construct a repository that would be used exclusively to dispose of *both* defense HLW and SNF *as well as* HLW and SNF from DOE research and development activities (DOE 2014, 2015a, p. 2).

[9] The figure does not explicitly address disposal of wastes in deep boreholes. Some small-diameter waste forms in the categories of waste depicted for a separate defense repository could be disposed of in deep boreholes.

2,333 MTHM for DOE SNF, and 4,667 MTHM for HLW.[10] The quantity of commercial SNF, DOE SNF, and DOE-managed HLW (Figure 1-2A) are each greater than DOE's (2009a) allotment for the first repository.

In 2009, after the Administration decided that "Yucca Mountain is not a workable option" (Chu 2009), the Board stated that it would continue to monitor and evaluate DOE technical work related to managing and disposing of DOE's HLW and SNF (Garrick 2009). The Board also noted that the time at which a repository or storage location for SNF will become available is unknown, and that uncertainty may continue well into the future (Garrick 2010a). After the 2015 Presidential finding that a dedicated repository for defense HLW is "required," the Board evaluated some technical issues associated with developing a separate repository (Nuclear Waste Technical Review Board 2015a). In that report, the Board identified several issues related to DOE SNF as a waste form and indicated that it would elaborate on those issues in a future report.

This report elaborates on those issues and provides a summary of the quantities and characteristics of DOE SNF (Chapter 2), the legal and regulatory framework for managing and disposing of DOE SNF (Chapter 3), and the detailed characteristics of the facilities at four sites at which it is currently stored (Chapters 4, 5, 6, and 7). Based on this information, the Board reviews[11] the alternatives under consideration for continued storage to be followed by eventual disposal (Chapter 8).

Through this review, the Board identified technical issues that should be addressed as a result of

- the delay in developing a geologic repository for DOE SNF disposal;
- the uncertainties associated with the geologic media and engineered systems that may be used for disposal;
- DOE's use of three types of multi-purpose (storage, transportation, and disposal) canisters (multi-canister over-pack, naval canister, and a DOE standardized canister), without future SNF removal from the canisters and repackaging, to determine under what conditions that approach might work; and
- DOE's overall strategy for managing and disposing of DOE SNF and HLW.

The information on which this report is based was obtained during Board visits to the Hanford Site in Washington, the Idaho National Laboratory in Idaho, and the Savannah River Site in South Carolina, as well as from presentations made by representatives of DOE and other organizations at the Board's public meetings, the open technical literature, DOE's National Spent Nuclear Fuel Program, and analyses performed by the Board and the Board's staff. In providing its analysis of the issues associated with DOE SNF management that need to be addressed, the Board attempts to apply a broad and integrated systems perspective to the waste management program.

[10] For DOE HLW, emplacement limits are based on comparing the curie content (radioactivity) of a typical DOE HLW canister with the curie content of a typical commercial HLW canister. For design purposes, the DOE has used an estimate of 0.5 MTHM per canister equivalence for DOE HLW to determine the number of HLW canisters that can be accepted within the planned DOE material allocation. The sum total of HLW canister production from the DOE sites is expected to far exceed the 4,667 MTHM allowed total (DOE 2009a).

[11] For naval SNF the review is limited as details on characteristics of naval SNF and its management are not publicly available.

2. Characteristics of U.S. Department of Energy Spent Nuclear Fuel and Its Management and Disposal

2.1 Spent Nuclear Fuel

The total quantity of U.S. Department of Energy (DOE) spent nuclear fuel[12] (SNF) is approximately 2,510 metric tons of heavy metal (MTHM).[13] The volume of this SNF is approximately 3,670 cubic meters. Most of the DOE SNF is stored at four sites: the Hanford Site, Idaho National Laboratory (INL), Savannah River Site (SRS), and the Fort St. Vrain (FSV) independent spent fuel storage installation. The approximate mass of SNF at each site is provided in Figure 2-1. A small amount (~10 MTHM) of DOE SNF is at other locations (not shown in Figure 2-1), including at 30 domestic research reactors—mainly at universities (Morrell 2011). The inventory of DOE SNF (2,510 MTHM) is larger than the DOE SNF allocation[14] (2,333 MTHM; DOE 2009a) for the first geologic repository.

About 85% (by mass) of DOE SNF derives from atomic energy defense activities (*e.g.*, plutonium and tritium production reactors, and nuclear reactors in U.S. Naval vessels). The Naval Nuclear Propulsion Program manages naval SNF.[15] The program is operated jointly by the Navy and DOE, and DOE is responsible for the ultimate disposition of naval SNF. The DOE SNF also comes from non-defense-related activities such as DOE research and development activities, commercial nuclear facilities that were decommissioned decades ago, and commercial SNF that DOE took title to for testing and examination.

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[12] Upon first use in this chapter, underlined terms and phrases are explained in the Glossary (Chapter 11) and abbreviations are introduced.

[13] The mass and volume of SNF changes with time as new SNF is generated. The quantities of SNF presented in this report represent a snapshot of the DOE SNF inventory as of 2011. The values used in this report are from a query of DOE's Spent Fuel Database (described in INL 2007), Version 6.2.3, released on March 24, 2011, provided by Sandra Birk, Idaho National Laboratory, e-mail message, with attachments, to Gene Rowe, former NWTRB staff, January 21, 2013. From 2011 until 2016, the database was accessible but not maintained or updated. The quantities of SNF at the four sites and at other locations are listed in Table A1-1.

[14] DOE allocated 2,333 MTHM of DOE SNF, including 65 MTHM of naval SNF and 2,268 MTHM of non-naval DOE SNF (DOE 2009a, Table 1.5.1-1). The inventory of naval SNF is 28 MTHM as of August 2014 and will grow to 65 MTHM as SNF is removed from naval vessels with nuclear propulsion units. The inventory of non-naval DOE SNF is 2,482 MTHM.

[15] Many characteristics of naval SNF and information on its management are generally not publicly available.

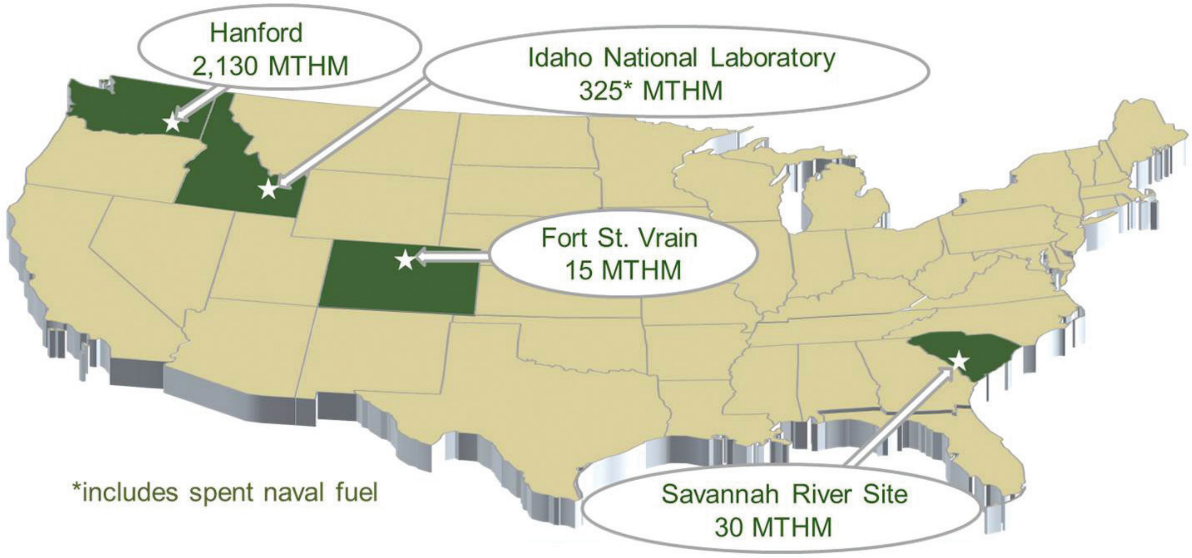

Figure 2-1. The approximate mass of U.S. Department of Energy spent nuclear fuel at four sites.
Mass of spent nuclear fuel is in metric tons of heavy metal (MTHM).

The quantities of DOE SNF, in MTHM, for major categories of DOE SNF are presented in Figure 2-2. SNF from the N Reactor, which was a plutonium production reactor, is the largest contributor, by mass, to the total inventory. Both the N Reactor fuel and the chemical reactions that affect its management and disposal are described in Box 2-1.

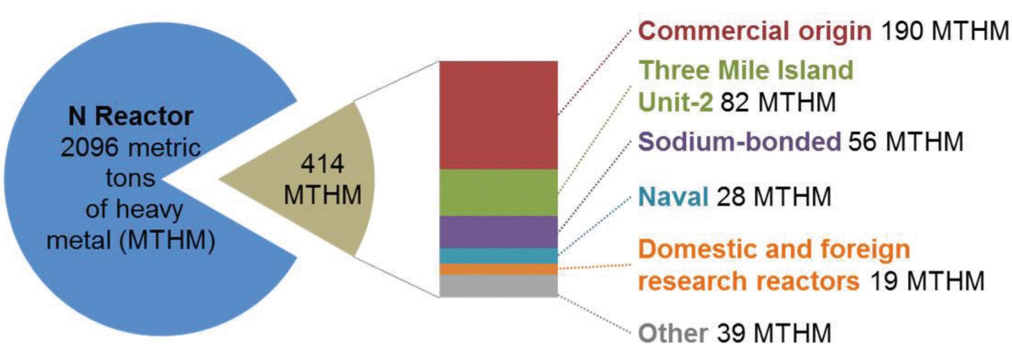

Figure 2-2. Mass of U.S. Department of Energy spent nuclear fuel for major categories of fuel.
The approximate mass of spent nuclear fuel in MTHM is provided for major categories of DOE SNF. Information on the groups[16] of DOE SNF within the categories is provided in Appendix 1. The tan wedge is expanded into six categories to the right. The combined mass of the N Reactor, naval categories, and 4 MTHM from the other category is the mass of the "Defense SNF" category depicted in Figure 1-2. The combined mass of the commercial origin and Three Mile Island Unit 2 categories is the mass of the "SNF of commercial origin" category depicted in Figure 1-2. The combined mass of the sodium-bonded and domestic and foreign research categories, and 35 MTHM from the other category, is the mass of the "SNF for DOE research and development activities" category depicted in Figure 1-2.

[16] DOE classified all of its SNF into 34 groups (DOE SNF Groups; Table A1-1) based on fuel characteristics that have a major impact on the release of radionuclides from DOE SNF and are important to nuclear criticality. DOE aggregated its SNF into different groups, for example "degradation groups" and "criticality groups," using the 34 DOE SNF Groups. For instance, degradation group 2 consists of DOE SNF Groups 3 and 4.

A. N Reactor fuel prior to irradiation. (Source: McCormack 2014a).

B. Damaged cladding on outer element and corroded fuel. (Source: McCormack 2014b).

C. Damaged and corroded fuel element. (Source: Abrefah et al. 2002).

At the Hanford Site, DOE stores large quantities of zirconium-alloy-clad (Image A) N Reactor SNF that was generated as part of the defense weapons-grade plutonium production program. Some of the SNF cladding was damaged, exposing the metal fuel, when DOE discharged the fuel from the reactor. The exposed uranium metal in the damaged fuel subsequently corroded during more than a decade of wet storage in two basins (Images B and C). DOE retrieved the SNF from the basins, cleaned it, packaged and dried it, and stored the dried fuel in helium-filled canisters.

Uranium metal is chemically reactive in air and water environments. In such environments uranium metal oxidizes to increasingly higher oxidation states (a higher ratio of oxygen to uranium) until the oxygen in a closed system is consumed or until a stable oxide is reached (*e.g.*, UO_3).

Uranium metal also reacts with hydrogen to form uranium hydride, which is also chemically reactive. Uranium hydride can react vigorously with water or water vapor, producing uranium dioxide and hydrogen, or with oxygen, generating uranium dioxide plus hydrogen or water, depending on the relative concentration of oxygen. Both uranium metal and uranium hydride are pyrophoric materials, which means they can spontaneously ignite in the presence of air. This is of concern when these materials are in a form with a high specific surface area (ratio of surface area to mass), which is always the case for uranium hydride. Uranium dioxide, formed from uranium metal and uranium hydride reactions, hydrates in water, forming uranyl hydrate minerals with varying amounts of water incorporated into their structure that complicates drying of the SNF, which is part of the packaging process for dry storage of SNF.

Processes that occur during dry storage, such as gas pressurization resulting from chemical reactions, can affect continued use of the canisters. Because the SNF drying process does not completely remove all water from the canisters, reactions between the uranium minerals and water vapor, oxygen, and hydrogen can continue during dry storage. Two additional processes can occur during dry storage. First, water vapor can be released into the surrounding gas in the canisters as liquid water evaporates or from decomposition of uranyl hydrate minerals. Second, radiolysis, which is the molecular decomposition of a substance by ionizing radiation, of residual water and water-containing minerals, such as uranyl hydrates, will generate hydrogen and oxygen.

Because of the many reactions that can occur, understanding how damaged uranium metal SNF evolves during wet storage, drying, and dry storage is a challenge. Monitoring sealed dry storage canisters for temperature, pressure, and gaseous constituents provides key insights on that evolution.

Box 2-1. N Reactor spent nuclear fuel and chemical reactions affecting its management and disposal

The category "commercial origin" SNF in Figure 2-2 includes (1) commercial SNF that was sent to the reprocessing plant at West Valley, New York, but was not reprocessed before the plant shut down permanently (now stored at INL); (2) SNF from the decommissioned FSV reactor (stored at INL and FSV); (3) SNF from the decommissioned Peach Bottom Unit 1 reactor (stored at INL); and (4) small amounts of SNF from over 20 other commercial reactors (stored at Hanford, INL, and SRS). Although depicted as a separate category in Figure 2-2, Three Mile Island Unit 2 (TMI-2) core debris stored at INL is also of commercial origin. The DOE SNF of commercial origin totals about 272 MTHM.

The U.S. Government Accountability Office (GAO 2011) noted that the total mass of DOE SNF will grow by about 1% through 2035, which is the end date that DOE used to evaluate environment impacts from its SNF management efforts. The growth will occur as SNF is removed from naval vessels with nuclear propulsion units and, to a lesser extent, due to SNF that DOE is responsible for from domestic and foreign research and test reactors. The DOE program that takes custody of SNF from foreign research reactors—described in Section 3.2—expires in 2019.

The slight growth in DOE SNF inventory over time takes into account of the projected removal of about 1% of the current DOE SNF inventory that is unsuitable for disposal in its present form and is processed into high-level radioactive waste (HLW) at the Materials and Fuel Complex at INL and H Canyon at SRS. Although the mass of SNF will increase by about 1% through 2035, the volume of DOE SNF will approximately double, which is due to removal of SNF from naval vessels in the form of entire cores. These cores contain both assemblies of SNF and portions of the structural components of the reactor, which are then stored in large-volume canisters (see Appendix 2 and discussion of canisters in Section 2.3.2).

The inventory of DOE SNF includes (1) intact, non-defective fuel assemblies and fuel rods; (2) failed fuel assemblies (*e.g.*, broken) and fuel rods (*e.g.*, ruptured cladding); (3) segments of fuel rods and pieces of fuel derived from SNF rods resulting from experimental activities at DOE national laboratories; and (4) nonfuel components and structural parts of irradiated fuel assemblies (*e.g.*, "control rods"). There are over 200,000 fuel pieces or assemblies of DOE SNF that are handled individually. The inventory includes a large number of pieces from a single reactor (*e.g.*, approximately 105,000 N Reactor fuel elements; Loscoe 2000) all managed at a single site, Hanford, and a few individual pieces from other, in some cases unique, reactors (DOE 2009a). The DOE SNF inventory also includes debris.[17]

The characteristics of DOE SNF vary greatly. For example, there are over 250 types of DOE SNF that DOE has grouped into 34 categories (see Appendix 1). Twelve types of DOE SNF are depicted in Figure 2-3.

Most types of DOE SNF have important characteristics that are different from commercial SNF. Primarily, these differences occur in the chemical forms of the SNF, which include the chemical form of the nuclear material and any matrix containing the nuclear material, the cladding materials that encase the SNF, and the isotopic composition of the nuclear material. These different characteristics affect the SNF's chemical stability and potential for gas generation, decay heat generation, and inadvertent nuclear criticality. For example, some DOE reactors used sodium as a coolant. The "sodium-bonded" fuel from some of these reactors also has sodium inside the fuel rod between the fuel and the cladding (Figure 2-4A and Box 2-2). This sodium-bonded SNF can degrade during storage (Figure 2-4B and Figure 2-4C) and is unsuitable for disposal in its current form.

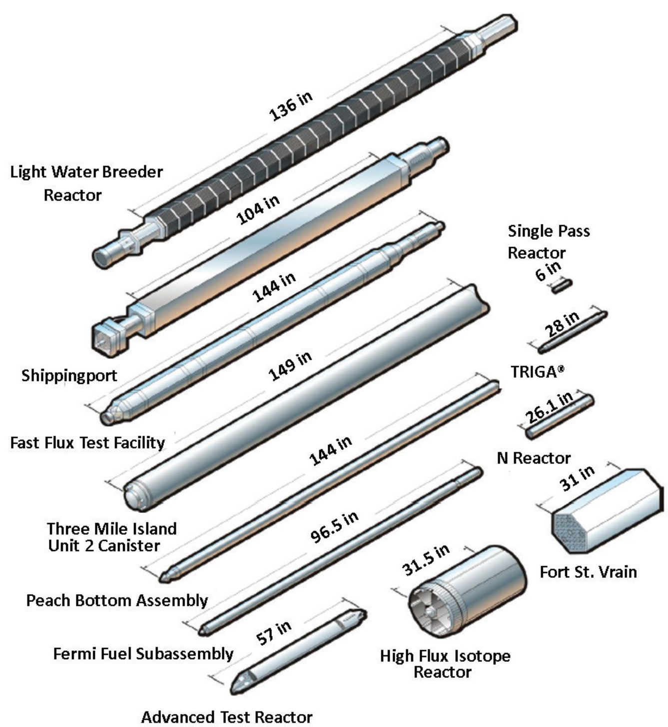

Figure 2-3. Comparison of size of 12 of the approximately 250 spent nuclear fuel types and their sources.
The figure depicts a selection of the many types of DOE SNF and the reactors they came from—some of which are described further in the following caption text. Defense SNF produced in plutonium production reactors includes the very small N Reactor SNF and Single Pass Reactor SNF, both composed of uranium metal. Examples of commercial-origin SNF that DOE manages include Fort St. Vrain fuel, which is thorium-uranium carbide in graphite; Three Mile Island Unit 2 Canisters, which contain SNF debris, and Light Water Breeder Reactor fuel, composed of thorium-uranium oxide pellets; and Shippingport SNF. Research reactor SNF that is still being produced includes High Flux Isotope Reactor and Advanced Test Reactor fuels, which have high concentrations of fissile material and are aluminum-based. (Source: INL 2007).

[17] For example, at Hanford the debris includes knockout pot sludge, which refers to material (ranging in size from 500 microns to 0.25 inches) that was loosened from cleaning N Reactor SNF, as well as SNF elements from other Hanford production reactors that was collected as the fuel was being transferred to multi-purpose canisters.

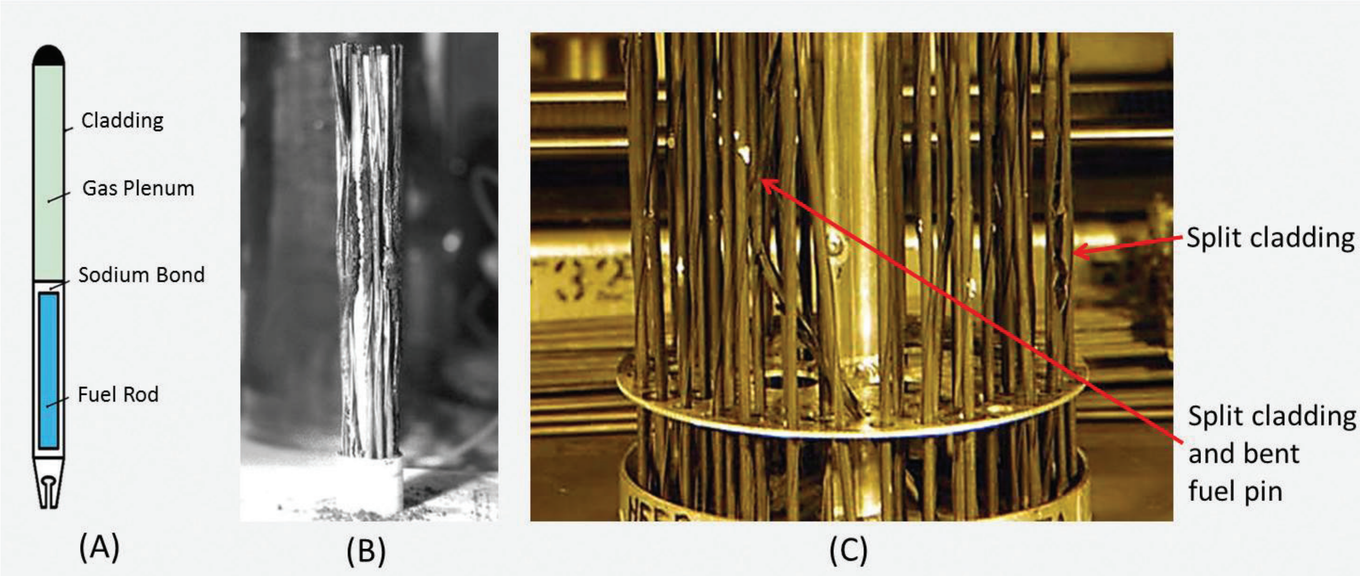

Figure 2-4. Sodium-bonded SNF from the Experimental Breeder Reactor 2.
A. Sodium-bonded driver fuel element from INL's Experimental Breeder Reactor 2. (Source: DOE 2006). B. Corroded SNF elements from a sealed metallic canister, initially air-filled, that leaked while in a water storage basin. After leakage of water into the container, corrosion of the stainless steel cladding in some elements ruptured the cladding (Pahl 2000). The metallic fuel reacted with water to produce hydrogen gas and uranium corrosion products, and also released radionuclides into the water in the container. (Source: DOE 2006). C. Moisture in dry storage containers penetrated small holes—pinhole-sized—in stainless steel cladding surrounding the spent nuclear fuel from a reactor that used sodium for heat transfer (cooling) and reacted vigorously with metallic sodium inside the cladding, creating hydrogen and sodium hydroxide, which split the cladding. Hydrogen evolved and accumulated in the storage canisters due to reaction of water with sodium. (Source: DOE 2006).

Why does sodium-bonded SNF require special consideration and treatment?

"Metallic sodium reacts with water to produce explosive hydrogen gas and corrosive sodium hydroxide that would likely not be acceptable for geologic disposal" (DOE 2000a). Elemental sodium is considered a hazardous waste and is regulated under the Resource Conservation and Recovery Act (RCRA) of 1976 (U.S. Congress 1976). Sodium-bonded SNF is not listed under RCRA as a hazardous waste, but it could be considered characteristically hazardous under RCRA because of its chemical reactivity.

What types of sodium-bonded SNF does DOE manage?

Sodium-bonded SNF was generated from the operation of fast reactors as part of DOE's fast nuclear reactor development program. Unlike typical commercial nuclear reactors that use water as a coolant and uranium oxide as fuel, fast reactors used sodium as a coolant and, almost exclusively, uranium metal (Experimental Breeder Reactor 2) or uranium-molybdenum alloy (Fermi-1) as a fuel. Other fuels, including test assemblies with uranium-zirconium alloy and uranium–plutonium-zirconium alloy driver fuel pins (Fast Flux Test Facility), constitute less than 1%, by mass, of sodium-bonded SNF. Those fast reactors that used two types of fuel (Experimental Breeder Reactor 2 and Fermi-1), known as driver and blanket fuel, created two types of sodium bonding in the fuel.

What are the differences between driver and blanket fuel?

Driver fuel contains high-enriched uranium, with more than 65% uranium-235, while blanket fuel contains depleted uranium, with less than 0.35% uranium-235. Both the blanket and driver fuel contain metallic sodium between the stainless steel cladding (outer layer) and the metallic fuel pins inside. During irradiation in the reactor, this cladding served to isolate fuel and fission products from the reactor coolant. The sodium metal melted during reactor operation by design and enhanced heat transfer from the fuel. When driver fuel was irradiated for some period of time, metallic sodium entered the metallic fuel and became inseparable from it. In addition, "fuel and cladding components inter-diffused to such an extent that mechanical stripping of the driver spent nuclear fuel cladding is not a practical means of removing sodium" (DOE 2000a). When metallic blanket fuel was irradiated, it did not swell to the same degree as the driver fuel because less fission occurred. "Minimal metallic sodium entered the [blanket] fuel and there was no inter-diffusion between the fuel and cladding" (DOE 2000a). This allows mechanical stripping of the metallic blanket SNF cladding. Because of these differences between irradiated driver fuel and blanket fuel, there are different treatment alternatives for each fuel type.

Box 2-2. Sodium-bonded spent nuclear fuel

The ranges of DOE SNF characteristics as described by DOE (2009a), such as fuel and cladding composition and thermal output, are generally greater than those of commercial SNF (see Table 2-1). DOE SNF has been discharged from a wide variety of reactor types. The DOE SNF has different designs (size, shape, and composition), cladding materials, and degrees of cladding degradation[18] (DOE 2009a). DOE SNF also has a wide range of enrichments (varying from depleted uranium to over 93% enriched uranium-235, compared with enrichments in commercial SNF of 0.27% to 4.95%; DOE 2009a). In some cases, the DOE SNF fuel compounds were incorporated in a matrix composed of other material such as graphite or zirconium-oxide. In addition, the stored DOE SNF may not have cladding that can serve as a long-term barrier to release of radionuclides because it either lacks cladding or because the cladding is too degraded.

In contrast to DOE SNF, there is only one commercial SNF fuel compound (uranium dioxide) and it is not incorporated into a non-nuclear-material matrix. This commercial fuel has cladding that generally is not currently degraded and is not readily degraded in most common environments such as air and water.

The chemical form of the DOE SNF affects its chemical reactivity and potential gas generation during storage, during transportation, and after disposal in a geologic repository. For example, sodium-bonded SNF (Box 2-2) and uranium metal SNF (Box 2-1) are chemically reactive with water and air if the cladding is breached. Carbide-containing DOE SNF can create combustible gases such as methane and acetylene when contacted by water (Kingrey 2003) if the coatings on the carbide particles are damaged.

"Naval SNF consists of solid metal and metallic components that are nonflammable, highly corrosion-resistant, and neither pyrophoric, explosive, combustible, chemically reactive, nor subject to gas generation by chemical reaction or off-gassing" (DOE 2009a). Naval nuclear fuel is highly enriched (approximately 93–97 weight %) in the isotope uranium-235. Unlike the four general categories of DOE cladding for DOE SNF, naval cladding is categorized as intact[19] or nonintact (DOE 2009a, p. 1.5.1-64). Most naval SNF cladding is intact—less than 2% of the approximately 400 loaded naval SNF canisters will contain naval SNF with nonintact cladding (DOE 2009a). DOE took credit for the naval fuel as an item important for waste isolation in the Yucca Mountain license application[20] but did not credit DOE SNF as an item important for waste isolation (*i.e.*, DOE SNF does not prevent the release or substantially reduce the release rate of radionuclides from the waste).

2.1.1 Criticality

Criticality[21] is when nuclear fuel sustains a fission chain reaction. Primarily due to differences in the isotopic composition of the fuel, several types of DOE SNF have significantly higher criticality potentials during storage, handling, and disposal than those for commercial SNF.

As a standard practice, inadvertent criticality (an uncontrolled chain reaction) evaluations for storage and handling operations focus on worker safety because criticality can create dangerous radiation fields. Also as a standard practice, criticality in an underground repository after disposal is also considered and analyzed by the disposal operator to determine the design of the SNF basket that will maintain a known geometry of the SNF after disposal and the materials[22] that should be added to the disposal canister to limit the potential for criticality to occur.

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[18] Unlike non-naval DOE SNF, most naval SNF cladding is intact—"less than 2% of the approximately 400 loaded naval SNF canisters will contain nonintact naval SNF" (DOE 2009a). Intact cladding inhibits degradation of the SNF during storage and subsequent fuel cycle steps.

[19] "Intact cladding is undamaged but may have hairline cracks or pinhole leaks in very few cases. Cladding with hairline cracks or pinhole leaks is not 'damaged fuel' as defined in the U.S. Nuclear Regulatory Commission's (NRC)" (DOE 2009a) guidance for interim storage and transportation (NRC 2007). The nonintact category means "cladding has either been intentionally removed to expose fuel for examination during material testing or tested to failure" (DOE 2009a).

[20] NRC's review of the license application, including classified information on naval SNF, addressed DOE's (2009a) description of the naval SNF (NRC 2014a). NRC noted that the "naval SNF is more robust and would release less radionuclides than commercial SNF" (NRC 2014a, p. 7-20).

[21] Criticality is the normal operating condition of a reactor, in which nuclear fuel sustains a fission chain reaction. A reactor achieves criticality (and is said to be critical) when each fission event releases a sufficient number of neutrons to sustain an ongoing series of reactions. In nuclear waste management, criticality refers to the probability and circumstances in which a quantity of waste could achieve criticality.

[22] Adding a neutron-absorbing material, such as a metallic basket or pellets containing hafnium or gadolinium, reduces the number of neutrons available for fission. Both hafnium and gadolinium are strong neutron absorbers.

Table 2-1. Comparison of properties of commercial spent nuclear fuel and U.S. Department of Energy spent nuclear fuel[23]

	Commercial (1 - see Notes below)	**DOE (2)**
Configuration	Assemblies containing a square array of fuel rods	Tubes, plates, rods, cans of scrap, scrap, assemblies, elements, pin clusters, and capsules
Length (feet)	7–16.6 (mostly ~14–16)	0.3–14.7
Width or diameter (inches)	4.28–8.54	0.2–22.3
Cladding composition	Zirconium-based alloys and stainless steel	No cladding, Zirc (which includes zirconium and Zircaloy™), stainless steel, Hastelloy™, aluminum, Incoloy™, and other (for example, lead covered by aluminum covered by aluminum-silicon)
Cladding condition (3)	Good (generally)	Good, fair, poor, and none
Fuel compound (4)	Uranium dioxide	Uranium metal (84%), uranium-zirconium (0.27%), uranium-molybdenum (0.16%), uranium oxide including uranium dioxide (8%), uranium-aluminum (0.38%), uranium silicide (0.28%), thorium-uranium carbide (1.05%), plutonium-uranium carbide (0.003%), mixed oxide (0.51%), thorium-uranium oxide (2.0%), and uranium-zirconium hydride (0.08%)
Fuel matrix	None	None, graphite, zirconium-oxide, zirconium-oxide-calcium-oxide, and aluminum
Enrichment in percent U-235 (5)	0.27–4.95	0.2–93
Burnup (Gwd/MTU) (6)	Average: **28.6**/<u>36.2</u> Maximum: **65.1**/<u>69.4</u>	0.1–500
Thermal output (watts) (7)	186 and 601	<50 to >2,000
Approximate average thermal output in 2030 (watts/MTHM) (8)	1,278	206

Notes
(1) Information from Wagner *et al.* (2012), Carter *et al.* (2012), and DOE (2009a). Reflects assembly data of discharged SNF as of December 31, 2002.
(2) Information from DOE (2009a) and Carter *et al.* (2012).
(3) Cladding conditions are defined by DOE (2009a) as good (*i.e.*, no known or suspected through-cladding defects), fair (*i.e.*, known or suspected defects are limited to hairline cracks or pinhole leaks), poor (*i.e.*, known or suspected defects are greater than hairline cracks and pinhole leaks), and none (*i.e.*, declad or unclad SNF).
(4) The quantity of each DOE fuel compound as a percent of the total mass of DOE SNF is shown in parentheses (percentages are calculated relative to total inventory of approximately 2,510 MTHM). For example, the mass of uranium metal fuel is 2,110 MTHM and is about 84% of the total mass of DOE SNF. The listed percentages do not total to 100 because sodium-bonded SNF and naval SNF account for the remainder of the mass of DOE SNF and are not categorized by fuel compound (see Table A1-1, Groups 31 and 32).
(5) High-enriched uranium means the concentration of uranium-235 has been increased through isotopic separation processing from its naturally occurring value of 0.71% to 20% or greater.
(6) Burnup is a measure of the thermal energy that has been extracted from the fuel; it is presented in the table in units of gigawatt-days per metric ton of uranium (GWd/MTU). In the case of commercial SNF, the values reflect average and maximum burnup of assemblies for the two types of commercial reactors: boiling water reactors (**in bold**) and pressurized water reactors (<u>underlined</u>). The range of burnup for DOE SNF is provided.
(7) Decay heat output for commercial SNF is given per SNF assembly, 25 years after discharge from a reactor (DOE 2009a, Table 1.5.1-11). The figure of 186 watts is for an average boiling water reactor, and the figure of 601 watts corresponds to SNF from an average pressurized water reactor. The range of thermal output shown for DOE SNF is per canister in 2030 (Carter *et al.* 2012).
(8) Average decay heat output for commercial SNF, in watts per MTHM, is calculated using information on the average age of commercial SNF, the discharge rate of SNF from commercial reactors, and thermal output for both types of commercial SNF assemblies (pressurized water reactor and boiling water reactor), weighted by each type's share of the overall commercial SNF inventory. In 2011, the average age of commercial SNF since discharge was about 15 years (Carter *et al.* 2012, Table 3-4). Given that the current discharge rate from commercial reactors is approximately 2,000 MTHM per year, the average age of commercial SNF in 2030 will be about 25 years. Given a total of 221,000 commercial SNF assemblies (DOE 2009a, Table 1.5.11), of which about 57% are from boiling water reactors (Carter *et al.* 2012, Table 3-4), the total thermal output of commercial SNF assemblies is approximately 8.05×10^7 watts. The average thermal output for commercial SNF is calculated by dividing this estimate of total thermal output by the total mass of commercial SNF, at approximately 63,000 MTHM (DOE 2009a, Table 1.5.11). The average thermal output for DOE SNF is calculated given a total thermal output, for the nominal case, of 4.67×10^5 watts in 2030 (DOE 2009a, Table 1.5.1-28) and a total mass for DOE SNF of 2,268 MTHM (DOE 2009a, Table 1.5.1-1).

[23] The properties and their description are based on DOE (2009a) and are described in more detail in Appendix 1.

The potential for some DOE SNF to go critical is greater than for commercial SNF because of its greater concentration of fissile isotopes. For the purpose of analyzing criticality, DOE classified DOE SNF into nine separate groups (DOE 2009a) and analyzed the potential for naval SNF criticality separately. Within each of the nine criticality groups, DOE selected a single fuel design as being representative of the remaining fuel within each group (Table 2-2).

Table 2-2. Criticality groups with their fuel type and representative fuel

Group Number (1 - see Notes below)	Fuel Type	Representative Fuel (2)
1	Uranium metal	N Reactor
2 (3)	***Mixed-oxide fuels***	***Fast Flux Test Facility***
3 (3)	***Uranium-molybdenum/uranium-zirconium alloy fuels***	***Enrico Fermi***
4	High-enriched uranium oxide fuels	Shippingport pressurized water reactor Core 2 seed
5 (3)	***Uranium-233/thorium oxide fuels***	***Shippingport Light Water Breeder Reactor***
6	Thorium-uranium carbide fuels	Fort St. Vrain
7 (3)	**Uranium-zirconium hydride fuels**	**Training, Research, Isotopes, General Atomics (TRIGA®)**
8 (3)	**Aluminum-based fuels**	**Advanced Test Reactor**
9	Low-enriched uranium oxide fuels	Three Mile Island Unit 2 debris

Notes
(1) DOE SNF Groups described in Appendix 1 are listed for each criticality group number. Criticality group 1 is DOE SNF Groups 1 and 2. Criticality group 2 includes DOE SNF Groups 22, 23, and 24. Criticality group 3 is DOE SNF Groups 3 and 4. Criticality group 4 includes DOE SNF Groups 5, 6, 8, 9, 11, 12, 14, and 15. Criticality group 5 includes DOE SNF Groups 25 and 26. Criticality group 6 includes DOE SNF Groups 19, 20, and 21. Criticality group 7 includes DOE SNF Groups 27, 28, 29, and 30. Criticality group 8 includes DOE SNF Groups 16, 17, and 18. Criticality group 9 includes DOE SNF Groups 7, 10, and 13.
(2) DOE defined the term "representative" to mean "... that all fuels would perform similarly regarding chemical interactions within the waste package and basket, and that canister loading limits from the representative fuel (ranges of key parameters important to criticality such as linear fissile loading and total fissile mass) are established, for which other fuels within the group can be shown to not exceed" (DOE 2009a). The design of a representative fuel (e.g., N Reactor) is used during criticality calculations for the associated fuel type (e.g., uranium metal) for each criticality group (e.g., criticality group 1).
(3) Several criticality groups require the addition of neutron absorbers during packaging of SNF into DOE standardized canisters for criticality control. **DOE planned to use nickel-gadolinium alloy neutron absorber baskets during packaging for those groups in bold font**. *Also, DOE planned to add supplemental gadolinium-bearing shot (pellet) during packaging to those groups in italic font.* DOE projected that 214 canisters need the shot and absorber baskets and another 1,080 canisters need the neutron absorber baskets (DOE 2009a, Table 2.2-12). DOE stopped developing the DOE standardized canister and associated neutron absorber materials before it completed the necessary research and development activities.

To provide criticality control, as described more fully in Section 2.3.2, when packaging DOE SNF into DOE standardized canisters—a type of multi-purpose canister (for use during storage, transportation, and disposal)—DOE planned[24] to use different canister internal fuel basket designs and add supplemental neutron absorber materials, as required, to provide criticality control (DOE 2009a). For each representative fuel, DOE comprehensively evaluated various states of degradation from fully intact to fully degraded, with criticality control design limits set based on maintaining subcriticality for the most restrictive degraded scenario for each criticality group (DOE 2009a).

[24] DOE planned to use the DOE standardized canister at the proposed Yucca Mountain geologic repository but has not yet completed the necessary research and development activities to finalize the design and produce and use the canister (Carlsen 2014a). In 2008, DOE put development of the DOE standardized canister on hold (Carlsen 2008, 2014b).

2.1.2 Heat Generation

Heat generation of DOE SNF varies widely. Burnup is a measure of the energy produced per unit mass by nuclear fuel during its operational time in a reactor, and it affects the heat produced by SNF after removal from the reactor. As uranium enrichment in fresh fuel increases, burnup in SNF may—but doesn't always—increase, which in turn may increase the concentration of the fission products responsible for most decay heat production. DOE SNF has uranium-235 enrichments that vary from less than the 0.711 weight % of uranium-235 found in natural uranium to more than 93% uranium-235 (Table 2-1). The burnup of DOE SNF ranges from very slightly irradiated to over 500 gigawatt-days per metric ton of uranium. The age of SNF (*i.e.*, how long since reactor discharge) affects heat generation, with thermal power decreasing with increasing age. On average, DOE SNF is older than commercial SNF.

The range of thermal power[25] and projected number of canisters for four types of waste that will be disposed of in a geologic repository is depicted in Figure 2-5. Comparing thermal power of different waste types on a per canister basis (*e.g.*, Figure 2-5) can be misleading if canister dimensions differ and if the SNF mass in each canister type is not the same. Larger volume canisters can contain more waste than smaller volume canisters, and thus can have a proportionally higher thermal power even when the burnup is held constant. Canister dimensions are compared in detail in Table A2-2.

Non-naval DOE SNF and defense HLW canisters have similar volumes. These canisters are nine to 24 times smaller in volume than canisters containing naval or commercial SNF. The average thermal power of DOE SNF, not including naval

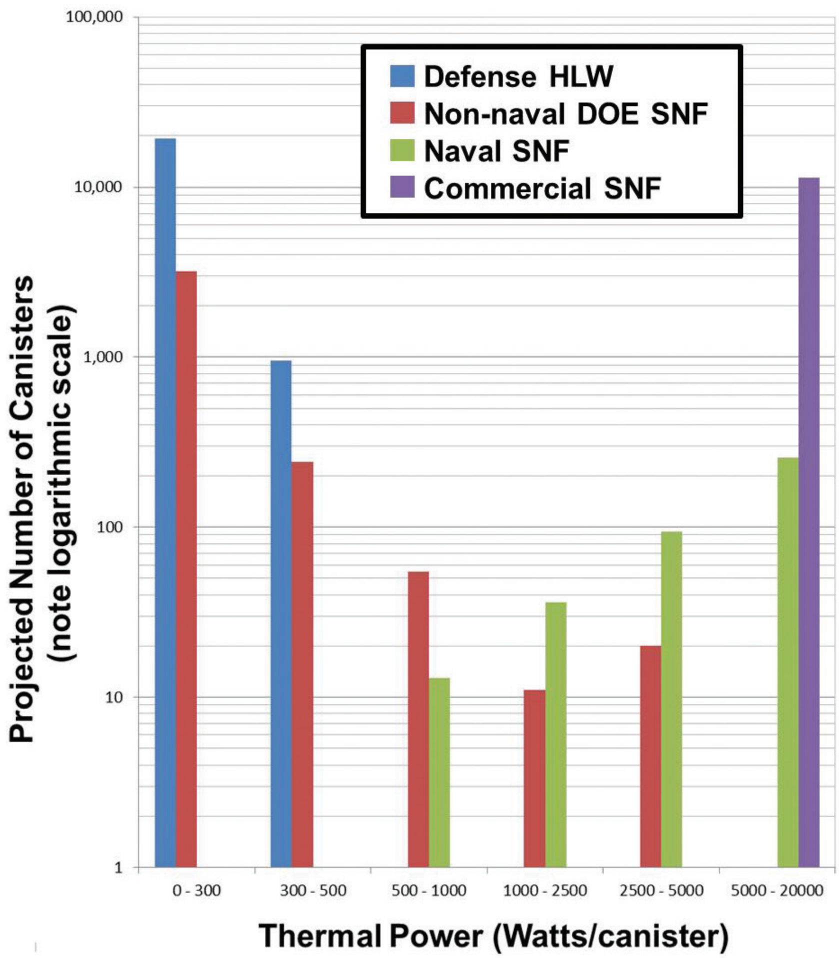

Figure 2-5. Number of projected canisters for four types of waste binned by average thermal power. Projections assume completion of currently planned treatment of high-level radioactive waste (HLW) at DOE-managed sites. DOE spent nuclear fuel (SNF; both non-naval DOE SNF and naval SNF) is projected to 2035. "Commercial SNF" is projected to 2048 and is assumed to be packaged in dual-purpose storage and transportation canisters of existing designs. Naval and all non-naval DOE SNF are depicted in Figure 2-2. Both the "commercial" and "defense HLW" types are the same as described in Figure 1-2. The logarithmic scale for projected canisters allows the order-of-magnitude differences between the number of canisters in adjacent thermal bins to be depicted more clearly (Source: DOE 2014, Figure 3, redrawn for clarity).

[25] Thermal power is the measure of the heat output, such as the radiant heat given off by the sun.

SNF, is approximately 130 watts per canister[26] (DOE 2009a). The average thermal power of defense HLW is approximately 164 watts per canister[27] (DOE 2009a).

For naval SNF, the average thermal power is 4,250 watts per canister (Sandia National Laboratories 2014). For commercial boiling water reactor SNF, the average thermal power is approximately 8,200 watts per transportation, aging, and disposal canister[28] (DOE 2009a). The average thermal power of commercial pressurized water reactor SNF is approximately 12,600 watts per transportation, aging, and disposal canister[29] (DOE 2009a). The transportation, aging, and disposal canisters are approximately the same volume as the dual-purpose storage and transportation canisters of existing designs.

2.2 Storing Spent Nuclear Fuel

DOE uses both wet and dry storage for SNF. Most DOE SNF (approximately 2,455 MTHM or 98%) is in dry storage. DOE dry storage occurs both inside buildings (in hot cells, vaults, dry storage casks, and rail transportation casks) and outside (in vaults, drywells, dry storage casks, and rail transportation casks). DOE has 10 dry storage facilities (two at Hanford, seven at INL, and one at FSV). Four of the seven INL storage facilities are over 40 years old[30]—the typical design life of such a facility is 40 years—although all of the other DOE storage facilities are younger. In the past few years, the Navy expanded an existing dry storage facility at INL and other new dry storage facilities at INL are planned to accommodate future dry storage requirements. One other storage facility at INL, which was designed for wet storage, also has some SNF in dry storage.

DOE has approximately 52 MTHM of SNF in wet storage. For wet storage, DOE stores its SNF in a container [*e.g.*, "bottles" (Beller 2014a)] filled with air, an inert gas, or water within a storage pool, or bare (*i.e.*, not in a container). SRS stores approximately 30 MTHM in one pool. INL stores approximately 22 MTHM in two pools and manages less than one MTHM SNF in one reactor canal. One of the two pools at INL and the single SRS pool are both over 60 years old, and the other INL pool is over 30 years old.

Not all DOE SNF that is currently stored will be disposed of without processing. As described in Section 5.2.2.4, DOE is using an electrometallurgical treatment at INL to process approximately 22 MTHM of sodium-bonded SNF[31] that is currently unsuitable for disposal. This process uses an electrorefiner with a molten salt electrolyte to dissolve the fuel (Ebert 2005). The process separates the cladding from the fuel, which results in the sodium and fission products accumulating in the molten salt. The cladding, along with some added metals, is then converted into a metallic HLW form in a furnace. Once the molten salt reaches its capacity to accumulate radionuclides, the salt and accumulated radionuclides in the salt will be converted into a ceramic HLW form (Ebert 2005). DOE believes these waste forms are acceptable for repository disposal (Ebert 2005), but this has not yet been confirmed as part of a repository licensing process. As described in Section 6.2.2.3.5, to allow for additional receipt of SNF in the SRS storage facility, DOE is using conventional aqueous processing at SRS to treat and convert 3.3 MTHM of aluminum-based SNF[32] into a glass waste form that will be disposed of in a geologic repository. DOE will separate and recover the uranium during the aqueous processing to

[26] This reflects the nominal total thermal power for DOE SNF in 2030 of 4.67 x 10^5 watts (DOE 2009a, Table 1.5.1-28) and assumes 3,500 canisters of DOE SNF.

[27] This reflects the total thermal power for defense HLW in 2017 of 3.48 x 10^6 watts (DOE 2009a, Table 1.5.1-28) and assumes 21,228 canisters of defense HLW (DOE 2009a, p. 1.5.1-30).

[28] DOE planned to use a multi-purpose canister known as the transportation, aging, and disposal canister at the proposed Yucca Mountain geologic repository for commercial SNF, but it has not deployed them. This average value reflects the thermal power for the average boiling water reactor fuel assembly 25 years after discharge from a reactor of 186 watts per assembly (DOE 2009a, Table 1.5.1-11) and 44 assemblies per transportation, aging, and disposal canister. The transportation, aging, and disposal canister is about the same size as the naval canister and contains substantially more SNF mass than a DOE standardized canister (Table A2-3).

[29] This reflects the thermal power for the average pressurized water reactor fuel assembly 25 years after discharge from a reactor of 601 watts per assembly (DOE 2009a, Table 1.5.1-11) and 21 assemblies per transportation, aging, and disposal canister.

[30] As a storage facility (dry or wet) ages, additional actions may be needed to ensure that all functions necessary for continued storage (*e.g.*, cooling or SNF handling) are maintained. This issue is known as aging management and is discussed in Section 3.3.1.

[31] As described in Section 5.2.2.4, for the remaining entire inventory of sodium-bonded SNF, which is about 34 MTHM, DOE will decide whether to treat it using "electrometallurgical treatment or to use another treatment method and/or disposal technique" (DOE 2000a).

[32] There is about 10 MTHM of aluminum-based SNF stored at SRS.

allow for future use of the uranium in a reactor. DOE intends to dispose of all remaining stored SNF (approximately 2,485 MTHM), without further processing into HLW, in one or more geologic repositories.

SNF heat generation, physical condition, fissile isotope enrichment, and chemical reactivity are some of the primary factors that influence the type of storage DOE uses and the required monitoring activities. DOE SNF removed from water-cooled reactors is stored initially in water for five to 10 years, depending on the burnup, to allow for decay heat to dissipate before it is stored dry. Fuel in poor condition may need storage in redundant containers (container within a container) to ensure containment of radionuclides. For example, DOE stores some SNF in cans within aluminum oversized isolation cans in the SRS pool storage facility. Furthermore, fuel in this condition requires additional monitoring during wet storage.

As part of its monitoring programs, DOE periodically measures hydrogen in gas samples from some dry storage containers at INL and Hanford. At INL, DOE monitors hydrogen released from canisters that store damaged SNF from TMI-2. At the Hanford Site, N Reactor, uranium metal SNF with degraded cladding in wet storage reacted with water, creating uranium oxides and hydrated uranium oxides from the uranium metal (Box 2-1; Loscoe 2000). As described in Section 2.3.1, DOE removed the SNF from the water basin, cold-vacuum dried it, and stored it in a helium atmosphere within multi-purpose (storage, transportation, and disposal) canisters known as multi-canister overpacks (MCOs; Bader 2010). Although the SNF was dried, residual water[33] and hydrated materials still remain within these MCOs. During interim storage in MCOs, "gas composition and inventory will evolve as a consequence of competing rates of gas formation by radiolysis[34] (chiefly hydrogen and oxygen) and thermal decomposition (chiefly water), and rates of gas depletion by reactions with fuel (hydrogen, oxygen, and water). The relative rates of these processes determine whether the MCO gas is flammable and whether the pressure is within design specifications" (Bader 2010). As described in Section 4.1.1, DOE monitors representative MCOs—the contents of the canisters range from pristine, undamaged SNF to fine-grained fuel debris—during storage to assess the sufficiency of its drying and to provide confidence that MCOs can eventually be transported to and stored in a national repository without the need to repackage (Bader 2013).

Increasing fissile isotope concentrations in fuel increases the potential for unintended criticality of stored SNF and increases the need to control access to the SNF for security purposes. Unintended criticality is prevented during storage by controlling factors such as the presence of moderators (*e.g.*, water) around or in dry storage containers, maintaining an appropriate distance or geometry between stored SNF pieces, and using neutron absorbers such as boron.

Chemical reactivity of DOE SNF affects how some SNF is stored. For example, SNF from helium-cooled reactors that contains coated carbide fuel particles—such as that from the Peach Bottom Unit 1 Core 1 at INL and FSV SNF, which is at both INL and FSV—is stored in a gas environment (helium or nitrogen) within containers (Kingrey 2003) because if the coatings on the carbide particles are damaged, the carbide will react with water to produce flammable gases.

Whether DOE SNF is packaged in a container designed for storage, transportation, and disposal also influences storage, SNF retrieval, and SNF packaging activities. A requirement for a container designed for storage, transportation, and disposal (*i.e.*, a multi-purpose canister) is that the SNF be dried prior to storage. Approximately 2,135 MTHM of DOE SNF in dry storage is already stored in multi-purpose canisters, including 2,121 MTHM in MCOs at Hanford and 14 MTHM of naval SNF in naval canisters at INL. Of the approximately 375 MTHM of remaining DOE SNF that needs to be disposed of, most of it will need to be retrieved from its current storage arrangement and packaged in multi-purpose canisters before it can be transported off site for disposal.

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[33] Prior to drying, DOE estimated a bounding nominal total water mass per MCO, including free water, to be approximately 1.3 kilograms (Bader 2010, Table 2-1). The free water design limit for an MCO is less than 200 grams (Bader 2010, Table 2-7). Calculations based on concentrations of gas constituents measured during storage indicate the free water design limit was met (Bader 2013). Bader (2013) also summarizes the MCO gas sampling process.

[34] Radiolysis is the molecular decomposition of a substance by ionizing radiation. In this case, ionizing radiation interacts with water, both liquid and vapor, aluminum hydroxide, and hydrated uranium oxides contained in the MCOs.

2.3 Packaging Spent Nuclear Fuel for Transportation and Disposal

The crucial link between stored SNF at each of the sites and its disposal is DOE's strategy for packaging it into containers that can be transported off site to a repository. DOE planned to use bare fuel transportation casks,[35] which are described in Section 2.4, and three types of multi-purpose canisters (Section 2.3.2) in its strategy for packaging and transporting all its SNF to a repository (Figure 2.6). The strategy was DOE's plan for the proposed Yucca Mountain repository (DOE 2009a). As described in Section 3.4.1, DOE continues to implement technical requirements associated with that repository, including use of this packaging strategy. Under this strategy, DOE plans to transport only intact DOE SNF of commercial origin having "no known defects" and "having handling features interchangeable with either boiling water reactor or pressurized water reactor assemblies" in bare fuel transportation casks (DOE 2009a). DOE plans to use multi-purpose canisters for all other DOE SNF.

Packaging DOE SNF into multi-purpose canisters requires considering a number of factors. Repository disposal environments and disposal concepts influence the materials that can be used to make multi-purpose canisters. Characteristics of DOE SNF, including the concentration of fissile isotopes and the size and shape of individual pieces, influence the size of multi-purpose canisters and materials used inside the containers. Designs for multi-purpose canisters need to meet applicable U.S. Nuclear Regulatory Commission (NRC) storage, transportation, and disposal regulatory requirements, which are described in Section 3.3. These requirements can influence when multi-purpose canisters are deployed.

As part of the multi-purpose canister packaging process, DOE needs to prepare most of its SNF by drying it—and, in some cases, treating[36] it. The need for drying, and any other required treatment, is determined by the composition of the SNF, its degree of degradation, and whether it was stored in water. Because DOE SNF with degraded cladding may continue to react with residual water and hydrated materials that remain in the multi-purpose canister, the design of multi-purpose canisters containing degraded SNF needs to accommodate any required monitoring of the canister while it is in storage.

2.3.1 Drying Spent Nuclear Fuel

Drying SNF during packaging is crucial to DOE's success in implementing its SNF management strategy. The drying process is described in Box 2-3.

Water that remains in a sealed canister used to store SNF can lead to material interactions that may include corrosion of the SNF and canister, gas pressurization, and potential embrittlement of the canister metal. A flammable environment within the canister may develop if free oxygen and hydrogen[37] accumulate from the radiolysis of water.

According to the ASTM[38] standard guide for drying SNF, "DOE dry storage canisters are expected to contain DOE SNF through interim storage, transport, and repository packaging" into an overpack (waste package), which is used for disposal (ASTM 2008). The objectives for the drying processes for DOE SNF are to "preclude geometric reconfiguration of the packaged fuel, prevent internal damage to the canister from overpressurization or corrosion, and minimize hydrogen generation or materials corrosion that could be a problem during transport or repository handling operations" (ASTM 2008, p. 8).

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[35] Casks that are designed to accommodate individual ("bare") used fuel assemblies (*i.e.*, fuel assemblies not contained in large multiple-assembly canisters) are known as bare fuel casks.

[36] For example, some SNF has epoxy from its use in fuel characterization studies. The epoxy is an organic material and may need to be removed from the SNF.

[37] Depending on the composition of DOE SNF and cladding, and the presence of corrosion products on the surface of the SNF and cladding, the amount of hydrogen generated per unit time and unit radiation exposure will vary. Higher rates of predicted hydrogen generation would suggest that the SNF should be packaged closer to the time of transport to ensure an adequate margin relative to NRC's transportation acceptance criterion for combustible gasses of less than 5% of the free gas volume. The approach to characterize gas generation typically is strictly empirical, relying on determination of the *G* value (the number of molecules produced per 100 eV of energy absorbed by a substance) from which production of hydrogen in systems is estimated (Westbrook *et al*. 2015).

[38] ASTM International is an international standards-setting organization and was formerly known as ASTM, which stood for American Society for Testing Materials. Since 2001, ASTM International has been the official name of the organization.

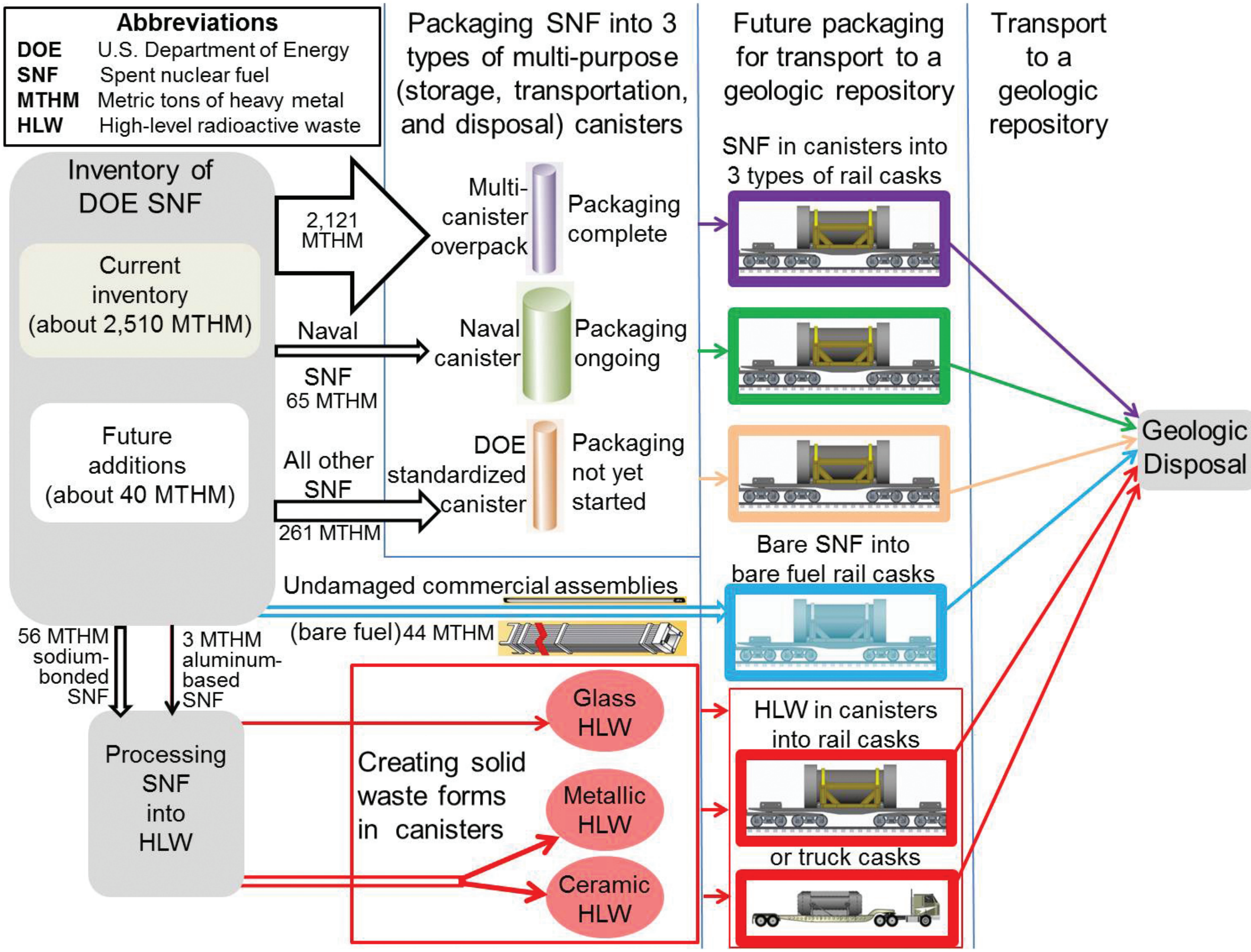

Figure 2-6. Schematic representation of spent nuclear fuel management activities.
Major SNF management activities (e.g., packaging SNF into three types of multi-purpose canisters) are listed across the top of the figure. Simplifications include using approximate masses of SNF for the inventory, amount packaged, and amount processed. Other simplifications include depicting all sodium-bonded SNF processed into HLW (Sections 2.2 and 5.2.2.4) and not depicting details of storage or packaging (e.g., drying).

What is the drying process?

First, the spent fuel is placed in the canister in an appropriate basket. If this transfer occurs underwater, then the water is drained from the canister. After draining, and for fuel that was previously stored dry and requires additional drying, a vacuum drying process, with or without added heat, is used to remove as much water from the system as possible, consistent with limiting degradation of the fuel from elevated temperatures. After the canister is evacuated, adequate moisture removal is generally assessed by monitoring the pressure increase while the canister is isolated from the vacuum pump (rebound test); too much pressure increase is interpreted as an indicator of an unacceptable amount of residual water in the canister. If acceptable, the canister is backfilled with an inert gas (such as helium) for applicable pressure and leak testing.

How is water retained in a canister and why are the different forms of water retention important?

Water retained in a sealed canister can be present in three forms: free water, water that is physically adsorbed on the exposed fuel and canister surfaces (physisorbed), and water that is bound in various corroded fuel and fuel components (chemisorbed). Free water is water in vapor or liquid form that is not physically or chemically bound; it is more easily removed by adding heat and reducing pressure than the physisorbed or chemisorbed water. Free water is the most detrimental form of water from a materials degradation point of view because it can cause corrosion and hydrogen gas production, which increases pressure, even at ambient conditions. Physically bound water is in equilibrium with the free water and can replenish free water even at ambient conditions. For most surfaces with physically bound water, the outermost layer of water is readily removed by heating to 50°C under vacuum (Hurt 2013). For some DOE SNF, such as aluminum-based fuel, the amount of chemisorbed water can be three orders of magnitude larger than the amount of free and physisorbed water (Hurt 2013). Removal of chemisorbed water requires higher drying temperatures, which may not be well-tolerated by aluminum-based fuel. Although chemisorbed water does not participate in degradation mechanisms as readily as other forms of water, chemisorbed water may, over the long term, release water via decomposition mechanisms and thereby replenish free and physisorbed water.

Box 2-3. Drying spent nuclear fuel for storage, transportation, and disposal

The drying process can vary depending on the characteristics of the fuel, the presence of any material contained in the canister that can retain water, and the intended purpose of the canister (*e.g.*, whether the canister will be used only for storage[39] or for storage, transportation, and disposal). For example, DOE used a cold-vacuum drying process to dry degraded, uranium-metal-based fuel, which is pyrophoric, in the multi-purpose MCOs at Hanford (Bader 2013; ASTM 2008, Annex A2.2) to minimize the possibility of fire during drying. DOE used a heated-vacuum drying system (at temperatures above 200°C) at INL to remove large volumes of water during drying—and reduce drying times to less than 25 hours per cask—for water-containing debris from TMI-2. The debris contained low-density concrete in addition to the SNF (Beller 2014b).

Hurt (2013) addressed the potential material interaction and degradation issues that could affect the performance of aluminum-clad DOE SNF loaded into a DOE standardized canister during a postulated interim storage period (up to 50 years) between canister loading and transportation for final disposal. Hurt (2013) proposed that aluminum-based DOE SNF, including uranium metal and uranium oxide fuels clad in aluminum, could be vacuum-dried at 200–250°C using a drying criterion that calls for maintaining a pressure of 3 torr or less when isolated from the vacuum pump for a period of 30 minutes.

Several factors should be considered in determining how dry is dry enough. The length of time the canister will be in use and the temperature of the canister are important factors. The longer the sealed multi-purposed canister will be stored prior to transportation and disposal, the greater the potential for material degradation and gas pressurization. The composition of the SNF and any corrosion products, including the nature of the corrosion products, will affect the balance

[39] NRC provides guidance for storage licensees concerning the implementation of vacuum drying for commercial SNF (NRC 2010a). "… NRC staff has accepted vacuum drying methods comparable to those recommended in … *Evaluation of Cover Gas Impurities and their Effects on the Dry Storage of LWR Spent Fuel* (Knoll and Gilbert 1987), which specifies less than 0.25 volume percent oxidizing gases in the canister" (Miller *et al.* 2013). The Knoll and Gilbert (1987) "report evaluates the effects of oxidizing impurities on the dry storage of light-water reactor fuel and recommends limiting the maximum quantity of oxidizing gases (such as O_2, CO_2, and CO) to a total of 1 gram-mole per cask. This corresponds to a concentration of 0.25 volume percent of the total gases for a 7.0 m^3 (about 247 $feet^3$) cask gas volume at a pressure of about 0.15 MPa (1.5 atmosphere) at 300°K (80.3°F). This 1 gram-mole limit reduces the amount of oxidants below levels where any cladding degradation is expected. Moisture removal is inherent in the vacuum drying process, and levels at or below those evaluated in PNL-6365 (about 0.43 gram-mole H_2O) are expected if adequate vacuum drying is performed" (NRC 2010a).

of water in the canister and may affect both gas pressurization and material degradation of the canister over the long term. A higher temperature for drying can reduce the amount of water remaining but can lead to embrittlement of the canister welds (Hurt 2013). Once dried, the canister must remain below the temperature at which it was dried to limit potential degradation mechanisms.[40]

Because all types of DOE SNF in a single fuel group have similar characteristics (fuel compound and enrichment), their drying and packaging processes will also be broadly similar. However, within each fuel group, adjustments to drying procedures or processes may be necessary to accommodate variations among the fuel type in dimensions or in the condition of the cladding. In describing drying aluminum fuel, Hurt (2013) noted that the specific time-temperature recipe for fuel drying is highly dependent on the fuel configuration (*e.g.*, plate fuel with crevices), fuel condition (*e.g.*, fuel with various oxyhydroxides of various thicknesses containing chemically bound and adsorbed waters), and features of the fuel-in-canister system to be dried (*e.g.*, debris on fuel, configuration of the fuel/canister). The diversity of SNF types and SNF groups at a site affects the potential complexity and amount of time necessary for drying and packaging SNF for storage, transportation, and disposal. The Board's analysis of the technical basis underlying proposed drying procedures of DOE SNF is addressed further in Section 8.3.

2.3.2 Multi-purpose Canisters

The MCO, the naval SNF canister, and a "standardized" canister are the three multi-purpose canisters in DOE's packaging, transportation, and disposal strategy (Figure 2-6). All three types of canisters are stainless steel and welded closed but vary in size (Figure 2-7, Figure 2-8, and Figure 2-9).

DOE packaged low-enriched Hanford SNF into MCOs from 2002 to 2012 (Bader 2013). As illustrated in Figure 2-7, the MCO is designed to allow five or six N Reactor fuel baskets to be loaded and stacked within its cavity, depending on the fuel type (DOE 2009a). Section 4.1.1 and Appendix 2 have additional details on the MCOs and packaging SNF into the MCOs.

The Navy began packaging stored naval SNF into its canisters at INL in the 2000s and will continue to package its SNF inventory into the canisters until all its inventory is packaged (McKenzie 2010a). The total expected naval SNF inventory is 65 MTHM (Figure 2-6; DOE 2009a), but as of August 2014, there is only 28 MTHM of naval SNF. A typical naval canister packaging design is illustrated in Figure 2-8. Additional details on the naval canisters and SNF packaging are included in Sections 5.1.3.2 and 5.2.2.3, and in Appendix 2.

DOE, through its National Spent Nuclear Fuel Program (Section 3.4.2), developed but did not deploy a standardized canister design known as the DOE standardized canister[41] for disposal in a volcanic tuff repository. DOE stopped developing the DOE standardized canister when DOE stopped its Yucca Mountain repository program efforts. The DOE standardized canisters are described here because the functions that the DOE standardized canister must fulfill, such as containment of radionuclides, fitting the different sizes and shapes of the different SNF types (Figure 2-3), and criticality control, will be required for any standardized multi-purpose canister design that DOE uses for packaging the "all other SNF" category depicted in Figure 2-6.

The DOE standardized canister includes a canister shell (Figure 2-9) and internal basket assemblies. The four configurations of the DOE standardized canister vary in size (height and diameter), but all serve the same functions and have the same features. As described by DOE (2009a), the four sizes of canisters are needed to accommodate the variable sizes and shapes of

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[40] Carlsen (2008) concluded that "there are no credible degradation mechanisms that would significantly degrade canister performance during a 50-year interim storage period provided that canister temperatures remain below drying temperatures." Carlsen's comment is pertinent to vacuum-drying techniques and not the forced helium dehydration method wherein during the drying stage moisture is driven out using a refrigeration cycle.

[41] The U.S. Nuclear Waste Technical Review Board (Board) adopts DOE's nomenclature for this canister even though it is not standard by any conventional definition. The DOE standardized canister is a canister system that consists of four cylindrical stainless steel canisters with two different diameters (18 inches and 24 inches) and two different lengths (10 feet and 15 feet). The different sizes and eight internal basket designs of the multi-purpose canisters accommodate the wide dimensional variability of DOE SNF.

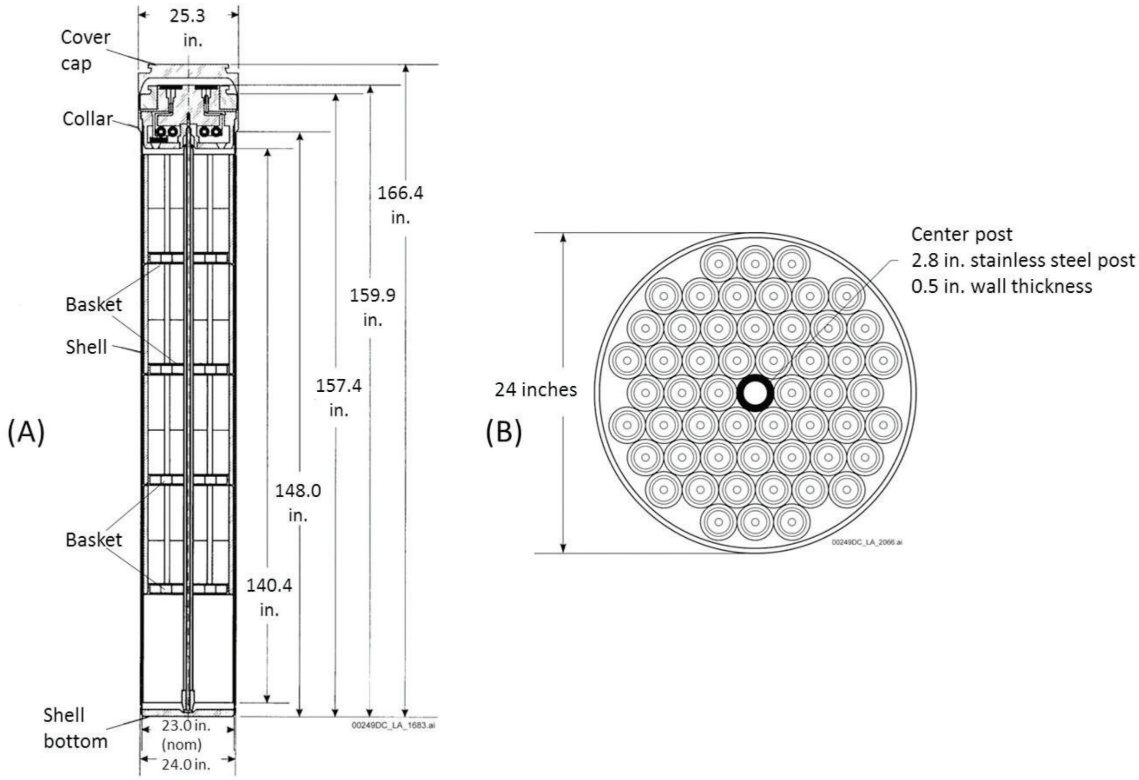

Figure 2-7. Multi-canister overpack and fuel baskets.
A. Multi-canister overpack with four baskets. Canister dimensions are in. (inches). (Source: DOE 2009a, Figure 1.5.1-18). B. Cross-sectional layout for Mark IV fuel basket. (Source: DOE 2009a, Figure 1.5.1-21). A photo of MCO baskets with loaded SNF is provided in Figure 4-5A.

DOE SNF (Figure 2-3 and Appendix 1). DOE chose four configurations to minimize the number of canisters that needed to be qualified under a quality assurance[42] program (DOE 2008b) and to maximize packaging efficiency (DOE 1999).

DOE incorporated a design option for a threaded plug in the top and bottom heads; however, the plug is not part of the baseline design (Figure 2-9). DOE indicated that the threaded plugs can be used, when necessary, for a number of functions, including draining, inerting, leak testing, venting, and remote inspection. If included as part of a canister, the threaded plug is seal-welded prior to shipment (DOE 2009a).

The internal basket assemblies within DOE standardized canisters facilitate loading DOE SNF into the canister during packaging and provide structural support of the DOE SNF during packaging (DOE 2009a) and subsequent fuel operations (*e.g.*, transportation). As described in Section 2.1.1, the canister internal supports also serve a criticality control function by fixing the geometry of the contents in both the pre- and post-closure phases of a repository.

The amount of fissile materials in a canister is determined by the canister internal fuel basket because it sets the number of assemblies that can be loaded. DOE planned to add supplemental neutron absorber materials to the internal basket design, as needed, to provide criticality control (DOE 2009a). The amount of neutron-absorbing materials added during packaging will be a function of the concentration of fissile isotopes in the SNF and the geometry of the SNF. “Basket construction materials may include either stainless steel, with or without supplemental neutron-absorbing materials, and nickel/gadolinium alloy material with or without supplemental neutron-absorbing materials” (DOE 2009a). DOE still

[42] “Quality assurance comprises all those planned and systematic actions necessary to provide adequate confidence that the geologic repository and its structures, systems, or components will perform satisfactorily in service. Quality assurance includes quality control, which comprises those quality assurance actions related to the physical characteristics of a material, structure, component, or system that provide a means to control the quality of the material, structure, component, or system to predetermined requirements” (10 CFR 63, Subpart G). The topic of quality assurance is explained in Section 3.3.

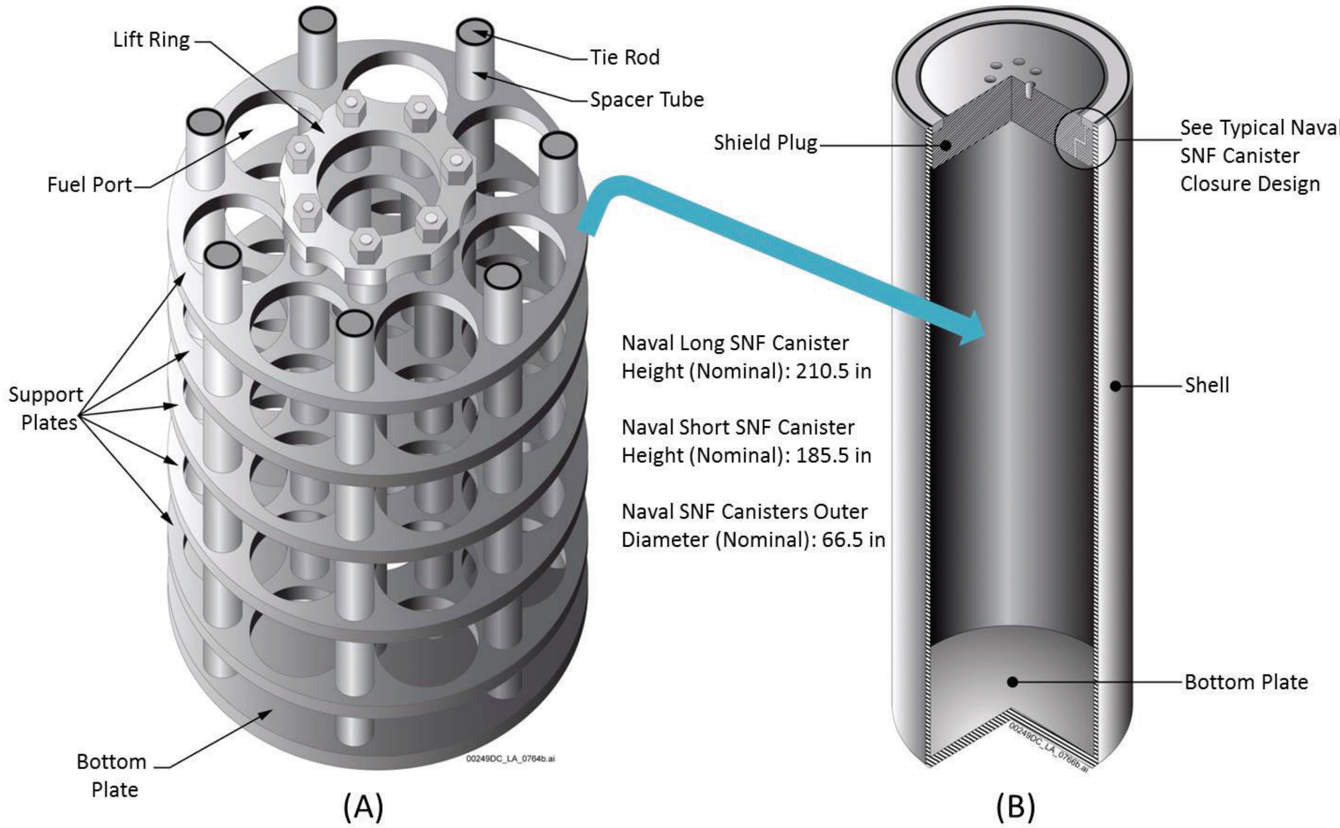

Figure 2-8. Packaging design for naval canisters.
A. "There are three different methods for packaging naval SNF into naval SNF canisters: Packaging Methods A, B, and C; however, the design of the naval SNF canister [shown in Figure 2-8B] is the same irrespective of packaging method" (DOE 2009a). Typical Packaging Method A naval SNF basket is depicted. (Source: DOE 2009a, Figure 1.5.1-32). B. Typical naval SNF canister with nominal dimensions in. (inches). (Source: DOE 2009a, Figure 1.5.1-29). For Packaging Method A, a naval SNF basket is placed inside the SNF canister prior to canister closure.

needs to complete development of the supplemental neutron absorbers and remote canister welding technology (Carlsen 2014a). The dimensions of the DOE SNF assemblies to be loaded into a canister establish the basket configurations within the DOE standardized canister. The basket for each configuration is customized to accommodate the physical dimensions, type, and number of fuel assemblies to be packaged in a DOE standardized canister.

DOE (2009a) designed eight basket configurations for the DOE standardized canister. Five illustrative examples are depicted in cross-sectional layouts in Figure 2-10. DOE calculated the number of canisters needed for a particular fuel type from the dimensions of the standardized canister and the dimensions of the fuel type (Table A1-2). For example, 505 DOE standardized canisters are required just for packaging the graphite-based thorium-uranium carbide FSV fuel (DOE SNF Group 19) stored at INL and FSV (Table A1-2), which represents about 14% of all DOE SNF–containing canisters (Table A1-3) that would be disposed of in a geologic repository. Once deployed, about one-third of DOE standardized canisters will contain aluminum-based SNF (Table A1-2, Figure 2-10A). The large number of packages for these fuel types is needed because the fuel uses high-enriched uranium in particles dispersed in a low-density matrix, either graphite for FSV SNF or aluminum for aluminum-based SNF.

2.3.2.1 Status of Packaging Multi-purpose Canisters

For all DOE SNF that will be packaged for transport to a geologic repository (Figure 2-6), packaging will occur at Hanford, INL, and SRS. As described in Section 7.3.2, DOE will transport FSV to INL for packaging into DOE standardized

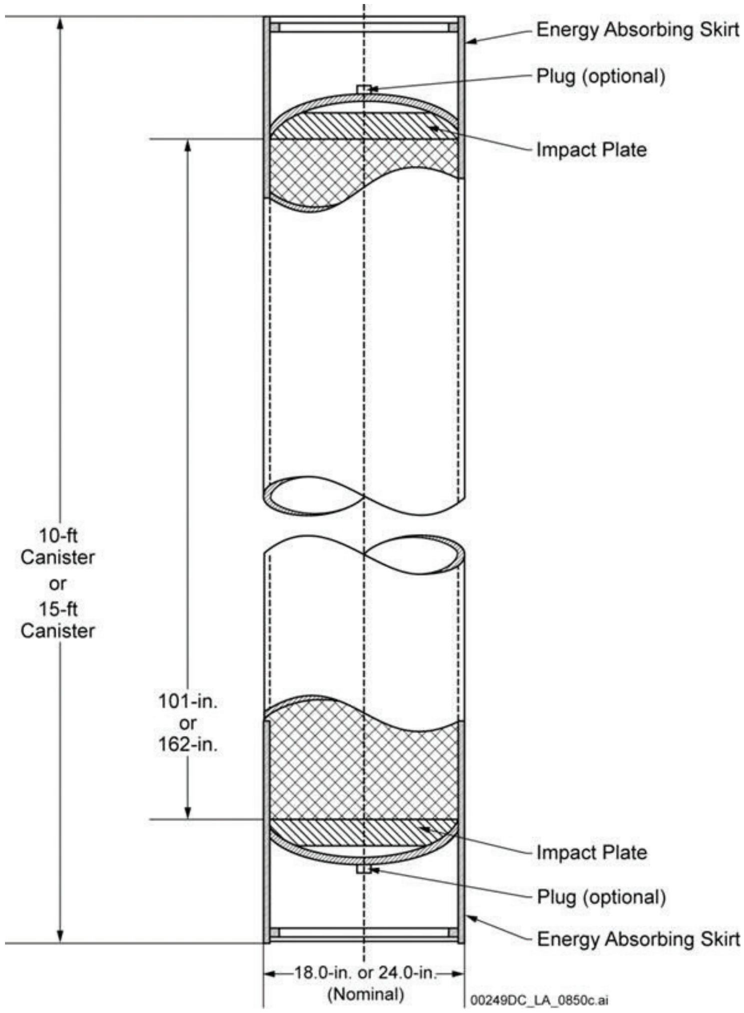

Figure 2-9. U.S. Department of Energy standardized spent nuclear fuel canister.
A cutaway perspective of a representative canister. The two different heights (10 feet and 15 feet) and diameters (18 inches and 24 inches) of the DOE standardized canister are labeled. Features of the canister, such as optional plugs at the top and bottom of the canister, are depicted and labeled. (Source: DOE 2009a, Figure 1.5.1-9).

canisters. Approximately 10 MTHM of DOE SNF from sites other than Hanford, INL, SRS, and FSV (Table A1-1; see "Other" sites) will be transported to SRS or INL for packaging into DOE standardized canisters. Figure 2-11 illustrates three different views of the status of DOE SNF packaging. Figure 2-11A depicts the mass of SNF at each site and what percentage at each site is already packaged in multi-purpose canisters that were designed for transportation and disposal at the proposed Yucca Mountain repository. Figure 2-11B depicts the diversity of SNF at each site and how many of the fuel groups (Appendix 1, Table A1-1) DOE has packaged into multi-purpose canisters. As described in Section 2.3.1, because each type of SNF will have a different "recipe" for drying the fuel—how long and at what temperature—depicting the diversity of SNF at a site suggests the complexity of site packaging and drying operations. Figure 2-11C depicts both the number of each container type that DOE projected[43] would be used at the three sites that would package SNF for transport to the proposed Yucca Mountain repository and what percentage of the containers DOE has packaged.

[43] The number of containers depicted in Figure 2-11C is based on values in Table A1-2, which is information that INL provided to the Board. DOE (2009a) noted that a range of canister counts, which includes all MCOs, naval canisters, and DOE standardized canisters, is likely because so little of the DOE SNF has been packaged for final disposal and packaging efficiencies can only be estimated. Depending on packaging efficiencies, DOE estimated that the number of DOE canisters required can range from a minimum of 2,500 to a maximum of 5,000, with a point estimate of 3,500 canisters.

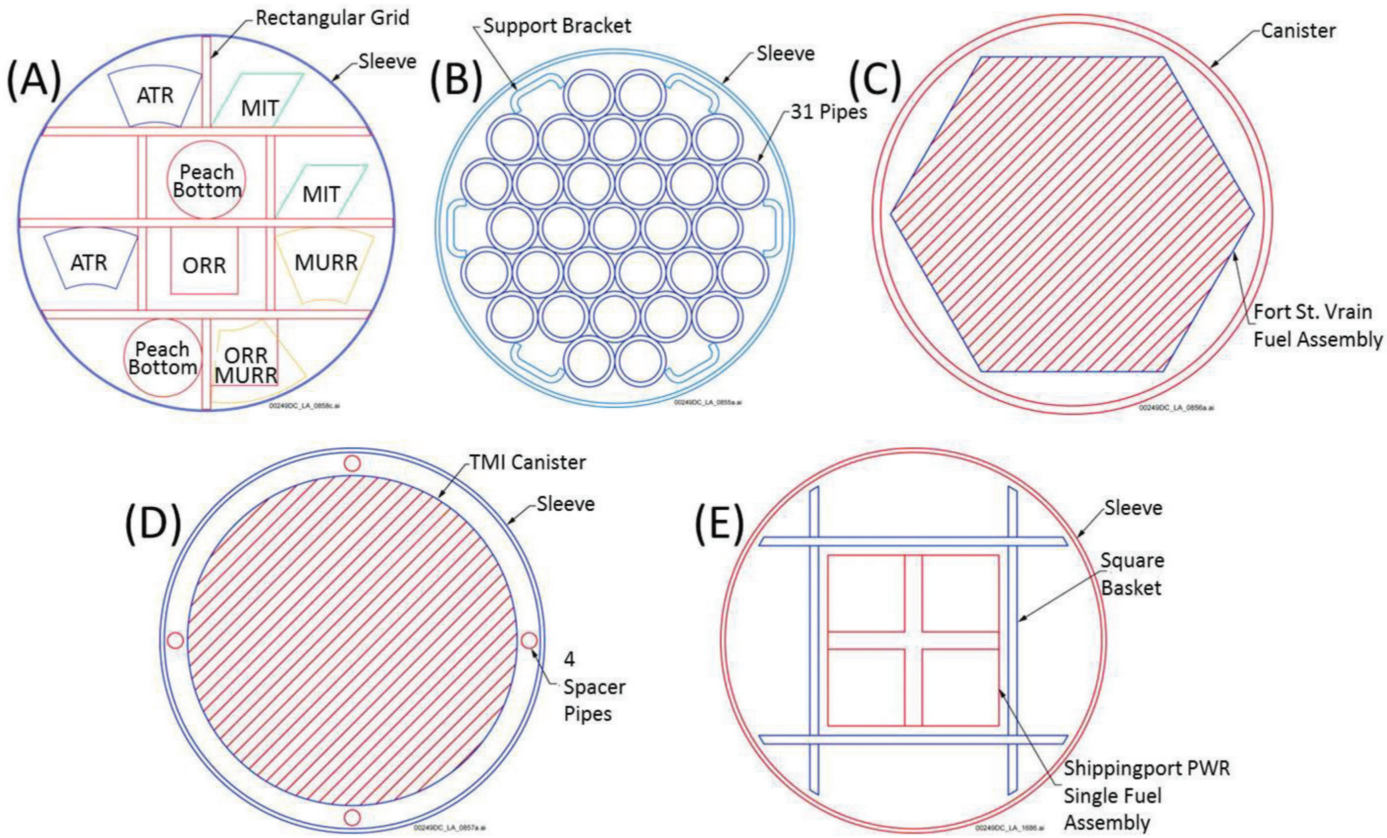

Figure 2-10. Basket arrangements for spent nuclear fuel in the U.S. Department of Energy standardized canister. Cross-sectional layouts of five of the eight basket arrangements. A. Aluminum fuels basket where all aluminum fuel can fit in any part of the basket (ATR—Advanced Test Reactor, MIT—Massachusetts Institute of Technology, MURR—University of Missouri Research Reactor, and ORR—Oak Ridge Research Reactor). (Source: DOE 2009a, Figure 1.5.1-17). This basket also can contain Peach Bottom SNF, which is thorium-uranium carbide fuel particles dispersed in graphite. B. TRIGA® fuel basket. (Source: DOE 2009a, Figure 1.5.1-14). C. FSV fuel basket. (Source: DOE 2009a, Figure 1.5.1-15). D. Three Mile Island (TMI) Unit 2 canister basket. (Source: DOE 2009a, Figure 1.5.1-16). E. Shippingport pressurized water reactor Core 2 fuel basket. (Source: DOE 2009a, Figure 1.5.1-12).

At Hanford, DOE has packaged 99.4% of the SNF mass—comprising three SNF fuel types—into 412 MCOs. At Hanford, DOE projected that packaging the remaining 0.6% of the SNF mass—comprising 10 SNF Groups—will require 138 DOE standardized canisters.[44]

At INL, DOE has packaged only 4.3% of its total SNF mass (325 MTHM). The packaged material is all naval SNF (14 MTHM) requiring 100 naval canisters. The remaining approximately 311 MTHM of SNF at INL that needs to be packaged is diverse (29 SNF Groups and approximately 250 fuel types). DOE projected that an additional 300 naval canisters, 1,466 DOE standardized canisters (Table A1-3), and four bare fuel casks will be needed (Table A1-2).

At SRS, DOE has not packaged any of its SNF into multi-purpose canisters. The approximately 30 MTHM of SNF includes more than 60 SNF types and 23 SNF Groups, and could require as many as 541 DOE standardized canisters to package all of the material.

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[44] About 90% of canisters would contain moderately enriched (about 24%) mixed uranium-plutonium oxide Fast Flux Test Facility SNF (Figure 2-3, Table A1-2, and Group 23).

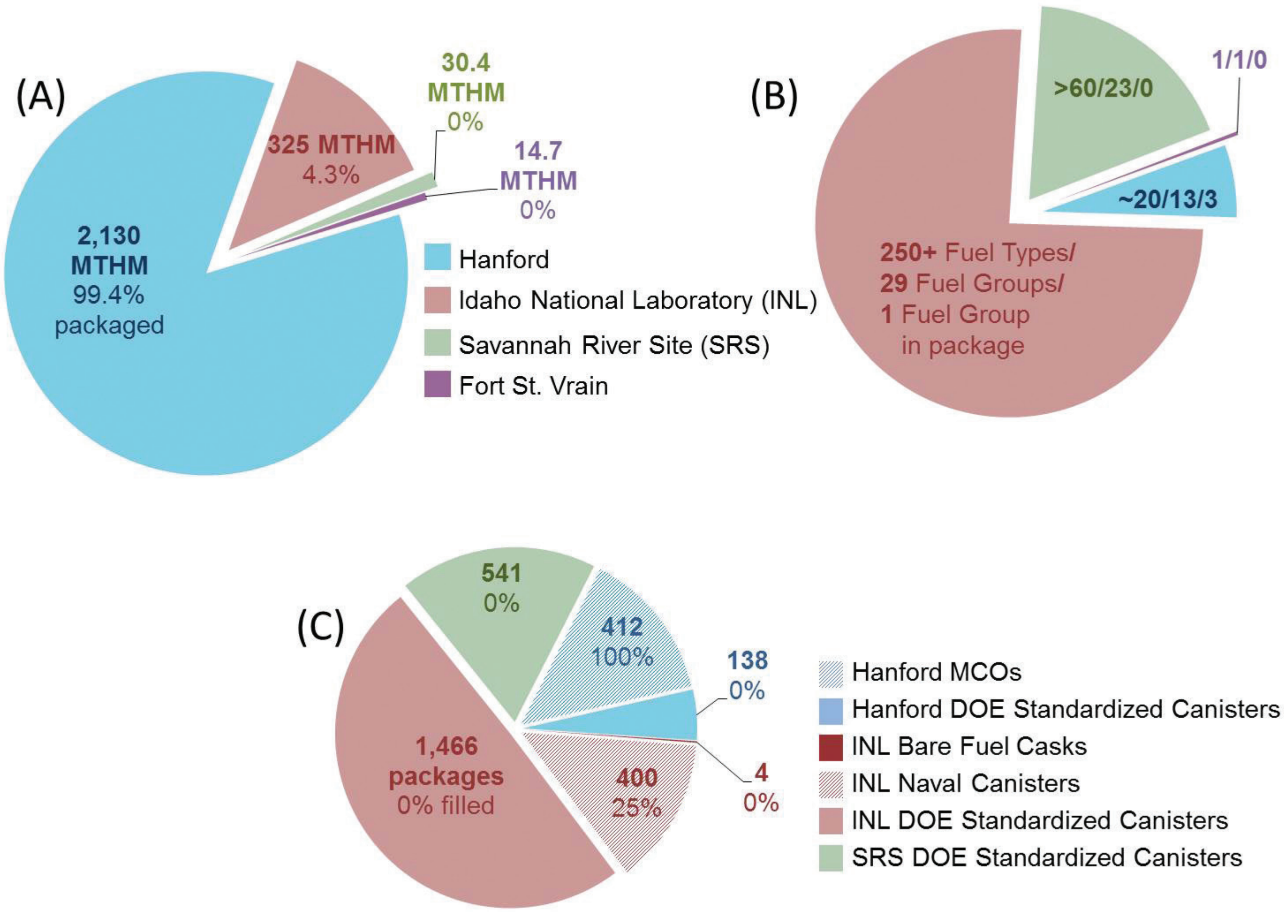

Figure 2-11. Analysis of status of spent nuclear fuel packaging.
A. Mass of SNF in metric tons of heavy metal (MTHM) and percent the mass packaged in multi-purpose canisters at Hanford, INL, SRS, and FSV as of August 2014. The portions of the pie chart are based on the total mass of SNF at all the sites depicted. As depicted in Figure 2-6, 44 MTHM of SNF, all at INL, will be packaged and transported to a repository in bare fuel casks. B. The diversity of SNF at each site is illustrated by the number of DOE SNF types, SNF Groups, and SNF Groups packaged in multi-purpose canisters at each site as of August 2014. The portions of the pie chart are based on the total number of fuel types at all the sites depicted. C. Projected number of required transportable containers and percent filled for Hanford, INL, and SRS as of August 2014. FSV is not depicted because DOE plans to ship the FSV SNF to INL for packaging into DOE standardized canisters. The portions of the pie chart are based on the total number of projected containers for all the sites depicted.

The 14.7 MTHM of SNF at FSV consists of one SNF type. DOE plans to transport the FSV SNF to INL for packaging into multi-purpose canisters. DOE will use the TN-FSV[45] legal-weight truck transport cask to transport the SNF to INL. The transported FSV SNF would require 293 DOE standardized canisters once it gets to INL.

2.4 Transporting Spent Nuclear Fuel

DOE plans to transport its SNF from Hanford, INL, and SRS to a repository via railroad. The plans include transport in both bare fuel transportation casks and in multi-purpose canisters (MCOs, naval canisters, and DOE standardized canisters) inside NRC-certified transportation packages (Figure 2-6). Each transportation option is described below, beginning with bare fuel transportation casks (Figure 2-12).

[45] "The TN-FSV cask is a steel and lead shielded transport cask for transporting irradiated nuclear fuel by legal-weight truck. The cask was designed and licensed by Transnuclear Inc. for Public Service Company of Colorado" (Greene *et al*. 2013). A loaded TN-FSV cask weighs 47,000 pounds, less than the legal limit for an 18-wheeled truck.

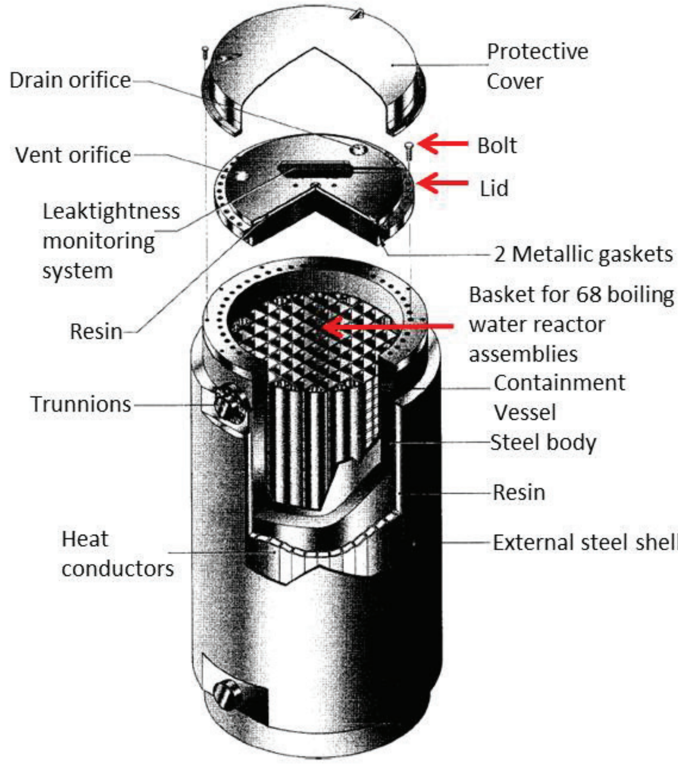

Figure 2-12. TN-68 bare fuel cask for transporting boiling water reactor spent nuclear fuel assemblies.
Bolts go through the lid and screw into the carbon steel body of the cask. The square holes in the basket accommodate 68 boiling water reactor assemblies. (Source: Greene *et al.* 2013).

All DOE SNF that DOE plans to transport to a repository in bare fuel transportation casks is stored at INL (Table A1-2) and would be packaged for disposal at the repository. DOE has approximately 44 MTHM of undamaged assemblies of commercial boiling water reactor fuel and pressurized water reactor SNF[46] that will be transported off site from INL in NRC-certified bare fuel transportation casks (Figure 2-6).

There is one bare fuel cask design for boiling water reactor fuel that is in use. The TN-68 was designed to transport 68 assemblies of boiling water reactor SNF. NRC certified the TN-68 cask for storage and transportation (Greene *et al*. 2013). There is also only one bare fuel cask design for pressurized water reactor fuel that is in use. The TN-40 was designed to transport 40 assemblies of pressurized water reactor SNF. NRC certified the TN-40 cask for storage and transportation (Greene *et al*. 2013). DOE SNF that is transported from INL as bare fuel will be subsequently packaged with commercial SNF at a repository (DOE 2009a) for disposal. The bare fuel transportation casks are constructed of carbon steel and are bolted closed.

Carlsen (2014b) described DOE's approach to transporting MCOs from Hanford—the only DOE site that uses MCOs—to a repository using an NRC-certified rail transport cask. DOE completed scoping analyses that evaluated a hypothetical transportation cask based on performance characteristics of the Holtec International HISTAR 100 cask (McCormack 2014a). The hypothetical cask has a cruciform insert capable of holding four MCOs (Carlsen 2014b). DOE's scoping transportability analyses addressed four topics (McCormack 2014a): structural analyses for transportability of the MCO, a steady state thermal analysis for a hypothetical MCO transportation cask, scoping analyses for transportability of a partially loaded MCO, and a criticality analysis for N Reactor fuels in a rail transportation cask.

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[46] Some of this SNF was at the West Valley, New York reprocessing facility when the reprocessing facility shut down. DOE then transported the commercial SNF in two rail casks to INL. Other commercial SNF, which DOE began to manage, was loaded into a number of casks as part of the DOE dry cask storage testing program during the 1980s at INL (see Section 5.1.1.5 for additional details). All of this commercial SNF is now DOE SNF.

These analyses suggested that the MCOs could be transported safely via rail, with one exception for MCOs placed bare into the cask. In describing the structural analyses, Carlsen (2014b) indicated that it would be problematic because the forces the MCO would be subjected to during an impact[47] from a transportation accident would exceed its design basis. He stated that the external rail cask impact absorbers would have to limit the deceleration to 60 g,[48] the design basis for the HI-STAR 100 impact limiters, and then "we would need to provide a supplemental impact limiter within the cask." To transport the SNF in MCOs off site, DOE will need to develop the supplemental impact limiter and ensure that the certificate of compliance for an NRC-certified rail transport cask, such as the HI-STAR 100 (Greene *et al*. 2013), is amended and approved by NRC for transport of the MCOs. DOE will transport 2,121 MTHM SNF in MCOs to a repository (Figure 2-6).

DOE plans to transport naval SNF cores—the entire inventory of 65 MTHM (Figure 2-6)—stored in naval canisters from INL to a repository in the M-290 rail transportation cask (DOE 2009a). Because the M-290 (Figure 2-13) will also ship a variety of fuel configurations from sites where the naval SNF is removed from naval vessels to INL, the Navy demonstrates compliance with NRC's packaging and transportation regulation using a combination of two safety reports known as "Safety Analysis Reports for Packaging" (Miles 2013). The first is the core-independent "Safety Analysis Reports for Packaging," which addresses safety aspects of the package that are common to all shipments. The core-independent M-290 "Safety Analysis Reports for Packaging" provides the peak deceleration (both dynamic deceleration curves and static peak loadings) for use in subsequent core-dependent analyses (Miles 2013). The second safety report is a core-dependent "Safety Analysis Reports for Packaging" for aspects that are specific to each fuel type or configuration, such as the fuel construction (Miles 2013). For example, the Navy will have 16 different core-dependent safety analysis reports, each reflecting a distinct configuration of SNF (*e.g.*, an A1W canister) that will require separate NRC approvals.

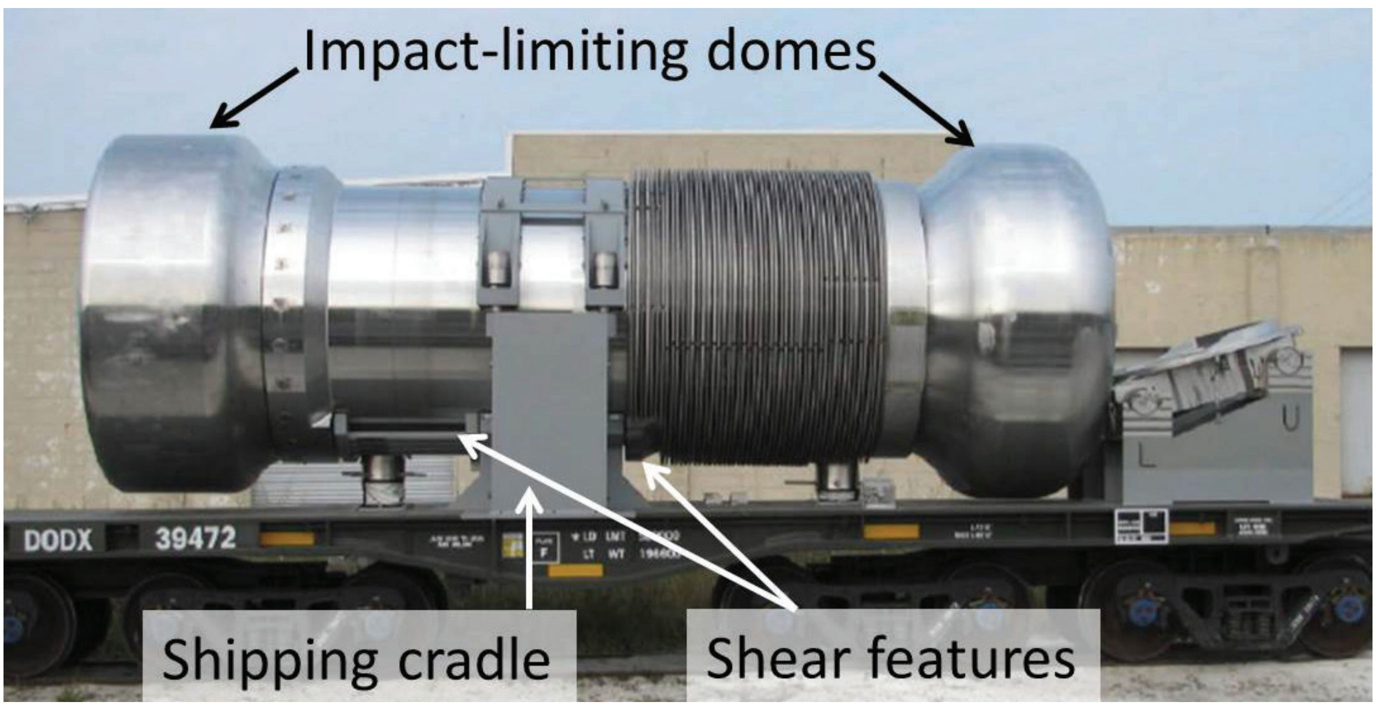

Figure 2-13. M-290 rail transportation cask for naval spent nuclear fuel.
The impact-limiting domes on the ends of the cask reduce loads felt by the cask body and its contents during an accidental impact. The shipping cradle secures the cask to the rail car. Shear features prevent M-290 axial motion. (Sources: Miles 2015 and Staab 2009).

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47 The impact forces on materials inside transportation casks are reduced by using impact limiters on each end of the cask, which serve as crumple zones during an impact.

48 Sixty times the amount of the standard gravity value (g), which is 9.80 m per sec^2 (32.17 ft per s^2).

The M-290 shipping container consists of a cask body plus impact-mitigating domes on either end (Figure 2-13). The M-290 also includes a containment plate, shear ring, backing ring, assorted dome attachment hardware and component fasteners, and fuel type–specific hardware.[49]

The DOE strategy for packaging, transporting, and disposing of its remaining SNF (about 261 MTHM; Figure 2-6) relies on a DOE standardized canister for transportation. In 1997, DOE, through its National Spent Nuclear Fuel Program, began developing a preliminary design for the DOE standardized canister (Figure 2-14) and its transportation by rail (Bridges *et al*. 2001).

Around 2002, the DOE Office of Civilian Radioactive Waste Management (OCRWM)[50] transferred the responsibility for designing the transportation cask that would transport the DOE standardized canisters to the DOE Office of National Transportation Safety (Carlsen 2014b). The National Spent Nuclear Fuel Program has not worked on cask development since then and DOE has not proceeded with designing a transportation cask. That early transportation package model, depicted in Figure 2-14, "… has still served as a good working model for our plan" for transporting the DOE standardized canister (Carlsen 2014b).

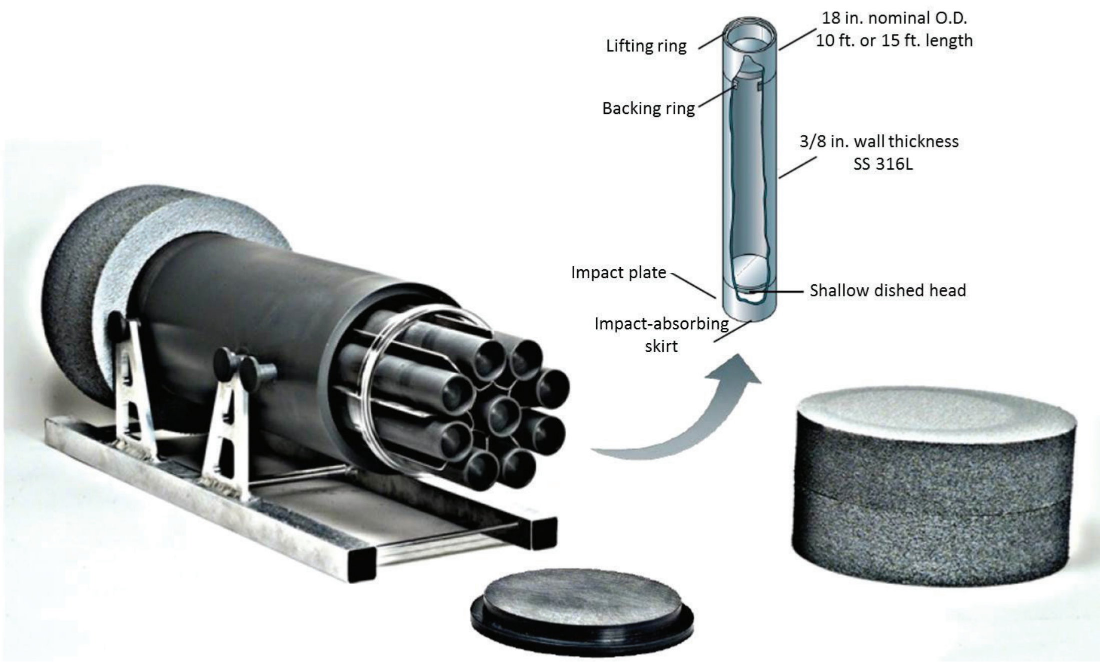

Figure 2-14. Envisioned transportation package for the U.S. Department of Energy standardized canister.
The rail cask could contain nine, 18-inch-diameter, DOE standardized canisters. (Source: Carlsen 2014a).

Although no longer responsible for cask development, the National Spent Nuclear Fuel Program is still responsible for making sure the packaging strategy for the DOE SNF in the standardized canisters is licensable for transport (Carlsen 2014b). As the National Spent Nuclear Fuel Program investigated the possibility of using an NRC-certified rail cask to transport DOE SNF, the program found that "… the list of data that they [commercial cask vendors] thought they would need to do traditional criticality analysis was daunting; and it was just outside the scope of what we thought we could

[49] Additional details of the M-290 are provided in NRC's Certificate of Compliance 71-9796 and in NRC's safety evaluation report of the "Core Independent M-290 Safety Analysis Report for Packaging" and the "A1W Spent Nuclear Fuel in the M-290 Safety Analysis Report for Packaging" (the core-dependent safety analysis for the A1W canister; Sampson 2014).

[50] Until 2010 when DOE closed it (DOE 2010b), the Office of Civilian Radioactive Waste Management was responsible for the transportation and disposal of DOE SNF and the disposal of naval SNF.

provide for the wide range of DOE fuels, particularly with the quality requirements[51] that would be expected" (Carlsen 2014b). As a result, the National Spent Nuclear Fuel Program adopted a licensing strategy for DOE standardized canisters that relies on two independent barriers (the cask and canister), each of which is tested to the hypothetical accident conditions of transportation,[52] including maintaining leak tightness (Carlsen 2014b).

The DOE standardized canister will need to meet NRC's moderator exclusion requirements in its packaging and transportation regulation, or DOE will need to obtain an exemption to the NRC requirement. The DOE safety analysis for the proposed Yucca Mountain repository, which is subject to the risk-informed and performance-based regulatory approach of NRC's Yucca Mountain disposal regulation (10 CFR 63), did allow credit for the leak tightness of the canister to maintain moderator exclusion when calculating risks for accidents there (Carlsen 2014b). Because NRC's packaging and transportation regulation is not risk-informed and performance-based, DOE proposed to submit a topical report on moderator exclusion to NRC. The DOE report would request NRC's approval to credit the leak-tight boundary of the canister for maintaining moderator exclusion during transport. From 2006 to 2007, DOE and NRC held five pre-application meetings and, in July 2007, determined a path forward for completing and submitting that topical report (Rahimi 2007a; Carlsen 2014b); however, DOE did not complete and submit the report "due to subsequent events, primarily political and financial events" (Carlsen 2014b).

As described by Carlsen (2014b), the objectives of the topical report are still very important and need to be carried forward to conclusion. If NRC reviewed and approved the topical report, DOE could be confident that the DOE SNF, if repackaged into standardized canisters, would be acceptable for transportation. Receiving NRC approval would minimize the data DOE needs to obtain, so that DOE "… would know exactly what data we need on the spent fuel in order to get the transportation licenses approved" (Carlsen 2014b). Obtaining NRC approval would also allow DOE "… to design or perhaps make any design changes necessary to our standardized canister before we have a need to use them, before they are loaded and sealed." The NRC approval would also allow DOE to move forward with consolidating some SNF "… into newer packages and to newer facilities with confidence that they would not have to reopen that package and package again at a later time." Finally, the NRC approval would allow DOE to "… provide a starting point for the future cask vendors so they would know exactly what their casks needed to provide in order to be able to credit our canisters for moderator exclusion and thus greatly simplify the amendments or changes to those certificates of compliance to transport our fuels."

2.5 Disposal of Spent Nuclear Fuel

A repository system used to dispose of DOE SNF would have both natural components—the host rock and tunnels (drifts) where the waste would be emplaced—and engineered components—the waste form, waste package, and drift seals (Nuclear Waste Technical Review Board 2015b). Both natural and engineered components would contribute to isolating and containing the SNF after the repository is closed (*i.e.*, during the post-closure period). Individual components of the natural or engineered system serve as barriers.[53] The most mature disposal concepts were developed for repository systems constructed in salt, crystalline rock, clay/shale, or volcanic tuff formations. Depending on the particular dis-

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[51] As described in Section 3.4.1, the "Waste Acceptance System Requirements Document" (DOE 2008a), which applies to SNF and HLW bound for the repository, requires that activities be conducted under a quality assurance program that is consistent with Title 10, Code of Federal Regulations (CFR), Part 63 (10 CFR 63), NRC's Yucca Mountain disposal regulation. The quality assurance requirements (DOE 2008b) are extensive (detailed in 160 pages).

[52] "A package used for the shipment of fissile material must be so designed and constructed and its contents so limited that under the tests specified in § 71.73 ("Hypothetical accident conditions"), the package would be subcritical" (10 CFR 71). Under the hypothetical accident conditions, the transportation cask is assumed to be fully flooded with water. NRC characterizes this topic as "moderator exclusion" for transportation packages because water is a moderator for thermal neutrons released from the SNF. The presence of water inside a transportation package increases the probability for a nuclear criticality accident.

[53] A "barrier means any material, structure, or feature that, for a period to be determined by NRC, prevents or substantially reduces the rate of movement of water or radionuclides from the Yucca Mountain repository to the accessible environment, or prevents the release or substantially reduces the release rate of radionuclides from the waste. For example, a barrier may be a geologic feature, an engineered structure, a canister, a waste form with physical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around the waste, provided that the material substantially delays movement of water or radionuclides" (10 CFR 63).

posal concept, waste isolation depends more on the engineered than natural components or vice versa (Nuclear Waste Technical Review Board 2015b; Hardin *et al*. 2012).

2.5.1 Characteristics of Spent Nuclear Fuel That Affect Its Disposal

The chemical composition, physical size, fissile material concentration, and radioactivity of DOE SNF affect processes that occur in a repository and contribute to the risks for the repository. For example, uranium metal-based fuel, such as Hanford's N Reactor SNF, is a potentially pyrophoric material[54] under oxic conditions and also reacts with water under anoxic conditions to generate hydrogen gas. If a pyrophoric event (*i.e.*, self-sustained rapid chemical oxidation or self-sustained burning) occurred in an oxidizing repository environment after repository closure, it could produce an adverse effect on repository performance by producing heat and increasing waste form degradation and radionuclide release rates. Also, after repository closure, water interacting with degraded carbide fuel particles can create combustible gases that can, if ignited, cause localized increases in temperature in the disposal zone, which might affect fuel degradation environments (Sandia National Laboratories 2008).

2.5.1.1 Heat Generation

Heat generated from radioactive decay of the radionuclides in SNF causes coupled thermal processes[55] to occur that can adversely affect both engineered and natural components in repositories, and affects the movement of fluids and radionuclides released from the waste through the engineered barriers and out into the surrounding natural system. Managing heat generated from radioactive decay in SNF is a key consideration in geologic disposal (Sandia National Laboratories 2014). For example, meeting a 100°C limit for disposal in some sedimentary rocks could require hundreds of years of aging for commercial SNF (Figure 2-5) before it could be disposed of (Hardin *et al*. 2015) in these formations. Because the thermal power of most naval canisters is similar to commercial SNF canisters (Figure 2-5), long periods of aging of SNF in some naval canisters could also be required if geologic disposal occurs in clay/shale rocks, or in crystalline rocks if a bentonite engineered barrier is used.

The substantially lower heat generation rate of most canisters of non-naval DOE SNF and HLW compared with commercial and naval SNF (Figure 2-5) provides flexibility in heat management in a repository that contains all those wastes. For example, in the proposed Yucca Mountain repository, DOE planned to use co-disposal waste packages containing canisters of HLW and DOE SNF interspersed along the length of a disposal tunnel with waste packages containing either commercial SNF or naval SNF. Approximately 90% of the co-disposal waste packages would contain five canisters of HLW and one DOE standardized canister of DOE SNF. The remaining co-disposal waste packages would contain two canisters of HLW and two MCOs containing DOE SNF. Thus, the average thermal power of a co-disposal waste package would be about 910 watts. The commercial and naval waste packages would each contain a single canister of their respective SNF. For that repository concept, the cooler co-disposal waste packages would allow a closer spacing in an emplacement drift of waste packages that contained hotter commercial and naval SNF.

2.5.1.2 Criticality

The potential for criticality of DOE SNF under disposal conditions is a function of the composition of water contacting the waste, the concentration of the fissile isotopes in the fuel, the supplemental neutron absorbers added to the multi-purpose canisters, and the geometry of the fuel and neutron absorbers.

The higher fissile material concentration in some DOE SNF—as compared with that in commercial SNF—may increase the probability of an inadvertent criticality incident. As described in Section 2.1.1, for any repository, post-closure criticality analyses are performed to demonstrate that the initial emplaced configuration of the waste form remains subcritical.

[54] A pyrophoric material is a material that spontaneously ignites in air below 55°C. Metallic uranium-based SNF has shown pyrophoric behavior when exposed to air environments (Sandia National Laboratories 2008).

[55] Coupled thermal processes include thermal-hydrogeologic processes, thermal-chemical processes, thermal-mechanical processes, and thermal-hydrogeologic-mechanical processes.

Water with a high chloride[56] concentration, such as that expected in a salt repository, reduces the possibility for criticality. Hardin *et al*. (2015) investigated saline groundwaters in salt, crystalline rock, and clay/shale formations and their impact on the potential for criticality of commercial SNF in existing dual-purpose (storage and transportation) canisters. The investigation found that the proportion of commercial dual-purpose canisters that could remain subcritical increases with the salinity of repository groundwater, with chloride concentrations ranging from that of seawater up to that of concentrated chloride brine, at which point criticality becomes impossible (Hardin *et al*. 2015).

2.5.1.3 Degradation of Spent Nuclear Fuel

Radionuclides released from DOE SNF into the disposal environment is a strong function of the composition of SNF and interacting fluids, as well as the amount of fluids contacting the SNF. Radionuclides can be released only if the waste package fails. Assuming a scenario in which the waste package fails, the release rate will be controlled by diffusion, except when flowing water enters the waste package, in which case the radionuclide release may be by advection.[57] In general, diffusive and advective releases of radionuclides from a failed waste package will be affected by the size of the openings into a waste package, the rate the waste degrades, solubility limits, sorption onto corrosion products, and the presence of colloids[58] (NRC 2014a).

Radionuclides cannot leave the waste package faster than the waste form degrades. Fast rates of degradation, up to the limit of instantaneous degradation, indicates that the degradation rate affects only those radionuclides that are very soluble and, thus, not limited by other release constraints inside the waste package. Examples include technetium-99, under oxidizing conditions, and iodine-129, which are neither solubility limited[59] nor sorbed onto corrosion products. Radionuclides such as plutonium (*e.g.*, plutonium-242) and neptunium (*e.g.*, neptunium-237) typically have low concentrations due to solubility limits; in these cases, the amount transported will increase as water flow into the waste packages increases. Certain radionuclides can attach onto corrosion products within the waste package; thus, their release from the waste package is delayed (*e.g.*, neptunium-237). Colloids that are mobile in the water can facilitate release of radionuclides out of the waste package. Radionuclides sorbed or attached onto “irreversible” colloids[60] are not affected by solubility limits and stationary corrosion products. A radionuclide such as plutonium-242 will contribute to annual dose[61] from aqueous transport in the form of dissolved radionuclides and reversible colloids (NRC 2014a).

DOE conducted disposal-related research and development activities that were specific to DOE SNF as part of the volcanic tuff repository program. For example, the DOE Office of Environmental Management (DOE-EM) estimated the radionuclide inventory for DOE SNF (DOE 2004a). To estimate the total radionuclide inventory, DOE aggregated its SNF into 11 degradation groups,[62] with similar characteristics, and estimated and bounded the radionuclide inventory by using calculation templates (DOE 2004a). DOE also conducted two activities—a comprehensive review of peer-reviewed

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[56] Chloride is a strong neutron absorber and reduces the number of neutrons that are available to interact with fissile isotopes in the SNF.

[57] Advection is the process in which solutes, particles, or molecules are transported by the motion of flowing fluids.

[58] Colloids are tiny particles that remain suspended in water and are thus able to move with the water and facilitate the transport of certain radionuclides.

[59] Some radionuclides have a solubility limit that is a function of the properties of the radionuclide and the water chemistry inside the waste package. The solubility limit controls the amount of a radionuclide that can be dissolved in water.

[60] The term “irreversible colloids” refers to colloids with radionuclides irreversibly, or permanently, attached to them. The term “reversible colloids” refers to colloids to which radionuclides may attach and detach reversibly.

[61] Risk from a repository is commonly measured in terms of a peak dose to a member of the public. The dose derives from the radionuclides that are released from the repository. The radionuclides travel from the disposal site to where a member of the public can access them via a transporting media, such as water. Each radionuclide has a specific dose conversion factor, which is the amount of dose per unit concentration of the radionuclide in the transporting media.

[62] In 1998, DOE decided to group DOE SNF types to support specific purposes (*e.g.*, criticality analyses) to represent DOE SNF behavior in a repository (DOE 2004b). DOE classified all of its SNF in 34 groups (DOE SNF Groups) based on fuel characteristics that have a major impact on the release of radionuclides from DOE SNF and are important to nuclear criticality. DOE aggregated its SNF into different “groups”—for example, “degradation groups” and “criticality groups”—using the 34 DOE SNF Groups. For instance, degradation group 2 consists of DOE SNF Groups 3 and 4.

and technical literature and an experimental program—to inform its decision for implementing models of DOE SNF degradation in a volcanic tuff repository.

DOE-EM developed a technical basis to understand and predict how DOE SNF may corrode in volcanic tuff repository conditions through a comprehensive assessment of peer-reviewed literature and technical reports on the oxidation rates of prototypic metallic and non-metallic nuclear fuels (Hilton 2000; Ebner 2003). Specifically, DOE reviewed literature on the oxidation behavior of three fuel types prototypic of metallic fuel in the DOE SNF inventory: uranium metal, uranium alloys, and aluminum-based dispersion fuels (Hilton 2000). DOE also reviewed the oxidation behavior of four fuel types prototypic of non-metallic fuel in the DOE SNF inventory: oxide, hydride, carbide, and nitride fuels (Ebner 2003). For prototypic metallic and non-metallic fuels, DOE evaluated the oxidation mechanisms and rates of these materials in oxygen, water vapor, and water. DOE used the oxidation kinetics and rate data to identify the bounding oxidation rates most appropriate for each prototypic fuel (Ebner 2003).

DOE-EM also conducted experimental testing of prototypical DOE SNF (Shelton-Davis 2003) to evaluate the rate of release of radionuclides from SNF. The release rate test project included three fuel groups (uranium metal, aluminum-based, and mixed oxide), used three experimental methods, and complied with quality assurance requirements (DOE 2008b). Graphite fuel was also originally planned for study, but the project was terminated before this type of fuel was tested (Shelton-Davis 2003). DOE used flow-through tests to evaluate the forward dissolution rate of the fuel with no back reactions. DOE used unsaturated drip tests[63] to simulate the expected repository conditions and to estimate more closely the actual release rates of radionuclides from SNF. DOE used static batch tests[64] to provide information on the solution composition at the fuel surface and to support the anoxic/oxic studies with uranium metal fuel. In addition, DOE performed some colloid generation and stability tests on all fuel types, but they focused primarily on uranium metal fuel. The project was terminated prematurely because of funding constraints. Shelton-Davis (2003) reviewed and compared the release rate experimental results with a general model that encompassed all the published results from the literature surveys (Hilton 2000; Ebner 2003) and presented recommendations for describing the expected fuel performance in a repository.

It is important to note that OCRWM recognized that, for most DOE fuel types, "there is no known direct experimental test data for the degradation and dissolution of the waste form in repository groundwaters" (Bechtel SAIC Company 2004). Nonetheless, OCRWM examined the available data and information, including DOE-EM's reports (Hilton 2000; Ebner 2003; Shelton-Davis 2003) concerning the dissolution kinetics of DOE SNF matrices, to develop a degradation model suitable to describe the DOE SNF inventory (Bechtel SAIC Company 2004).

OCRWM and the National Spent Nuclear Fuel Program used 11 degradation groups (DOE 2004b)—the same groups DOE used to estimate the total radionuclide inventory—and developed release or degradation models. They estimated fractional corrosion rates for all DOE SNF to be disposed of in the repository (Table 2-3; Bechtel SAIC Company 2004, Table 6-9). Except for naval SNF, for which DOE used the commercial SNF release model (Bechtel SAIC Company 2004), DOE did not use the degradation models in the performance assessment for the volcanic tuff repository (DOE 2009a) because it asserted that the corrosion rates of these waste forms (with the exception of degradation groups 5, 6, 9, and 11)[65] compared with the long disposal timeframes (tens of thousands of years to a million years) are high enough to be effectively instantaneous (Bechtel SAIC Company 2004).

Instead, once a waste package fails and water enters a waste package, DOE used instantaneous degradation of the waste form in its performance assessment for the repository (Bechtel SAIC Company 2004; DOE 2009a). DOE chose this upper-limit model because most of the best-estimate models (other than degradation group 7) are currently based on limited

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[63] Tests where water was dripped onto pieces of SNF that were in a water vapor environment were called unsaturated drip tests.

[64] A static batch dissolution test is a type of accelerated testing in which crushed fuel samples are placed in a holder with just enough liquid to form a constant thin film of water on the surface of the fuel particles. The fuel surface area to solution volume in a batch dissolution test is larger than in a drip test, but is much less than in a flow-through test (Shelton-Davis 2003).

[65] DOE noted also that the mass of degradation groups 5, 6, 9, and 11 is small relative to degradation group 7.

and unqualified corrosion, dissolution, or oxidation data, and because it believes the degradation of most of the DOE SNF inventory in a volcanic tuff repository is effectively instantaneous (Bechtel SAIC Company 2004).

DOE chose the upper-limit model, in part, because earlier total system performance analyses showed that the overall effect of the failure of DOE SNF–containing waste packages will not significantly contribute to the dose to a member of the public at the compliance point on the repository site boundary (Bechtel SAIC Company 2004). Those analyses demonstrated that the dose to a member of the public is dominated by radionuclide releases from commercial SNF.[66]

Table 2-3. Characteristics of spent nuclear fuel degradation groups

Degradation Group (1 - see Notes below)	Group Name	Typical DOE SNF Type	Inventory (MTHM) (2)	Number of Packages for Off-Site Transport (1)	Fractional Corrosion Rate (day^{-1}) (3)
1	Naval		65	400	(See Note 4)
2	Plutonium/uranium alloy	Fermi 1 SNF	8.5	29	5.9×10^{-4}
3	Plutonium/uranium carbide	Fast Flux Test Facility—test fuel assembly SNF	0.1	5	0.174
4	Mixed oxide and plutonium oxide	Fast Flux Test Facility—demonstration fuel assembly/Fast Flux Test Facility—test demonstration fuel assembly SNF	11.59	146	2.2×10^{-5}
5	Thorium/uranium carbide	Fort St. Vrain SNF	24.52	568	5.5×10^{-7}
6	Thorium/uranium oxide	Shippingport Light Water Breeder Reactor SNF	46.98	52	1.2×10^{-8}
7	Uranium metal	N Reactor SNF	1,984.81	402	7.7×10^{-3}
8	Uranium oxide	a) undamaged commercial SNF b) Three Mile Island-2 core debris (damaged)	166.2; sum of damaged and undamaged	727	1.9×10^{-5} 0.19
9	Aluminum-based SNF	Foreign research reactor SNF	19.54	1,307	1.2×10^{-6}
10	Miscellaneous SNF		4.24	6	0.2
11	Uranium-zirconium hydride	Training, Research, Isotopes, General Atomics (TRIGA®) SNF	1.51	90	3.3×10^{-8}

Notes

(1) DOE SNF Groups described in Table A1-1 and number of packages listed in Table A1-2 are listed here for each degradation group number. In this note, DOE SNF Groups that are of commercial origin are denoted in bold text. Degradation group 1 is DOE SNF Group 32. Degradation group 2 includes DOE SNF Groups 3 and **4**. Degradation group 3 is DOE SNF Group 21. Degradation group 4 includes DOE SNF Groups 22, 23, and 24. Degradation group 5 includes DOE SNF Groups **19** and **20**. Degradation group 6 includes DOE SNF Groups **25** and **26**. Degradation group 7 includes DOE SNF Groups 1 and 2. Degradation group 8 includes DOE SNF Groups **5**, 6, **7**, 8, 9, **10**, **11**, **12**, and **13**. Degradation group 9 includes DOE SNF Groups 14 through 18. Degradation group 10 is DOE SNF Group 34. Degradation group 11 includes DOE SNF Groups 27 through 30.

(2) Metric tons of heavy metal, based on disposal of a total of 2,333 MTHM of DOE SNF in the first repository (DOE 2009a, Table 1.5.1-1).

(3) Mass fractional degradation rates for DOE SNF at 50°C, pH 8.5, 0.002 molar CO32−, and 0.20 atmospheres oxygen calculated for best-estimate models (Bechtel SAIC Company 2004, Table 6-9). The listed values are for the total mass of each group. For example, the total mass of Group 7 is expected to degrade in 130 days (1 divided by the fractional corrosion rate).

(4) Bechtel SAIC Company did not provide a value for naval SNF. DOE used the commercial SNF release model for naval SNF. The base-case model calculated fractional release rate for commercial SNF is 8.42 × 10−7 (day-1) (DOE 2009a, Table 2.3.7-19). DOE "... suggests that the model-calculated fractional release rates are consistent with experimentally measured fractional release rates in the literature" (DOE 2009a, p. 2.3.7-42).

[66] The contribution of DOE SNF to the total release of radionuclides from the repository is swamped by the contribution of commercial SNF. This is not surprising because the total radioactivity of commercial SNF is much larger than that of DOE SNF (Figure A2-6) and the radioactivity of commercial SNF, per unit mass, is also larger than that of DOE SNF (Table A2-1).

2.5.2 Characteristics of Spent Nuclear Fuel Packaging That Affect Disposal

The characteristics of SNF packaging can affect how the material is disposed of in a repository. For example, the size of waste packages[67] affects how the DOE SNF is moved underground into the repository. The alloy used for DOE SNF multi-purpose canisters affects the potential compatibility of the canisters in different disposal concepts.[68] Waste package degradation processes and the rates of waste package failure control the release of radionuclides into the disposal environment, which are important considerations because "wherever the geosphere is relatively permeable or where it is difficult to reach consensus on the effectiveness of the natural barrier, the waste package is often relied on to provide a disproportionate degree of the safety of the entire system" (King 2013). Also, DOE relies on the standardized canister approach to overcome limitations in knowledge of its SNF. For example, Carlsen (2014b) states,

> The canister basically provides standardization for all the diverse DOE fuels that can be handled similarly at various facilities. There's cost savings; there's, we believe, risk reduction associated with that; and, more importantly, it provides a common barrier that we believe we can credit in the safety analyses for transport and disposal and get away from the need to have to characterize the chemical and mechanical properties of all of our DOE fuels, which would be a real costly challenge that I'm not sure would be successful even at any price.

Engineering feasibility, the multi-purpose canister alloy and its compatibility with different disposal concepts, and degradation of waste packages are addressed in more detail in the following sections.

2.5.2.1 Engineering Feasibility of Disposing of Planned Waste Packages

Waste packages potentially can be transported from the surface via a vertical shaft, a straight ramp, or a spiral ramp to where they are to be emplaced in a geologic repository (Hardin *et al*. 2015). The size and weight of DOE multi-purpose canisters vary widely (Table A2-2) and can affect the feasibility of transporting waste packages underground and emplacing them in disposal tunnels (DOE 2014).

The methods for transporting heavy waste packages (*e.g.*, the naval waste package) underground and emplacing them in disposal tunnels are not mature and may require additional developmental activities[69] (DOE 2014; Hardin *et al*. 2015) before the material can be disposed of in a repository. The naval SNF canister is the largest and heaviest of the DOE multi-purpose canisters—the maximum weight of a loaded naval SNF canister is approximately 45 metric tons (98,000 pounds) and a waste package containing a naval canister can weigh up to approximately 73 metric tons (162,000 pounds; DOE 2009a). In contrast, the maximum weight of a loaded DOE MCO is one-fourth that of a naval canister, and the maximum weight of a loaded DOE standardized canister is between one-tenth and one-twentieth that of a naval canister, depending on the dimensions of the DOE standardized canister (Table A2-2). The maximum weight for a co-disposal waste package[70] that contains DOE SNF and HLW (DOE 2009a) would be approximately 50 metric tons (127,900 pounds). The ease of transporting and emplacing non-naval SNF multi-purpose canisters underground depends on whether MCOs and standardized canisters are packaged together with HLW into a waste package or disposed of separately. Although designs and relevant experience exist for shafts, ramps, and funicular[71] options to transport waste packages underground, the required systems for heavy waste packages, in most cases, would be the largest of their kind and could require novel design features (Hardin *et al*. 2015).

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[67] The waste package serves as the disposal overpack to the multi-purpose canisters and is placed over the multi-purpose canister in the surface facilities of a repository.

[68] Each alloy or type of metal (*e.g.*, carbon steel and copper) will corrode at a different rate depending on the disposal environment (*e.g.*, as a function of water chemistry) and can potentially suffer galvanic corrosion if dissimilar metals are used for the multi-purpose canister and the waste package.

[69] The Board reviewed DOE research and development activities on this topic (NWTRB 2015a) and recommended that DOE evaluate approaches, benefits, and costs of repackaging cooler naval SNF into smaller disposal packages.

[70] The co-disposal waste packages are designed to contain either a DOE standardized canister and five HLW glass canisters or two MCOs and two HLW glass canisters (Section A2.4).

[71] A funicular is a cable railroad in which ascending and descending cars are counterbalanced.

2.5.2.2 Compatibility of Planned Packages with Different Disposal Concepts

The disposal overpack (waste package), which is placed around the multi-purpose canister in surface facilities at a repository, could be a highly important part of the engineered barrier system for waste isolation and for limiting post-closure criticality (Hardin *et al.* 2015). In general, corrosion-allowance (*e.g.*, sacrificial carbon steel) and corrosion-resistant (*e.g.*, Alloy 22 or copper) overpack materials are available and have been studied for repository waste packaging applications (King 2013). The classes of materials for disposing of SNF include copper, cast iron, carbon steel, stainless steels, titanium alloys, and nickel-based alloys (King 2013).

The overpack construction material is normally chosen to be compatible with the canister containing the SNF (to minimize the potential for galvanic corrosion between dissimilar metals), the disposal environment, and the planned engineered barriers surrounding the waste package. From a galvanic corrosion perspective, stainless steel, which is used in each of the DOE multi-purpose canisters, is compatible with all classes of materials considered (King 2013) for a disposal overpack.

Two strategies to ensure very long lifetimes of the disposal overpack are to select either a material that approaches thermodynamic "immunity" in the repository environment (*e.g.*, copper in a reducing environment) or a highly corrosion-resistant material (*e.g.*, Alloy 22; King 2013; Ilgen *et al.* 2014). No engineering material is truly "immune" to corrosion, but in the anoxic environments expected for some repositories, the general corrosion rate of copper is exceedingly slow (<nm/year; King 2013). As part of the DOE criticality control strategy, with the exception of a salt repository, groundwater (moderator) exclusion by the overpack and other engineered barriers for the duration of the regulatory performance period (*e.g.*, 10,000 years) is needed (Hardin *et al.* 2015). For example, highly compacted bentonite buffer material is used in crystalline rock and clay/shale repository concepts to limit corrosion by limiting the mass transport of corrosion-enhancing dissolved species to the waste package from waters contained in the surrounding rock (King 2013). This is the approach being taken in the Swedish (granite) and French (shale) repositories.

2.5.2.3 Waste Package Degradation

In a repository performance assessment, radionuclide releases are calculated on a waste package basis.[72] The overall release rate from the repository depends on the releases from the individual waste packages and how the releases from all the failed waste packages add together (or overlap at a particular time)[73] to produce an overall release rate for the repository. The failure behavior of waste packages is controlled by the corrosion processes that affect the waste package. Both the time of failure of the waste package and the extent of the surface that fails, which controls the amount of water that enters the package, are strong functions of specific corrosion processes and mechanical loads on the packages. Localized corrosion and stress corrosion cracking can occur rapidly in comparison to uniform corrosion if the waste package material is thermodynamically stable relative to its disposal environment or is corrosion resistant. However, localized or stress corrosion cracking leads to narrow waste package surface failure areas compared with uniform corrosion. Different waste package materials are susceptible to different corrosion processes (King 2013) and are strongly affected by the engineered materials surrounding them. For each mature disposal concept, the important waste package degradation

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[72] Both the mass of SNF in a waste package and the number of packages that a DOE SNF degradation group is in will affect the release of radionuclides for that group of SNF into the disposal environment. The large size of FSV SNF, relative to its mass, means that FSV SNF would be in approximately 17% of the DOE standardized canisters even though it is only approximately 1% of the total MTHM of DOE SNF. Also, primarily due to its enrichment, the aluminum-based SNF group of fuels in Table 2-3 constitutes less than 1% of the total MTHM of DOE SNF, but would be about 45% of the DOE standardized canisters.

[73] NRC (2014a) summarized this behavior as follows, "… if all the packages failed at the same time, then the releases from all the waste packages would be occurring at the same time and would combine to produce the repository release rate. If, however, waste packages fail at different times, the potential for the releases to overlap in time will depend on the length of time between the failed packages and the time it takes a waste package to release the inventory of a particular radionuclide. When releases from a waste package are somewhat rapid, occurring over hundreds to thousands of years, as is the case for the high-mobility radionuclides, the potential for releases from all the waste packages to overlap in time is reduced unless all the waste packages fail within the same time period over which the rapid release occurs. High release rates will persist for short periods of time (*e.g.*, hundreds to thousands of years); thus, the overlap periods for high waste package release rates will be short (a smaller number of waste package releases could potentially overlap in time). In contrast, low release rates may persist for hundreds of thousands of years and longer and the overlap time period would be much longer and include the potential for a larger number of failed packages to contribute to the overall repository release rate."

processes are understood, but site-specific information such as water composition is needed to evaluate the timing and extent of waste package failure.

2.6 Key Observations on the Characteristics of U.S. Department of Energy Spent Nuclear Fuel and Its Management and Disposal

1. The total quantity of DOE SNF is about 2,510 MTHM, which includes about 272 MTHM of commercial-origin SNF that DOE cannot dispose of in a separate defense HLW repository. The total quantity of non-naval DOE SNF is greater than the amount that can be disposed of in the proposed Yucca Mountain repository. DOE stores more than 99% (by mass) of its SNF at four sites: the Hanford Site (2,130 MTHM); INL (325 MTHM); SRS (30 MTHM); and FSV (14.7 MTHM). Each site has commercial-origin DOE SNF. The remaining DOE SNF is located at domestic research and test reactors and foreign research reactors.

2. DOE plans to use three types of stainless steel multi-purpose canisters that are welded closed and are placed into a rail transport cask to transport most disposable SNF. However, DOE does not yet have NRC approval for transport of these canisters. The first type of canister is the MCO at Hanford, which DOE finished loading in 2012. The second type of canister is the naval canister at INL, which the Navy continues to fill. The third is a DOE standardized canister for use at Hanford, INL, and SRS, which DOE has not deployed but that would contain 261 MTHM of DOE SNF. DOE designed the MCO, naval canister, and DOE standardized canister for transport to, and use at, a volcanic tuff repository.

3. DOE will need to complete development of the DOE standardized canister and obtain NRC's approval for moderator exclusion credit during transport. For example, DOE will need to complete development of a nickel-and-gadolinium alloy basket and supplemental neutron absorber material, which would be used in roughly 40% of the DOE standardized canisters for post-closure criticality control in a volcanic tuff repository. DOE planned to credit the DOE standardized canister as a leak-tight boundary during transport inside a rail cask. This plan needs NRC's approval. The terms of NRC approval will define what SNF data DOE needs to develop and any needed canister design changes. NRC approval would allow DOE to move forward with confidence on packaging plans, including new packaging facilities.

4. Adequately drying SNF while packaging it in multi-purpose canisters is necessary to ensure safe interim storage and safe transport and disposal. Water in a sealed multi-purpose canister can react with the SNF over time, which can create hydrogen (a flammable gas), cause an increase in gas pressure, and potentially lead to internal corrosion of the container. The diverse DOE SNF types, their varying states of degradation, and the need to include supplemental neutron absorbers, which could release physically and chemically absorbed water after DOE seals the canisters, will all complicate DOE's packaging efforts.

5. DOE will need to understand better how DOE SNF and its surrounding multi-purpose canister degrade if disposal occurs in a repository sited in salt, crystalline rock, or clay/shale. For example, as uranium metal SNF (about 85%, by mass, of the inventory) degrades, it will generate hydrogen when anoxic water reacts with fuel. Gas pressurization from hydrogen generation is a process that DOE did not evaluate in detail for the unsaturated volcanic tuff repository, but would need to understand better for other disposal concepts. DOE has limited SNF corrosion data that were collected under a nuclear quality assurance program. Those data focused on corrosion under oxidizing conditions.

3. Legal and Regulatory Constraints on Management and Disposal of U.S. Department of Energy Spent Nuclear Fuel

This chapter introduces the overarching legal and regulatory framework that both guides and constrains how the U.S. Department of Energy (DOE) manages and disposes of its spent nuclear fuel[74] (SNF). Chapters 4–7 include additional details about the legal and regulatory environment governing each of the four DOE SNF storage sites.

3.1 Legal Agreements

One of the most significant legal agreements affecting how SNF is managed and disposed of by DOE is the 1995 Settlement Agreement (Idaho *et al.* 1995) between the state of Idaho, DOE, and the U.S. Navy. Although the 1995 Settlement Agreement primarily concerns how to manage nuclear waste at Idaho National Laboratory (INL), it also places constraints on SNF transfers between INL and Savannah River Site (SRS), and limits shipments of SNF from Hanford and Fort St. Vrain (FSV) to INL. For example, the agreement (Idaho *et al.* 1995) requires that no shipments of SNF from FSV be made to INL unless a permanent repository or interim storage facility for SNF—located outside Idaho—has opened and is accepting SNF from INL.

The 1995 Settlement Agreement also stipulates that DOE's failure to meet certain deadlines or requirements for action at INL results in SNF shipments to INL being suspended. For example, the state of Idaho stopped non-naval DOE SNF

[74] Upon first use in this chapter, underlined terms and phrases are explained in the Glossary (Chapter 11) and abbreviations are introduced.

shipments to INL because DOE did not meet a December 31, 2012, deadline to complete solidification[75] of sodium-bearing liquid high-level wastes at INL. The agreement also requires that "DOE shall remove all spent fuel, including naval spent fuel and Three Mile Island spent fuel from Idaho by January 1, 2035"[76] (Idaho *et al.* 1995), although this requirement was amended in 2008 to allow no more than 9 metric tons of heavy metal (MTHM) of naval SNF to be kept at INL after January 1, 2035. The agreement also requires DOE to transfer all INL SNF in wet storage into dry storage at the site by December 31, 2023, although the aforementioned amendment now allows any naval SNF[77] arriving at INL after January 1, 2017, to be kept in wet storage for up to six years. The 1995 Settlement Agreement specifies that "DOE and the Navy shall employ multi-purpose canisters or comparable systems to prepare spent fuel at the Idaho National Engineering Laboratory[78] for shipment and ultimate disposal of such fuel outside Idaho."

3.2 Decisions

Adhering to the National Environmental Policy Act of 1969 (U.S. Congress 1969) process, DOE issued two decisions[79] that influence how its SNF is managed at multiple sites. In the first case, DOE issued a final programmatic environmental impact statement (EIS) in 1995 on DOE-wide management of DOE SNF through 2035 (DOE 1995a). In this EIS, DOE analyzed the impacts of alternatives related to the transportation, receipt, processing, and storage of DOE SNF (DOE 1995a). DOE's decision (DOE 1995b), based on the programmatic EIS, was to consolidate regionally nearly all its SNF at three sites—Hanford, INL, and SRS—pending future decisions on ultimate disposition. Under this regional consolidation approach, defense production reactor SNF, which was generated in plutonium production reactors, was to be stored at Hanford; aluminum-clad SNF was to be stored at SRS; and all other SNF was to be stored at INL. In 1996, DOE's record of decision for the SNF management programmatic EIS was amended (DOE 1996a) to reflect the 1995 Settlement Agreement (Idaho *et al.* 1995) that limited shipments of SNF to INL. This limitation reduced consolidation of SNF by type and left similar types of SNF at all three sites.

In the second case, DOE issued a final EIS and a revised record of decision (DOE 1996b) in 1996 on a proposed nuclear weapons nonproliferation policy concerning foreign research reactor SNF. Although foreign research reactor SNF was already part of the scope of DOE's programmatic environmental impact assessment and decision (DOE 1995a, 1995b) described above, DOE deferred its policy decision on accepting foreign research reactor spent nuclear fuel until after a separate EIS was completed. The 1996 decision applied to target material[80] containing uranium enriched in the United States and two types of foreign research reactor SNF—aluminum-based SNF and Training, Research, Isotopes, General Atomics (TRIGA®) SNF (DOE 1996b). The aluminum-based foreign research reactor SNF (about 18.2 MTHM) and target material (about 0.6 MTHM) would be transported to and managed at SRS. The TRIGA® foreign research reactor SNF (about 1 MTHM) would be transported to and managed at INL in accordance with DOE's record of decision on SNF management (DOE 1995b) and the 1995 Settlement Agreement (Idaho *et al.* 1995). DOE revised the 1996 record of decision multiple times and extended the deadline for fuel acceptance from the foreign reactors from 2009 to 2019 (DOE 2008c). Further details describing how foreign research reactor SNF at INL and SRS is managed are presented in Chapters 5 and 6, respectively.

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[75] As of August 16, 2017, suspension of non-naval DOE SNF shipments to INL remains in place as solidification has not begun.

[76] The agreement provides for the Federal parties (DOE and Navy jointly) to pay the state of Idaho $60,000 for each day after January 1, 2035, that any SNF remains in Idaho. The payment for not moving SNF out of Idaho is subject to the availability of advance appropriations.

[77] An addendum (Idaho *et al.* 2008) to the agreement governs receipt and handling of shipments of naval SNF.

[78] The Idaho National Engineering Laboratory subsequently was renamed Idaho National Laboratory.

[79] In the National Environmental Policy Act process, a decision can be a finding of no significant impact issued after completion of an environmental assessment or a record of decision can be issued after publication of a final environmental impact statement.

[80] Targets are radioactive materials that cannot sustain a chain reaction and that are placed inside a nuclear reactor. Targets are used to produce particular radioisotopes such as tritium, molybdenum-99, and plutonium-238. Target material is the residual materials left after the desired radioisotopes have been removed from the targets.

3.3 Regulatory Requirements

Regulations pertaining to storing, transporting, and disposing of DOE SNF cover a broad spectrum of safety management issues and affect the activities that DOE undertakes to manage and dispose of its SNF.

DOE self-regulates the safety management of DOE SNF at its storage sites. The two primary DOE regulations are Title 10, Code of Federal Regulations, Part 830 (10 CFR 830), which regulates nuclear safety management of facilities, and 10 CFR 835, which regulates occupational radiation protection. The latter regulation requires that radiation protection programs include formal plans and measures for applying the as low as reasonably achievable (ALARA)[81] process to occupational exposure.

Additional regulatory requirements established by the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Environmental Protection Agency also influence storage, transportation, and disposal of DOE SNF. For example, a multi-purpose canister DOE designed for storage, transportation, and disposal of DOE SNF could be subject to three different NRC regulations depending on DOE's licensing approach (*e.g.*, DOE could seek NRC's approval for storage; storage and transportation; transportation and disposal; or storage, transportation, and disposal) for the multi-purpose canister. The NRC regulations vary in restrictiveness and can vary in regulatory scope for the same topic (*e.g.*, the quality assurance[82] requirements). The NRC (Title 10) and U.S. Environmental Protection Agency regulations (Title 40) that affect how DOE SNF is managed and disposed of are provided in Table 3-1.

Table 3-1. U.S. Nuclear Regulatory Commission and U.S. Environmental Protection Agency regulations

Regulated Activity	Part of the Code of Federal Regulations (1)	Title of Regulation
Storage	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*
Transportation	10 CFR 71	*Packaging and Transportation of Radioactive Material*
Disposal	40 CFR 197	*Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada*
Disposal	10 CFR 63	*Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada*
Disposal	40 CFR 191	*Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes* (applicable to disposal at sites other than Yucca Mountain)
Disposal	10 CFR 60	*Disposal of High-Level Radioactive Wastes in Geologic Repositories* (applicable to disposal at sites other than Yucca Mountain)
Hazardous Chemical Waste Management	40 CFR 261, Subpart C	*Characteristics of Hazardous Waste*

Note
(1) NRC regulations are in Title 10 of the Code of Federal Regulations (*e.g.*, 10 CFR 72). U.S. Environmental Protection Agency regulations are in Title 40 of the Code of Federal Regulations (*e.g.*, 40 CFR 191).

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[81] "ALARA means 'As Low As is Reasonably Achievable,' which is the approach to radiation protection to manage and control exposures (both individual and collective) to the work force and to the general public to as low as is reasonable, taking into account social, technical, economic, practical, and public policy considerations. As used in this part, ALARA is not a dose limit but a process which has the objective of attaining doses as far below the applicable limits of this part as is reasonably achievable" (10 CFR 835.2). NRC also includes the ALARA concept in its standards for protection against radiation (10 CFR 20).

[82] Quality assurance comprises all those planned and systematic actions necessary to provide adequate confidence that a structure, system, or component, or geologic repository and its structures, systems, or components, will perform satisfactorily in service. For storage, quality assurance requirements apply to "design, purchase, fabrication, handling, shipping, storing, cleaning, assembly, inspection, testing, operation, maintenance, repair, modification of structures, systems, and components, and decommissioning that are important to safety" (10 CFR 72). For transportation, quality assurance requirements apply to "design, purchase, fabrication, handling, shipping, storing, cleaning, assembly, inspection, testing, operation, maintenance, repair, and modification of components of packaging that are important to safety" (10 CFR 71). For disposal, the quality assurance program is "applied to all structures, systems, and components important to safety, to design and characterization of barriers important to waste isolation, and to related activities" (10 CFR 63).

3.3.1 Storage Regulation

This section describes the NRC storage regulations and guidance for SNF and the licensing requirements therein pertaining to independent[83] storage of SNF, the retrievability of SNF that has been stored, and the effects of aging on SNF and the storage facility.

The NRC storage-related regulation (10 CFR 72) addresses licensing of storage facilities and certification of SNF storage cask designs. NRC has the authority to regulate storage of non-defense-related SNF (*e.g.*, DOE-managed SNF from commercial nuclear power plants). The NRC regulation prescribes the requirements for two types of storage facilities at which DOE could store commercial-origin DOE SNF. Those facilities are an independent spent fuel storage installation and a monitored retrievable storage facility.[84] The description that follows focuses on the requirements associated with independent spent fuel storage installations and SNF storage cask designs because DOE has NRC-licensed independent spent fuel storage installations at INL (DOE has two licenses, but only one facility was built) and at FSV (one license) and has an NRC-certified storage cask design, which is used in conjunction with the operating storage facility at INL. These facilities are described in Chapters 5 (INL) and 7 (FSV).

The NRC storage-related regulation (10 CFR 72) provides the requirements, procedures, and criteria to issue licenses to receive, transfer, and possess power reactor SNF and other radioactive materials associated with storing SNF in independent spent fuel storage installations. NRC requires that the design of the facility be able to receive, handle, package, store, and retrieve SNF without undue risk to the health and safety of the public. NRC requirements, procedures, and criteria to issue certificates of compliance approving SNF storage cask designs are also included in the regulation. The NRC storage regulatory requirements are prescriptive and deterministic.[85]

The NRC storage regulation focuses on confining radionuclides, radiation shielding, criticality safety, heat removal capability, structural integrity, and retrievability. The regulation specifically requires that "storage systems must be designed to allow ready retrieval[86] of spent fuel … for further processing or disposal." NRC defines damaged SNF as any fuel rod or fuel assembly that cannot fulfill its fuel-specific or system-related functions (*e.g.*, a function could be that the SNF assembly will be retrievable) relevant to the phase (storage or transportation) for which it is certified. According to NRC guidance, SNF that has been classified as damaged for storage must be placed in a canister designed for damaged fuel, which serves as a confinement system.

Each NRC license issued to DOE must include technical specifications [10 CFR 72.44(c)], which include the "functional and operating limits and monitoring instruments and limiting control settings" for fuel or waste handling and storage conditions, limiting conditions, surveillance requirements, design features, and administrative controls.

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[83] A spent fuel storage facility may be considered independent even if it is located on the site of another NRC-licensed facility.

[84] A monitored retrievable storage facility is a Federal storage facility described in section 141(b)(1) of the Nuclear Waste Policy Act. The act prohibits beginning construction of such facility until NRC has issued a license for the construction of a geologic repository.

[85] NRC found that "the regulatory approach for SNF storage is largely based on meeting applicable industry consensus standards and conservative guidance to ensure adequate safety margins in the facility and cask designs and operations" (NRC 2012). The regulations require that dry storage systems are designed "to withstand the effects of 'worst-case' events or design-basis events and phenomena while still maintaining the capabilities to provide adequate shielding and confinement of radioactive contents and prevent nuclear criticality" (NRC 2012).

[86] The NRC storage regulation and its associated guidance apply to DOE storage facilities, and the SNF stored within, that are licensed by NRC. Although, most DOE SNF, by mass, and most DOE SNF facilities are not regulated by NRC, the concepts embodied in NRC regulations and guidance are relevant to how DOE manages its SNF. In its guidance for reviewing retrievability, NRC defines "ready retrieval as 'the ability to safely remove the spent fuel from storage for further processing or disposal.' In order to demonstrate the ability for ready retrieval, a licensee should demonstrate it has the ability to perform any of the three options below. These options may be utilized individually or in any combination or sequence, as appropriate. A. remove individual or canned spent fuel assemblies from wet or dry storage, B. remove a canister loaded with spent fuel assemblies from a storage cask/overpack, C. remove a cask loaded with spent fuel assemblies from the storage location" (NRC 2016a). The Board would be remiss if it did not note that "under the provisions of the Standard Contract, DOE does not consider [commercial] spent fuel in canisters to be an acceptable waste form, absent a mutually agreed to contract modification" (Howard 2013).

The NRC license term for a storage facility is up to 40 years, and subsequent renewal periods are for up to 40 years (NRC 2011a). Licensees are required to address the effects of aging on the facility's structures, systems, and components that are important to safety when renewing their storage license, and during the renewed license periods. Box 3-1 addresses how aging SNF and SNF facilities are managed, and NRC provides guidance for how to assess aging effects in its standard review plan (NRC 2016b). The guidance addresses both internal and external canister aging mechanisms.

As materials age, they can degrade. For example, spent nuclear fuel can degrade due to radiation effects or corrosion in the presence of water or water vapor. Degradation is a change in material properties that adversely affects the behavior of the material. In nuclear operations, an aging management program manages degradation effects to ensure continued safe operations for extended periods of time. Aging management activities may include prevention, mitigation, condition monitoring, and performance monitoring.

How is it determined whether an aging management program should be used?

First, the facility operator identifies required functions, such as cooling or handling spent nuclear fuel, needed to safely operate the facility or conduct a process. Then, the operator identifies the structures, systems, and components of the facility or process that are required to perform the functions; for example, a pool, active ventilation system, or crane might be needed to cool or handle the SNF. For each structure, system, or component needed for safe operation, the operator assesses three factors to decide the requirements for an aging management program: the materials used, the environments in which they operate, and the degradation modes of those materials to decide whether aging effects could adversely affect operations over the expected life of operations.

How is age-related degradation managed?

The facility operator takes actions to control or prevent aging by preventing adverse environments, avoiding chemical reactions, or controlling allowable physical conditions. The operators monitor or inspect features (*e.g.*, cracks and their size) linked to the effects of aging on the intended functions of the structure or component. The aging management program detects aging effects before there is a loss of any structure or component intended function. In developing the aging management program, the operators consider the method of detection (for example, visual surface or volumetric inspections or surveys), selection and calibration of equipment, frequency of inspection, sample size, data collection, and timing of inspections. An aging management program defines acceptance criteria to enable operators to decide whether the results of an inspection suggest that aging is occurring and are the metric against which the need for corrective action is evaluated. The facility operator monitors and identifies trends in aging effects to predict the extent of the effects of aging and to take timely actions that correct or mitigate the problem. The aging management program uses operating experience from the facility, and other facilities, so the operators of the licensed facility can learn and change the program with time to increase or decrease management actions, as necessary.

Box 3-1. Managing aging spent nuclear fuel and aging spent nuclear fuel storage facilities

3.3.2 Transportation Regulation

Under the terms of the 1987 Nuclear Waste Policy Amendments Act, SNF transported by DOE to either a monitored retrievable storage facility or geologic repository must occur in an NRC-certified transportation package. All DOE SNF transportation, whether it is defense-related or commercial-origin, is subject to NRC regulation. NRC's transportation-related regulation includes requirements that address structural integrity, criticality control, radiation shielding, thermal analysis, and containment analysis. Like the NRC storage requirements, the NRC transportation regulatory requirements are prescriptive and deterministic. For example, "a package used for the shipment of fissile material must be so designed and constructed and its contents so limited that under the tests specified in § 71.73 ("Hypothetical accident conditions"), the package would be subcritical."[87] The regulation also includes required assumptions; for example, "a non-mechanistic assumption of full flooding" (Carlsen 2014a) must be used to analyze the potential for criticality for hypothetical accident conditions. In addition, NRC guidance for reviewing SNF transportation packages also contains prescriptive acceptance

[87] NRC characterizes this topic as "moderator exclusion" for transportation packages because water is a moderator for thermal neutrons released from the SNF. The presence of water inside a transportation package could lead to inadvertent nuclear criticality. NRC's regulation allows it to approve an exception to the requirement that the package must be subcritical with water in the containment system; however, NRC's long-term practice has been to consider this exception to be appropriate only for limited shipments and not for general approval of a design (Reyes 2007).

criteria—for example, "combustible gases should not exceed 5% of the free gas volume in any confined region of the package while the containment vessel is sealed and under normal transport conditions" (NRC 2000).

3.3.3 Disposal Regulations

DOE activities related to disposing of all its SNF are subject to both U.S. Environmental Protection Agency radiation protection standards and NRC requirements for high-level radioactive waste (HLW)[88] disposal in geologic repositories that implement the U.S. Environmental Protection Agency standards (Table 3-1). Requirements in 10 CFR 63 for disposing of HLW in a geologic repository at Yucca Mountain, Nevada, implement the U.S. Environmental Protection Agency's 40 CFR 197 standard.

In contrast to NRC's storage and transportation regulations, which use a more prescriptive and deterministic regulatory approach, NRC's disposal regulation at 10 CFR 63 uses a risk-informed and performance-based regulatory approach. The NRC Yucca Mountain regulation is consistent with NRC's policy to increase use of "probabilistic risk assessment"[89] technology in NRC regulatory activities "to the extent supported by the state-of-the-art in probabilistic risk assessment methods and data and in a manner that complements the NRC's deterministic approach" (NRC 1995).

NRC's 10 CFR 60 contains requirements that apply to repositories that are subject to the U.S. Environmental Protection Agency's 40 CFR 191 standard. Both these regulations are generic and apply to sites other than Yucca Mountain. The NRC's 10 CFR 60 was promulgated in the 1980s prior to adopting a philosophy of risk-informed regulation that uses probabilistic risk assessment results (NRC 1995). The NRC regulation relies on quantitative, subsystem performance standards. For example, NRC required that "[c]ontainment of HLW within the waste packages will be substantially complete for a period … that such period shall be not less than 300 years nor more than 1,000 years after permanent closure of the geologic repository." NRC also required that "[t]he release rate of any radionuclide from the engineered barrier system following the containment period shall not exceed one part in 100,000 per year of the inventory of that radionuclide calculated to be present at 1,000 years following permanent closure." The Blue Ribbon Commission on America's Nuclear Future suggested that existing generic geologic disposal standards (40 CFR 191 and 10 CFR 60) be revisited and revised (BRC 2012); however, even though both the U.S. Environmental Protection Agency and NRC[90] generally agreed with this suggestion, they decided not to act to revise their respective standards until there is Congressional action on the Blue Ribbon Commission's recommendations (Forinash *et al*. 2013; Vietti-Cook 2012).

Both NRC disposal regulations require a quality assurance program be applied to systems that are important to safety or waste isolation.

3.3.4 Hazardous Chemical Waste Regulation

Hazardous waste in the United States is regulated under the Resource Conservation and Recovery Act (RCRA; U.S. Congress 1976). DOE (1995c) evaluated how RCRA subtitle C hazardous waste regulations apply[91] to DOE SNF. A solid waste must appear as an RCRA-listed hazardous waste under 40 CFR §261.31-33, or it must be determined to be a characteristic hazardous waste as detailed under 40 CFR §261.21-24 to be regulated as RCRA hazardous waste. Based on

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[88] The definition of HLW in 10 CFR 60 and 63 includes SNF.

[89] Probabilistic risk assessment is a systematic method for assessing three questions that NRC uses to define "risk." These questions consider (1) what can go wrong, (2) how likely it is, and (3) what its consequences might be. These questions allow NRC to understand likely outcomes, sensitivities, areas of importance, system interactions, and areas of uncertainty that the staff can use to identify risk-significant scenarios.

[90] When NRC published 10 CFR 63, it noted, "[t]he Commission recognized that its generic part 60 requirements will need updating if applied to sites other than Yucca Mountain" (NRC 2001).

[91] DOE decided "to only accept HLW and/or SNF that is not subject to regulation as hazardous waste under the Resource Conservation and Recovery Act [RCRA 1976 (U.S. Congress 1976)] Subtitle C for disposal in the first geologic repository licensed by NRC under the Nuclear Waste Policy Act" (DOE 2008a). The states of Washington, Idaho, and South Carolina implement the hazardous chemical waste regulation and do not regulate any DOE SNF as RCRA waste.

DOE's knowledge of fuel composition and reactor operations, DOE identified some known or suspected characteristics of DOE SNF that could potentially subject certain categories of SNF to regulation as RCRA hazardous waste (DOE 1995c). For example, DOE identified that the reactivity of uranium metal SNF and carbide-based fuel could be a concern under RCRA. DOE also determined that some DOE SNF contains beryllium, which is a listed RCRA hazardous waste.

For each category of SNF that could be subject to regulation under RCRA, DOE completed an evaluation relative to the requirements of RCRA (DOE 1995c) and determined that uranium metal, as well as carbide-based fuel, is excluded from RCRA solid waste regulation as a special nuclear material under 40 CFR §261.4(a)4. Beryllium in SNF (used fuel) is also not subject to RCRA requirements because RCRA regulates beryllium as a listed hazardous waste when it is discarded as an unused commercial chemical product or in powder form (40 CFR §261.33). DOE (1995c) determined that sodium-bonded SNF "potentially has characteristics" that correspond to those of hazardous waste as defined by the U.S. Environmental Protections Agency (40 CFR 261)—hazardous waste is characterized by being ignitable, corrosive, reactive, or toxic. Because sodium is reactive, DOE determined that that sodium-bonded SNF is the only DOE SNF possibly subject to RCRA. DOE is processing the sodium-bonded fuel to convert it to a form that is not reactive.

3.4 U.S. Department of Energy Spent Nuclear Fuel Management Program

Depending on the source of the SNF, different DOE offices are responsible for managing the many steps in the lifecycle of SNF (Figure 1-1). The majority of SNF is managed by DOE's Office of the Environmental Management (DOE-EM). DOE-EM is responsible for storing most DOE SNF; managing SNF storage facilities, which can hold SNF from multiple DOE offices;[92] and packaging all non-naval DOE SNF into disposable canisters. DOE-EM is not responsible for transporting the SNF off site to a repository or storage facility, or for disposing of the SNF at a geologic repository (Section 3.4.1). The Naval Nuclear Propulsion Program manages naval SNF by storing it, packaging it into disposable canisters at INL, and transporting[93] it to and from INL. DOE's Idaho Operations Office, through funding from the DOE Office of Nuclear Energy (DOE-NE), manages specific types of DOE SNF (*e.g.*, sodium-bonded) by storing and processing it. The National Nuclear Security Administration manages the foreign research reactor program by arranging the return of the SNF back to the United States and transporting it, once it has reached a U.S. port, to SRS or INL.

3.4.1 Office of Civilian Radioactive Waste Management

DOE's Office of Civilian Radioactive Waste Management (OCRWM) was integral to DOE's SNF management program from 1982 until 2010, when it closed. The office was responsible for the transport and disposal waste management activities (Figure 1-1) for DOE-EM-managed SNF and HLW, and for disposal of naval SNF. OCRWM developed and maintained specific technical requirements documents (*e.g.*, "Waste Acceptance System Requirements Document," DOE 2008a) that formed the basis for accepting SNF and HLW for disposal in a repository (Gelles 2012a). A memorandum of agreement between DOE-EM and OCRWM (DOE 2007a) provided the "contract" that provided the terms and conditions for accepting DOE-EM waste forms for disposal by OCRWM, including technical and quality assurance requirements (Gelles 2012b). A similar agreement between the Naval Nuclear Propulsion Program and OCRWM (Bowman and Itkin 2000) served as the "contract" that provided the terms and conditions for accepting naval SNF for disposal in a repository. DOE's post-2010 SNF management program, including a discussion of the re-distribution of OCRWM's responsibilities, is presented in Section 3.4.3.

DOE's "current direction for managing" DOE SNF (Gelles 2012a) includes continuing to implement the technical requirements set out in the "Waste Acceptance System Requirements Document" (DOE 2008a). That document covers "all SNF and HLW bound for the repository" and provides waste acceptance criteria specific to the planned Yucca

[92] DOE-EM manages a pool storage facility at INL (Section 5.1.1.4) that stores naval SNF, SNF from DOE's Office of Nuclear Energy, and DOE-EM SNF.

[93] The Naval Nuclear Propulsion Program retains transportation responsibility to the disposal facility for its SNF.

Mountain repository. The primary regulatory basis[94] for defining these technical requirements comes from applicable provisions of 10 CFR Part 63, "Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada," and 10 CFR Part 71, "Packaging and Transportation of Radioactive Material." The requirements document indicates that DOE SNF will be held in disposable canisters and provides the requirements for those canisters. In accordance with these requirements, the three acceptable types of disposable canisters for DOE SNF are (1) canisters specifically designed for naval fuel, (2) the Hanford multi-canister overpack (MCO) storage container, and (3) the DOE standardized canister system (DOE 2008a). Pertinent aspects of the waste acceptance technical requirements that affect the disposal path for DOE SNF include

- the requirement that SNF is acceptable only if it is not subject to regulation as hazardous waste under RCRA;
- the requirement that DOE SNF be packaged in a DOE standardized canister or MCO prior to acceptance for disposal (with minor exceptions);
- a limit on canister thermal output of less than 1,970 watts;
- waste form requirements for pyrophoricity, explosivity, combustibility, chemical reactivity, and organic content such that the waste form does not cause the repository or transportation system to fail to meet applicable NRC performance requirements or any conditions of an operating license or certificate of compliance;
- requirements for canister contents that include those factors considered in the waste form requirements plus requirements with respect to gas generation, thermal effects, particulate concentrations, and internal corrosion of the canister and contained material such that the canister and its contents shall not cause a fire or explosion at the repository's receiving facility during normal handling operations and following a canister drop;
- requirements for limiting the potential for criticality during geologic repository operations; and
- requirements for limiting the potential for criticality after the repository is closed (*i.e.*, in the disposal period).

3.4.2 National Spent Nuclear Fuel Program

In the mid-1990s, DOE established the National Spent Nuclear Fuel Program (national program) at INL[95] to "provide coordination and integration of all non-commercial spent nuclear fuel activities for DOE" (DOE 2011a). In 2005, DOE expanded the focus of the national program to include activities required for disposition of DOE SNF, not including naval SNF, and DOE HLW (DOE 2011a). The national program had a key role in coordinating activities among DOE SNF storage sites and OCRWM. In addition, the national program was qualified to perform DOE SNF–specific analyses used for repository licensing and acceptance (*e.g.*, DOE SNF criticality analyses).

The national program supported efforts to develop a DOE SNF standardized canister system (Section 2.3.2) for shipping DOE SNF to a national repository. The program developed, tested, and analyzed the DOE standardized canister system.

A key national program responsibility was to develop, update, and maintain a database of the amounts, locations, conditions, and detailed descriptive information, including more than 200 distinct attributes, of the many tens of thousands of DOE SNF items (INL 2007). The most recent version of that database[96] (Spent Fuel Database, Version 6.2.3, released on March 24, 2011) served as a source of information for this report.

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[94] NRC's storage regulation (10 CFR 72) is not listed as a primary regulatory requirement in the "Waste Acceptance System Requirements Document" (DOE 2008a).

[95] The 1995 Settlement Agreement (Idaho *et al.* 1995) required that "DOE shall direct the research, development and testing of treatment, shipment and disposal technologies for all DOE spent fuel, and all such DOE activities shall be coordinated and integrated under the direction of the Manager, DOE-Idaho Operations Office."

[96] Sandra Birk, Idaho National Laboratory, e-mail message, with attachments, to Gene Rowe, former NWTRB staff, January 21, 2013. See Appendix 1 for additional details on the DOE SNF inventory derived from the database. From 2011 until 2016, the database was accessible but not maintained or updated.

The national program was managed by INL; however, in fiscal year 2011, DOE moved some of the program's disposition activities to DOE-NE (DOE 2011a). When the Yucca Mountain project was terminated, the national program activities were put on hold, and DOE reduced the program's funding by over 99%.[97]

3.4.3 Post-2010 Spent Nuclear Fuel Management Program

In 2010, OCRWM was closed resulting from the decision that a repository at the Yucca Mountain site was unworkable. In the closure memorandum (DOE 2010b), the Under Secretary of Energy assigned responsibilities to DOE offices to close OCRWM, the Yucca Mountain project, and related activities. The closure memorandum stated that "DOE-NE will be responsible for the activities associated with OCRWM and its mission that are not assigned to other offices" elsewhere in the memorandum. The closure memorandum assigned DOE-NE responsibility for ongoing, long-term disposition research and development for SNF and HLW. Since then, DOE-NE's efforts have focused on commercial SNF and defense HLW. DOE SNF and the small amounts of commercial HLW managed by DOE have received only limited research and development attention.[98] Also, the closure memorandum did not explicitly assign to another DOE entity OCRWM's previous responsibilities for transporting SNF; however, DOE-NE is currently performing system architecture studies and total waste management system integration evaluations on SNF transportation and disposal, albeit only for commercial SNF. DOE-NE is also conducting preparatory activities for transporting commercial SNF to a potential interim storage site.

Because there is currently no disposal site for DOE (or any other) SNF, DOE is focused on storing its SNF inventory at existing sites. This approach avoids directly addressing uncertainties in waste acceptance criteria in the absence of a designated repository site. For example, although DOE had developed plans for a standardized canister for disposal at Yucca Mountain, DOE-EM considers acceptance of this canister at another repository to be indeterminate.[99] Many of the plans DOE developed in preparation for licensing the proposed Yucca Mountain repository are no longer being pursued or are being delayed; for example, there is no current planning for construction and operation of SNF packaging facilities to place DOE SNF into disposable canisters.

3.5 Key Observations on Legal and Regulatory Constraints

1. Legal agreements between DOE and the states that host SNF storage facilities constrain DOE SNF activities to varying degrees. DOE SNF activities are most tightly constrained at INL due to the 1995 Settlement Agreement. For DOE SNF activities at INL, there are requirements to use multi-purpose canisters and to transfer SNF from wet to dry storage. There are also limitations on transfers of SNF to and from INL that are tied to operating a permanent repository or interim storage facility located outside Idaho.

2. DOE decisions made as a result of complying with the National Environmental Policy Act constrain SNF transfers between storage sites, acceptance of foreign research reactor SNF at INL and SRS, and treatment of sodium-bonded SNF at INL and aluminum-based SNF at SRS.

3. DOE, NRC, and U.S. Environmental Protection Agency regulations limit DOE's SNF management and disposal actions. The U.S. Environmental Protection Agency hazardous waste regulation affects disposal of DOE sodium-

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[97] In 2016, DOE increased funding for the program (to about 50% of what the program had before activities were put on hold) to update and modernize the DOE Spent Fuel Database (Birk 2016).

[98] In 2015, DOE began to apply generic disposal systems models to a defense HLW repository (Mariner *et al.* 2015). DOE evaluated disposal of only the HLW glass waste form, using a waste lifetime of approximately 1 million years, and not DOE SNF (Mariner *et al.* 2015). In 2016, DOE-NE began to focus on the inventory and its characteristics and preliminary design concepts for a defense repository. DOE-NE also initiated work on organizational and procedural frameworks, and began developing a safety analysis and preliminary regional site evaluations (Sevougian 2016).

[99] Carlsen (2014a, 2014b) questions this position, suggesting that the DOE standardized canister would work in any repository system.

bonded SNF under current policies and has led to these fuels being treated to remove their hazardous characteristic. NRC's storage, packaging and transportation, and disposal rules vary in prescriptiveness.

- NRC's storage rule requires DOE to address the effects of aging on the structures, systems, and components important to safety at two NRC-licensed dry storage facilities at INL and FSV.
- Challenges to DOE's drying and packaging plans and to its development of a standardized canister driven by NRC regulations include (1) NRC's acceptance criterion for a transport package that limits combustible gases (e.g., hydrogen) to less than 5% of the free gas volume, and (2) NRC's requirement for calculating the potential for nuclear criticality under a hypothetical transportation accident condition that a package is flooded.
- NRC's disposal regulations require that a quality assurance program be applied to systems that are important to safety or waste isolation; however, only limited DOE SNF information has been collected under a quality assurance program.

4. Spent Nuclear Fuel at the Hanford Site

The 586-square-mile Hanford Site (Hanford) is located on the Columbia River in southeastern Washington State (Figure 4-1). Starting in 1944 when the B Reactor was commissioned, and ending in 1987 when the N Reactor ceased operations, a total of nine, defense-related plutonium production reactors were operated—all in the 100 Area—at Hanford. These reactors generated spent nuclear fuel[100] (SNF) as part of the production process. SNF was also generated by the Fast Flux Test Facility operations in the 400 Area. The total quantity of U.S. Department of Energy (DOE) SNF currently stored at Hanford is approximately 2,130 metric tons of heavy

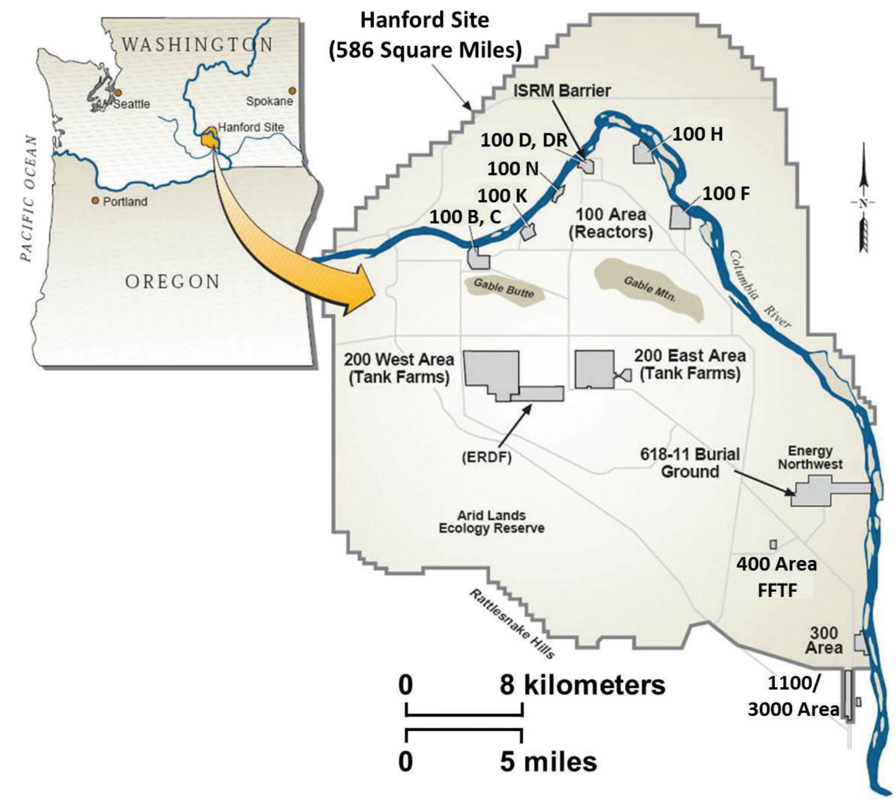

Figure 4-1. Hanford Site map. Geographic location and principal facilities at the Hanford Site. The N Reactor is one of the 100 Area reactors and its location is within the area of the map depicted as 100 N. Both the Canister Storage Building and the 200 Area Interim Storage Area are located along the western edge of the 200 East Area and are too small, at this scale, to show on the map. These two facilities store all Hanford's spent nuclear fuel.

[100] Upon first use in this chapter, underlined terms and phrases are explained in the Glossary (Chapter 11) and abbreviations are introduced.

metal[101](MTHM), of which the vast majority (approximately 2,096 MTHM) is from the N Reactor. Since 2000, all of the SNF at Hanford is now in dry storage; however, N Reactor fuel that was not reprocessed to recover plutonium was stored for more than 20 years in two water-filled storage areas (basins) at the K-East and K-West reactors in the 100 K Area, where it subsequently suffered substantial degradation. SNF from Hanford's N Reactor is more than 30 years old, while the SNF from the "single pass" production reactors[102] (less than 5 MTHM) is more than 40 years old. All of the Hanford SNF is now in dry storage in two facilities in the 200 East Area: at the Canister Storage Building and in the adjacent 200 Area Interim Storage Area.

4.1 Spent Nuclear Fuel Storage Facilities and Stored Spent Nuclear Fuel

As part of Hanford's SNF Project that began in the mid-1990s, DOE decided to develop new dry storage facilities to store its SNF (Garvin 2002a), which was deteriorating in the degrading K Basins. DOE required that the new facilities achieve nuclear safety equivalence with facilities licensed by the U.S. Nuclear Regulatory Commission (NRC). DOE constructed new SNF storage facilities consisting of the Canister Storage Building and the adjacent 200 Area Interim Storage Area, which are located on the western side of the 200 East Area (Figure 4-1 and Figure 4-2). Once the new facilities were completed, the SNF needed to be moved from wet storage in the K Basins to dry storage in the two newly constructed Area 2 facilities.

Table 4-1 provides summary information on SNF storage facilities at Hanford, including whether SNF in its existing storage container will need to be repackaged for eventual transport to a repository or off-site storage facility. All the SNF in the Canister Storage Building is stored in multi-purpose (storage, transportation, and disposal) canisters—prior to transport off site, these multi-purpose canisters will need to be placed into NRC-certified transportation casks. The remaining Hanford SNF, which is stored at the 200 Area Interim Storage Area, still needs to be properly packaged into standardized canisters, which have not been deployed, before it can be transported and disposed of off site.

Table 4-2 summarizes the characteristics of SNF stored at Hanford. The table provides a brief description of the SNF that is categorized using DOE's system for grouping fuels (Appendix 1, Table A1-1). N Reactor SNF accounts for more than 95% of the total SNF[103] being stored at Hanford (by mass). The SNF inventory also includes smaller amounts of SNF from 12 of the 34 different SNF groups defined by DOE (Figure 4-3 and Table A1-1).

Figure 4-3 depicts the estimated number of multi-canister overpacks (MCOs) and DOE standardized canisters needed to package DOE SNF in each fuel group. The Hanford inventory contains approximately 20 different types of fuels, including 18 MTHM of commercial-origin SNF. Although the values given for SNF mass in Table 4-2 are rounded to the nearest metric ton, DOE tracks its SNF inventory (Table A1-1) to one-tenth of a kilogram or 0.0001 MTHM.

[101] Metric ton of heavy metal is a commonly used measure of the mass of "heavy metal" initially present in nuclear fuel. Heavy metal refers to elements with an atomic number greater than 89 (*e.g.*, thorium, uranium, and plutonium). The mass of other constituents of the fuel, such as cladding, alloy materials, and structural materials, are not included.

[102] All plutonium production reactors at Hanford, other than the N Reactor, are called single pass reactors. In the single pass reactors, water was removed from the Columbia River, passed through the reactor for cooling, and left for a brief time (30 minutes to 6 hours) in retention basins to allow for short-term radioactive decay. The water was then returned to the Columbia River. The N Reactor cooling system recirculated and reused water many times before returning it to the Columbia River. The SNF from these reactors is known as Single Pass Reactor SNF.

[103] The amount of SNF changes with time, and the quantities (mass) of SNF presented in Tables 4-2 and A1-1 represent a snapshot of the DOE SNF inventory as of 2011. The values used in this report are from a query of DOE's Spent Fuel Database (described in INL 2007), Version 6.2.3, released on March 24, 2011, provided by Sandra Birk, Idaho National Laboratory, e-mail message, with attachments, to Gene Rowe, former NWTRB staff, January 21, 2013. Inventory information that was provided to the U.S. Nuclear Waste Technical Review Board (Board) from the Spent Fuel Database also included data on the estimated (projected) number and type of multi-purpose canisters that could be used to transport the SNF off site (Table A1-2).

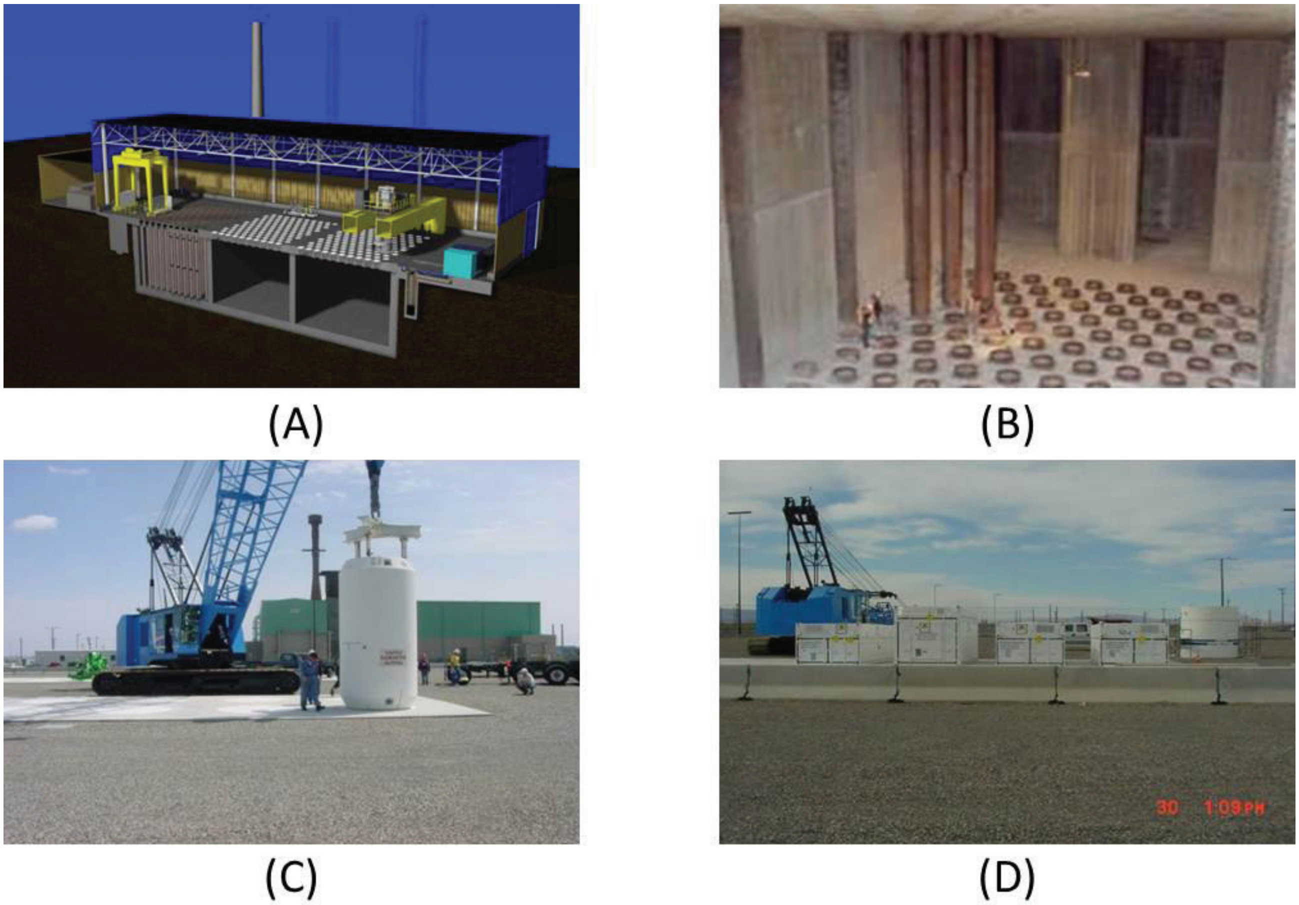

Figure 4-2. Hanford spent nuclear fuel storage facilities.
A. Interior of Canister Storage Building. B. Canister Storage Building vault construction with standard storage tubes extending into the vault. C. Interim Storage Cask being placed on a concrete pad at the 200 Area Interim Storage Area. D. NAC-1 casks inside four International Standards Organization containers (cubes, left) and Rad-Vault (cylinder right) at the 200 Area Interim Storage Area. (Source: McCormack 2014c).

Most of the SNF at Hanford (by mass) falls into one of three groups of DOE SNF (Group 1, Group 2, and Group 7) currently being stored in a single type of dry storage system in the Canister Storage Building. The remainder of Hanford's SNF inventory falls into one of 10 other DOE SNF groups and is being stored at the 200 Area Interim Storage Area (Figure 4-2C and Figure 4-2D) in a variety of storage arrangements (Table 4-1).

4.1.1 Canister Storage Building

The Canister Storage Building at Hanford is a 42,000-square-foot, rectangular, enclosed steel-framed structure (Figure 4-2A) that began operations in 2000. According to the facility's Final Safety Analysis Report (Hartlieb 2002), the design life of its structure, systems, and components is 40 years. "If the service life of the facility is extended beyond 40 years, then an appropriate analysis will be performed" (Alm 1996). The floor of the structure is a reinforced concrete slab that covers an approximately 42-foot-deep, reinforced concrete vault (Figure 4-2B). The top of the structure's floor is level with the land surrounding the building. The floor has 220 circular vertical penetrations large enough to accommodate the standard storage tubes and shield plugs, and six circular vertical penetrations for overpack storage tubes. Each overpack storage tube can accommodate a single abnormal or suspect storage canister and is designed to monitor and confine leaks (Hartlieb 2002).

Table 4-1. Characteristics of Hanford spent nuclear fuel storage facilities

Storage Facility	Type of Storage	Storage Containers and Arrangement	Need to Repackage to Transport	Storage Capacity	Currently in Storage	Design Life of Facility and Package	Year Facility Began Operations
Canister Storage Building (1; see Notes)	Dry vault inside building	220 standard storage tubes; 2 multi-canister overpack (MCO)-sized containers can fit in each standard storage tube	No (2)	440 MCO-sized containers	412	40 years	2000
200 Area Interim Storage Area (3)	Dry – outside					40 years	2002
	Cask storage on 2 concrete pads	Core component containers in 30 cylindrical Interim Storage Casks per pad	Yes	60 casks	45	50 years	
	Facility un-described (4)	Interim Storage Casks (4)	Yes	(4)	4	(4)	
	Cask storage on 1 concrete pad	Canister inside NAC-1 cask inside International Standards Organization container (an intermodal freight container)	Yes	7 containers	6	50 years	
	Cask storage	3 EBR-II (5) casks in concrete vault	Yes	(4)	1 vault	(4)	
	Cask storage on gravel pad	6 TRIGA® casks and 2 DOT-6M containers per Rad-Vault storage container (6)	Yes	3 Rad-Vaults	2 full Rad-Vaults	50 years estimated for Rad-Vault	

Notes
(1) Hartlieb (2002) and DeLeon (2011). Note that storage is reauthorized annually through reviews and updates to the facility's documented safety analysis.
(2) The MCO-sized containers (MCOs and Shippingport Spent Fuel Canisters) were designed for storage, transportation, and disposal. Off-site shipment of these canisters will require NRC certification of a transportation cask for all these payloads. The MCO-sized containers would need to be placed, along with any other required materials (e.g., a supplemental impact limiter), into the certified transportation casks.
(3) Carrell (2002). Note that storage is reauthorized annually through reviews and updates to the facility's documented safety analysis (telephone conversation between Bret Leslie, NWTRB staff, and Roger McCormack, CH2MHill Plateau Remediation company, on May 4, 2013).
(4) The storage arrangement, capacity, and design life of the facility and package is not presented here because the information is not publicly available.
(5) Experimental Breeder Reactor 2 (EBR-II).
(6) Carrell (2002); Training, Research, Isotopes, General Atomics (TRIGA®); and U.S. Department of Transportation Specification 6M (DOT-6M).

Multi-purpose canisters (MCOs and Shippingport Spent Fuel Canisters) are stored in vertical steel tubes, called standard storage tubes, which extend from the base of the vault to the bottom of the reinforced concrete slab (Hartlieb 2002). Each tube can hold a stack of two multi-purpose canisters. The facility has the capacity to house 440 storage multi-purpose canisters, but it currently contains only 412. No additional new storage containers are expected (DeLeon 2011). The heat generated by the SNF in the containers is removed by natural convection.

As part of the SNF Project, SNF stored in Hanford's K Basins was retrieved, cleaned, loaded into cylindrical stainless steel containers, and transported to a drying facility where the material was dried before being transported to the Canister Storage Building (Figure 4-4). Parameters for cleaning and drying the SNF for dry storage limited principal risks to the integrity of the sealed MCOs from overpressurization and potential combustion of oxygen and hydrogen (deflagration or detonation) within the MCO (Garvin 2002a; McCormack 2014b). The loading process included several steps. In the wet-storage basin, an empty MCO was placed inside a shielded transportation container called an MCO cask. The MCO, with a diameter of 25.3 inches and height of 160 inches (Boehnke 2001), could accommodate 270 N Reactor SNF elements. The cleaned SNF fuel elements were loaded into baskets (Figure 4-5A and Figure 2-7A), and the baskets were placed in the MCO until it was filled.

Table 4-2. Characteristics of stored spent nuclear fuel

SNF Source	Description (1; see Notes)	Amount MTHM	Initial Enrichment, Percent U-235	Burnup, MWd/ MTHM (1)	Storage System
Canister Storage Building					
N Reactor SNF – Group 1 (2)	Zirc-clad metallic uranium (3)	~2,100	0.947–1.25	1,500–3,000	388 MCOs
SNF Elements from Other Hanford Production Reactors – Group 2	Aluminum-clad metallic uranium	~5	~1	~1,000	1 MCO
Knockout Pot Sludge (4)	Dried sludge	<1	~1	<3,000	5 MCOs
Shippingport Core 2 Blanket – Group 7 (5)	Zirc-clad uranium oxide	~16	0.717 (natural enrichment)	6,500–24,600	18 Shippingport Spent Fuel Canisters
200 Area Interim Storage Area					
Fast Flux Test Facility Non-Sodium-Bonded SNF Groups 21 and 23 (6)	(6)	~10	(7)	Up to 200,000 Average ~70,000	49 core component containers inside Interim Storage Casks
Commercial BWR/PWR Rods/ Assemblies Group 7 (8)	Zirc-clad uranium oxide	~2	3.0–4.0	30,000–35,000	6 full or partial assemblies within canisters in 6 NAC-1 casks
LAMPRE (9)	Steel-clad metallic Pu alloy with Fe, Co, or Cs	<1	-	-	EBR-II shielded cask in concrete vault
TRIGA® SNF Assemblies (Neutron Radiography Facility and Oregon State University) Groups 27, 28, and 29	Aluminum or stainless steel–clad uranium-zirconium hydride	<1	20% or less	<1%	TRIGA® casks and DOT-6M containers

Notes
(1) Descriptions are from DOE (2009a). Megawatt-day (MWd) per metric ton of heavy metal (MTHM).
(2) Loscoe (2000) and Taylor (2000). The DOE SNF group number is provided. A more detailed description of the fuel in the group is included in Table A1-1.
(3) Zirc cladding includes zirconium cladding and Zircaloy™ cladding.
(4) DOE (2011b). Knockout pot sludge refers to material (ranging in size from 500 microns to 0.25 inches) that was loosened from cleaning N Reactor SNF, as well as SNF elements from other Hanford production reactors that were collected as the fuel was being transferred to the MCOs. Other sludge that is deemed not to be SNF (e.g., wind-blown sand and silt) is still being processed for disposal.
(5) Johnson (2001). The Shippingport Spent Fuel Canisters are similar to MCOs in size but have a separate safety analysis (Garvin 2002a) because of slight design differences. These calculated high-burnup levels are described by Johnson (2001, p. 12).
(6) Bergsman (1994); DeLeon (2011); DOE (1997).
(7) Most fuel was stainless–steel clad and composed of mixed plutonium-uranium oxide with 20%–30% plutonium.
(8) Boiling water reactor (BWR) and pressurized water reactor (PWR).
(9) Los Alamos Molten Plutonium Reactor Experiment (LAMPRE). Plutonium (Pu), iron (Fe), cobalt (Co), and cesium (Cs); Hess (1994).

The MCO cask was then removed from the basin and transported vertically to a drying facility. The drying process requirements for the MCOs were determined from mathematical models of the SNF (*e.g.*, a model for calculating surface area) and of various sources of bound water (*e.g.*, hydroxides of uranium, iron, and aluminum),[104] together with limited testing, to eliminate water within specified limits [*e.g.*, no more than approximately 200 grams (about 7 ounces) of free water remaining (McCormack 2014b)]. At the drying facility, water was drained from the MCO, and the MCO and its contents were cold-vacuum dried (at a pressure of 0.5 torr at 45°C), backfilled with helium, and temporarily sealed. The

[104] Single Pass Reactor fuel has aluminum cladding that severely degraded while the SNF was stored in the K Basins (DOE 1993).

MCO cask was then transported to the Canister Storage Building where the MCO was removed from the cask, prepared for storage (preparations included gas sampling and permanent sealing by welding), and stored (Hartlieb 2002).

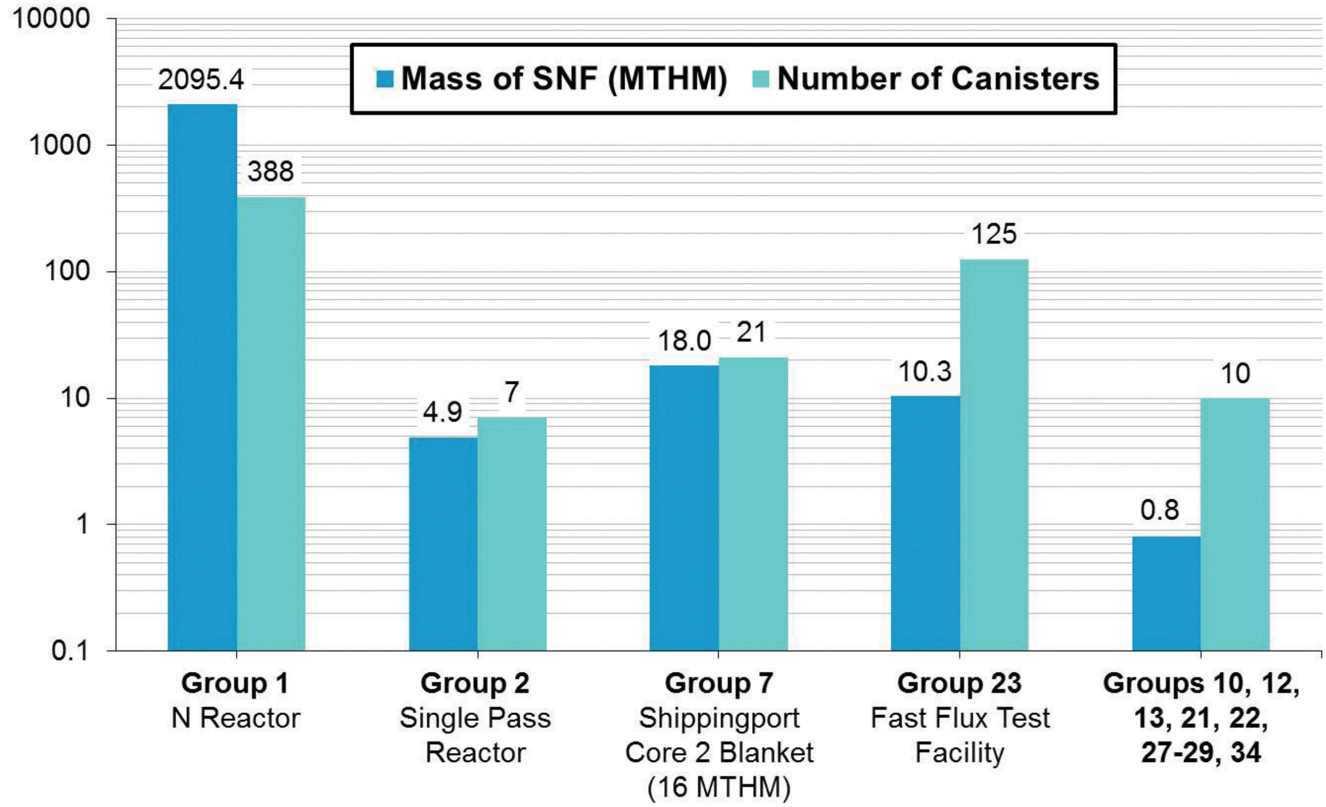

Figure 4-3. Mass of spent nuclear fuel at Hanford by spent nuclear fuel group and estimated number of multi-purpose canisters to be transported to a repository.
Mass of DOE SNF in MTHM and estimated number of multi-purpose canisters by DOE SNF group (Table A1-1and Table A1-2) with dominant SNF source at Hanford in fuel groups 1, 2, 7, and 23 listed beneath the group number. Multi-purpose canisters are MCOs for Groups 1 and 2, and 18 MCOs for 16 MTHM of Shippingport SNF in Group 7, and DOE standardized canisters for the remaining SNF in Group 7 and for SNF in Groups 10,12, 13, 21, 22, 23, 27, 28, 29, and 34. Note that only the Groups 1 and 2 and Shippingport SNF have been packaged in multi-purpose canisters. Because the standardized canisters have yet to be deployed by DOE, the remaining SNF from Groups 7, 10, 12, 13, 21–23, 27–29, and 34 has yet to be packaged.

DOE monitors 15 representative[105] canisters of the 394 MCOs (Table 4-2; Bader 2013; McCormack 2014a) at the Canister Storage Building. Monitoring includes measuring pressure and temperature, and sampling gas to ensure the oxygen and hydrogen contents of the MCOs remain below the lower limit for flammability. To achieve a flammable mixture within an MCO, both the hydrogen and oxygen concentrations would need to exceed 4%. In models of projected hydrogen concentrations during storage, DOE conservatively assumed that hydrogen would not react with SNF and therefore hydrogen would simply build up (Bader 2010). Projections for hydrogen range between 2% and 26% after 40 years of storage.

[105] The contents of the monitored representative MCOs range from "Good fuel, cladding intact, no scrap basket" (MCO numbers H-036 and H-172) to "scrap baskets" from the two K Basins (*e.g.*, MCO numbers H-136 and H-187) to small material (size is from 500 microns to 6.25 millimeters) loosened from cleaning N Reactor SNF and SNF elements from other Hanford production reactors collected as the fuel was being transferred to the MCOs (*e.g.*, MCO numbers H-170 and H-402).

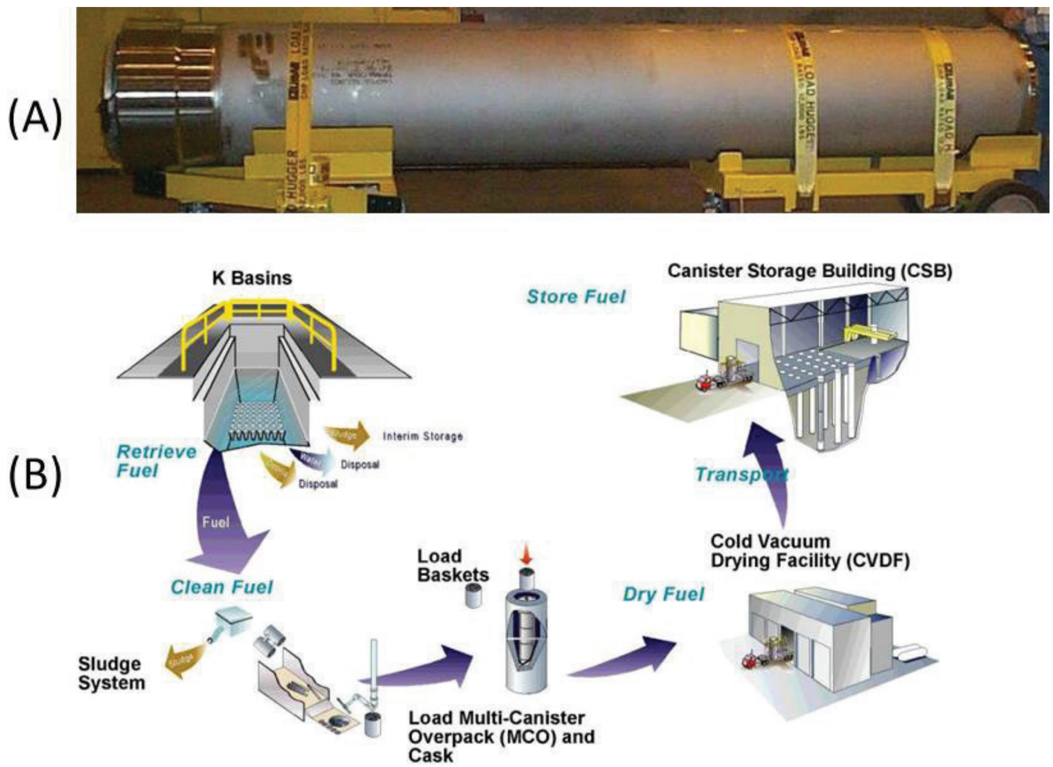

Figure 4-4. Multi-canister overpack and process operations at Hanford. A. Multi-canister overpack. (Source: McCormack 2014a). B. DOE process to retrieve, clean, load, and dry SNF in a multi-canister overpack with subsequent transport and storage of the multi-canister overpack. (Source: McCormack 2014a).

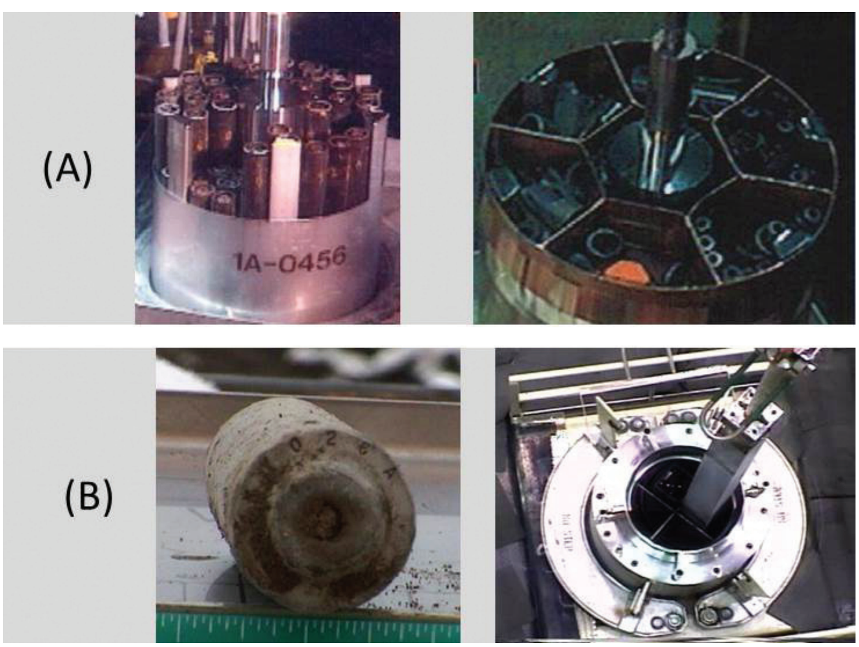

Figure 4-5. Hanford spent nuclear fuel. A. N Reactor SNF elements (left) and SNF scrap pieces (right) in MCO baskets. (Source: McCormack 2010). B. Single Pass Reactor SNF (left) and Shippingport blanket SNF loading (right) into a Shippingport Spent Fuel Canister. (Source: McCormack 2014a).

DOE collected data for most of the 15 MCOs at four months, one year, and two years after arriving at the Canister Storage Building. Results from sampling indicate only slight internal pressure increases and decreases in different MCOs, which are consistent with the different contents and expected processes [*e.g.*, MCOs containing aluminum-clad SNF (*i.e.*, Single Pass Reactor SNF) exhibited slight pressure increases due to radiolysis reactions of the aluminum-hydroxide that forms on the cladding] (McCormack 2014d). Actual samples ranged between <0.001% to almost 3% hydrogen and seem to be decreasing with time, consistent with SNF reaction with hydrogen (Bader 2013). As of September 2013, the highest oxygen concentration was 0.01938 volume percent (194 parts per million), which is more than two orders of magnitude below the limit of 4 volume percent (Bader 2013). The majority of oxygen concentrations sampled from the representative MCOs are under 100 parts per million (Bader 2013). DOE's long-term monitoring plan also includes sampling the MCOs once every 10 years thereafter (Bader 2013; McCormack 2014d).[106]

The 412 multi-purpose canisters currently in the Canister Storage Building include 394 MCOs and 18 containers that hold spent fuel blanket assemblies from the Shippingport reactor. DOE designed these multi-purpose canisters for on-site storage, off-site transportation, and disposal at the Yucca Mountain repository; however, DOE has yet to complete the repository facility design details, probabilistic event sequence categorization analyses, and criticality analyses that are necessary to demonstrate compliance with 10 Code of Federal Regulations (CFR) Part 63 for event sequences involving a low-probability drop and breach of these containers at the repository (DOE 2009a). DOE was developing the necessary information to demonstrate that the MCOs would not breach during a drop at the repository[107] when the project was put on hold (Carlsen 2014c).

The NRC's safety evaluation of DOE's repository license application (NRC 2015a) stated that DOE may not, without prior NRC review and approval, accept DOE SNF in these containers at the Yucca Mountain repository. In addition, NRC (2015a) noted that DOE will need to provide information "that confirms that the current pre-closure safety assessment bounds the intended performance of the waste packages and canisters at the geologic repository operations area." Alternatively, DOE will need to provide information "that demonstrates, through the pre-closure safety assessment, that these waste packages and canisters can be safely received and handled at the repository during the pre-closure period" (NRC 2015a).

The MCOs at the Hanford Site contain SNF (Figure 4-5B) from three sources: the N Reactor, other Hanford production reactors, and sludge from the K Basins (Table 4-2). The N Reactor SNF (Box 2-1) is in the form of cylindrical elements (clad in Zircaloy-2) that are 2.5 inches in diameter and 15 inches to 26 inches long (Figure 4-5A). The heaviest N Reactor element contains approximately 50 pounds of uranium. The average decay heat of N Reactor SNF is less than 400 watts[108] per full MCO. The initial enrichment of the fuel ranged from 0.947% to 1.25% uranium235 (Table 4-2). Unlike commercial SNF, the uranium in N Reactor SNF is in metallic form, which is typical of early reactors used for plutonium production. In assessing the potential for N Reactor SNF to reach criticality in an MCO, Loscoe (2000) assumed the SNF is at its pre-irradiation level of enrichment and demonstrated that it would not be possible to attain criticality even if all the fuel were reduced to rubble and optimally spaced in cold water. Nevertheless, a large, stainless steel center post (Figure 2-7B) was placed in the middle of each MCO basket to physically exclude fuel or scrap from the center region of the baskets, thereby reducing the mass of SNF that could contribute to possible criticality and ensuring compliance with administrative limits for criticality (Loscoe 2000).

All the material from the other Hanford production reactors is contained within one MCO, the SNF elements are aluminum-clad, and the fuel is metallic (DOE 1993). Compared with the N Reactor SNF, this SNF has comparable enrichment (Table 4-2), lower burnup, and a lower decay heat (Lorenz 1997).

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106 Calculations show that all monitored MCOs met the requirement that no more than 200 grams of water be left in an MCO following processing (Bader 2013). Hurt (2013) states that monitoring results indicate the dried MCO casks had an estimated residual water content of 0.04 to 0.72 milliliter (1 milliliter of water weighs 1 gram). Bader (2013) states that, by the first sample (four months after MCO is stored), all free water is in vapor form. "This water vapor is then reacting with the fuel. By the two-year sample, almost all MCOs show no water present" (Bader 2013); however, free water is only about 20% of the calculated mass of water remaining in the MCO (Bader 2010, Table 2-1, nominal case). The other water is associated with several other sources. These sources include, in decreasing importance (approximate percent of total water mass is in parentheses), aluminum hydroxide cladding film (65%), adhering particulate (6%), uranium compounds cladding film (3%), and canister particulate (3%).

107 "The design approach for the MCO is to develop handling designs that, when evaluated with drop sequences, will result in low probability of canister breach such that consequence analyses are not required. When acceptable results from this approach are obtained, the basis for MCO acceptance and disposal will be included in an update of the license application. The MCO is included in this section to provide a description of the analyses that have been completed and to demonstrate the intent of DOE to complete the above analyses and include DOE SNF in MCOs in future licensed operations of the repository" (DOE 2009a).

108 The value cited is based on Taylor's (2000) calculation of the design basis heat per MCO as of May 31, 1998.

Nearly 40 cubic yards of sludge accumulated in the K Basins while N Reactor SNF was stored underwater for an extended period. The sludge is a mixture of fuel corrosion particles, fuel rod and metal fragments, and wind-blown soil and sand. DOE collected the sludge and stored it in sealed containers underwater in the K-West Basin. DOE manages this sludge[109] as remote-handled transuranic waste.

DOE also generated sludge, known as knockout pot sludge,[110] while cleaning the fuel (Figure 4-4B). DOE manages the knockout pot sludge, which is about 1% of the volume of the remote-handled transuranic waste sludge, as SNF (DOE 2013b). DOE recovered the knockout pot sludge, placed it in five MCOs, dried it, and transported it to the Canister Storage Building (DOE 2012a).

The Canister Storage Building also contains 18 Shippingport Spent Fuel Canisters that contain Shippingport Core 2 Blanket SNF (Hartlieb 2002). The characteristics of this pressurized water reactor SNF are summarized in Table 4-2. These welded stainless steel canisters have the same dimensions as an MCO and are stored in the same manner. DOE treats them as MCOs in terms of packages to be sent to a repository. However, these canisters are modified MCOs[111] with their own safety analysis (see addendum A of Hartlieb 2002).

4.1.2 The 200 Area Interim Storage Area

The 200 Area Interim Storage Area is a 200,000-square-foot, at-grade facility located west of the Canister Storage Building. At the facility, DOE stores Fast Flux Test Facility SNF; commercial-origin SNF; Los Alamos Molten Plutonium Reactor Experiment SNF; and Training, Research, Isotopes, General Atomics (TRIGA®) SNF.

The facility consists of a boundary fence with gates, perimeter lighting, three concrete pads, and gravel pads on which a variety of aboveground dry storage cask systems can be placed (Table 4-1 and Figure 4-2C and Figure 4-2D). The fence delineates the area subject to safeguards and security controls and establishes a radiation protection buffer zone. DOE began operations at the 200 Area Interim Storage Area in 2002 and the facility has a design life of 40 years (Carrell 2002). The facility received SNF from various locations on the Hanford Site (*e.g.*, the 400 Area and facilities in the 300 Area—see Figure 4-1). The SNF was in canisters or casks that had been stored for varying lengths of time. A design life of 50 years is specified for dry storage cask systems (Carrell 2002); however, information on when the storage systems were first used is not readily available for all the materials stored at the 200 Area Interim Storage Area. Because of the passive nature of the facility and its components, maintenance and monitoring activities at the 200 Interim Storage Area are minimal (Carrell 2002). Annual surveillance of the storage systems includes visual inspection, radiation surveys, and smear[112] sampling. Long-term maintenance tasks include painting the storage cask systems, maintaining lamps, inspecting and repairing fences and gates, and removing vegetation.

Most of the mass of SNF in the 200 Area Interim Storage Area is from the Fast Flux Test Facility (approximately 10 MTHM). The Fast Flux Test Facility reactor was cooled with liquid sodium. DOE removed any adhering sodium[113] from the SNF cladding before storing the fuel. Approximately 0.25 MTHM of the fuel used in the Fast Flux Test Facility is known as sodium-bonded SNF because it has a small amount of sodium inside the cladding (Box 2-2). The remainder of the Fast Flux Test Facility SNF is non-sodium-bonded. In 2008, Hanford shipped the sodium-bonded SNF to Idaho National Laboratory (INL) for processing (Simpson 2010).

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[109] Ultimately, DOE will treat and package this material for disposal at the Waste Isolation Pilot Plant in New Mexico for permanent burial with other remote-handled transuranic waste from Hanford Site cleanup efforts.

[110] Knockout pot sludge refers to material (size is from 500 microns to 6.25 mm) loosened from cleaning N Reactor SNF and SNF elements from other Hanford production reactors collected as the fuel was being transferred to the MCOs.

[111] The Shippingport Spent Fuel Canister design is the same as the MCO except that the shield plug is modified to accommodate the assembly length and to eliminate unnecessary process ports.

[112] Wipes, also known as smears, swipes, and swabs, are used to estimate the levels of removable contamination by wiping the surface and measuring the radioactivity of the wipe.

[113] Sodium is highly reactive when exposed to air or water.

DOE stores the remaining non-sodium-bonded SNF assemblies from the Fast Flux Test Facility in cylindrical canisters known as core component containers that are fabricated from stainless steel and nickel-alloy material. Each container can hold up to seven assemblies. The containers are filled with inert gas (in this case, argon) and bolted shut. DOE stores core component containers in cylindrical steel-and-concrete-shielded casks known as Interim Storage Casks (Figure 4-2C). These casks are approximately 7 feet in diameter and 15 feet tall, and are filled with helium. Fully loaded, they weigh approximately 57 tons (Carrell 2002). Of the 49 Interim Storage Casks stored in the facility, 45 are on two reinforced concrete pads[114] (DeLeon 2011). Details on the location of the other four Interim Storage Casks are not available. DOE placed the last Interim Storage Casks in the facility in 2009 (DeLeon 2011). No additional Interim Storage Casks will be required for Hanford SNF.

On the facility's third reinforced concrete pad, DOE stores about 2 MTHM of commercial-origin SNF, consisting of six partial or full fuel assemblies. Each fuel assembly is contained in a cylindrical, welded stainless steel canister inside a NAC-1[115] transportation cask. Although NRC certified the NAC-1 only as a transportation cask, the Hanford SNF Project modified the casks for storage. DOE evaluated the safety of these casks prior to their use for storage and on-site transportation (Carrell 2002). Loaded NAC-1 casks, each weighing about 24 tons, are stored in a weather-tight International Standards Organization shipping container (an intermodal freight container; Figure 4-2D). In 2002, the average decay heat for the NAC-1 casks was about 340 watts per cask, significantly less than the design basis heat load (Carrell 2002, Table D2-11). DOE planned to package this SNF into three DOE standardized canisters (Table A1-2) for off-site transport, but the plans are on hold. The concrete pad, where this material is stored, houses six units with room for one more unit. No additional units are needed or anticipated (DeLeon 2011).

At the Interim Storage Area, DOE stores a small amount of SNF from the Los Alamos Molten Plutonium Reactor Experiment in three EBR-II shielded casks. Known as LAMPRE fuel, this SNF consists of plutonium-iron, plutonium-cobalt, or plutonium-cesium metallic alloy fuels. The containers include individual alloys or mixtures of alloys and may contain 97.5% maximum plutonium, with at least 6% plutonium-240. The alloys of cesium and cobalt have plutonium content greater than 38% of the alloy weight (Hess 1994). The EBR-II cask consists of an inner, double-encapsulated steel container that holds the fuel and an outer steel container that encloses lead shielding and the inner container. Both inner and outer containers are welded closed. The diameter of the inner container is 5 inches, and the outer container has a diameter of 30 inches and is about 60 inches tall (Hess 1994). Since 2009, the EBR-II casks have been stored inside a concrete vault on a gravel pad at the 200 Area Interim Storage Area; however, prior to 2009, DOE stored these concrete vaults in the Plutonium Finishing Plant (Hess 1994) in the 200 West Area (Figure 4-1).

DOE also stores a small quantity of TRIGA® SNF (less than 1 MTHM) from the shut-down Hanford Neutron Radiography Facility at the Interim Storage Area. The TRIGA® fuel is zirconium hydride with 8.0%–8.5% uranium (by weight), of which 20% is uranium-235. The SNF is clad with aluminum or Type 304 stainless steel (Carrell 2002). DOE stores the TRIGA® SNF inside cylindrical concrete vaults, known as Rad-Vaults, on a gravel pad (Figure 4-2D and Figure 4-6). The shielded Rad-Vaults are approximately 9 feet in diameter and 9 feet tall; each contains six TRIGA® casks and two DOT6M containers, which contain a nuclear control rod from the Neutron Radiography Facility (Carrell 2002). The vaults provide environmental protection, supplemental shielding, and protection from natural phenomena (*e.g.*, seismic vibrations and windblown objects; Carrell 2002). A TRIGA® cask is a cylindrical, lead-lined, stainless steel vessel that is bolted closed. Two types of TRIGA® casks are in use at the Interim Storage Area. One is approximately 16 inches in diameter and 3 feet tall and can accommodate 16 TRIGA® fuel assemblies. The other is the slightly larger Neutron Radiography Facility TRIGA® cask, which can hold 18 Neutron Radiography Facility TRIGA® assemblies. Each DOT-6M container stores one fuel follower control rod element in an inner DOT-2R container. The design life of a TRIGA® cask seal is 20 years, and the facility's operations include a seal replacement program (Carrell 2002).

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[114] One pad has 30 casks and is at capacity. The other pad has 15 casks and has room for 15 more.

[115] NAC-1 is a cask designation used by NAC International, a company involved in spent fuel management.

Figure 4-6. Loading TRIGA® spent nuclear fuel into a Rad-Vault for storage.
TRIGA® SNF is stored in a TRIGA® cask and the cask is placed inside the white cylindrical Rad-Vault for storage.

4.2 Legal Agreements and Decisions That Affect Spent Nuclear Fuel Management

4.2.1 Legal Agreements

Many DOE activities at the Hanford Site are governed by the Tri-Party Agreement (2013), known formally as the Hanford Federal Facility Agreement and Consent Order. The Tri-Party Agreement was signed on May 15, 1989, by representatives of the U.S. Environmental Protection Agency (Region 10), DOE (Richland Operations Office), and the Washington State Department of Ecology. The Tri-Party Agreement is a legal document that requires DOE to perform certain actions to comply with the Resource Conservation and Recovery Act (RCRA; U.S. Congress 1976); the Comprehensive Environmental Response, Compensation and Liability Act (U.S. Congress 1980); and the state of Washington's Hazardous Waste Management Act (http://www.hanford.gov/?page=81).

The Tri-Party Agreement sets forth numerous milestones and target dates by which DOE must complete those milestones. Only three of the milestones pertain to SNF—all of which related to removing SNF from the K Basins and were completed in 2004.

Milestones may be added, deleted, or amended as necessary by agreement of the parties, and on October 25, 2010, the Tri-Party signatories added a new milestone (M-036-01) to the Tri-Party Agreement requiring that DOE submit to the other parties, on an annual basis, a Hanford Lifecycle Scope, Schedule and Cost Report. For example, the 2013 Lifecycle Report (DOE 2012b) provides scope, schedule, and cost estimate information for meeting all applicable environmental obligations for the period from fiscal years 2013 to 2090. The report includes information on solid waste stabilization and disposition[116] in the 200 Area, including the management path for DOE SNF, which is discussed further in Section 4.3.

4.2.2 Records of Decision

DOE issued a programmatic environmental impact statement (EIS) on SNF management (Section 3.2), an EIS on SNF management in the K Basins (DOE 1996c), and an environmental assessment for Hanford's "non-defense production reactor SNF" (DOE 1997).

DOE's record of decision for the programmatic EIS on SNF management (DOE 1995b) determined that only SNF from production reactors will remain at the Hanford Site whereas the rest of Hanford's SNF inventory was to be shipped to INL. That decision, however, was amended in 1996 (DOE 1996a) to reflect the 1995 Settlement Agreement reached between the state of Idaho, DOE, and the U.S. Navy in 1995 (Idaho *et al.* 1995), which, among other things, precluded

[116] The DOE report uses the term "disposition," although the actions described therein infer future SNF disposal in a geologic repository. The 2013 report (DOE 2012b) is referenced here because the most recent 2016 Lifecycle Report (DOE 2015b) does not include a detailed long-term schedule-and-cost table for Hanford SNF management activities.

most shipments of SNF from Hanford to INL (Section 3.1). Consequently, the inventory of SNF being stored at Hanford (Table 4-2) continues to include more than just N Reactor and other production reactor SNF.

In 1996, DOE issued an EIS on SNF management in the K Basins (DOE 1996c). In the record of decision for that EIS, DOE decided to remove SNF from the K Basins. DOE also decided to vacuum-dry and condition[117] the SNF, seal it in canisters filled with inert gas for dry vault storage for up to 40 years—pending decisions on ultimate disposition (DOE 1996d)—and build a new SNF storage facility at Hanford. Since 1996, DOE has completed supplemental analyses to the EIS to support its determinations on whether further review under the National Environmental Policy Act is needed as DOE continues to manage SNF, which includes knockout pot sludge in MCOs at the Hanford Site (DOE 2011b). DOE met the objectives described in its 1996 record of decision and supplemental analyses and has not needed to supplement its 1996 EIS (DOE 1996c).

In 1997, DOE issued an environmental assessment (DOE 1997) that addressed managing Hanford's "non-defense production reactor SNF" (*e.g.*, Shippingport and Fast Flux Test Facility SNF). The preferred alternative for managing this SNF was to consolidate all Hanford SNF at a single location on the Hanford Site, which DOE accomplished by locating all SNF on the site in the Canister Storage Building and at the adjacent 200 Area Interim Storage Area.

4.3 The Path Forward for Managing and Disposing of Spent Nuclear Fuel

4.3.1 Changes to the Spent Nuclear Fuel Inventory

Future additions to the SNF inventory at the Hanford storage facilities are limited. Three activities may add to the quantities of SNF stored at the 200 Area Interim Storage Area (Figure 4-7; DeLeon 2011). First, any SNF that DOE retrieves as part of the transuranic waste retrieval and certification process (DOE 2013c) would be stored in "67 small dry storage casks" (McCormack 2013; TRU Retrieval Sites in Figure 4-7). Second, DOE discovered fragments of production reactor SNF elements while cleaning up the sites near burial grounds on the Hanford Site. DOE stored these fragments in undescribed storage containers at the 200 Area Interim Storage Area. DOE anticipates that any additional SNF found during 100/300/600 Area Burial Ground remediation will be put into "less than 20 small dry storage casks" (McCormack 2013). Finally, DOE may need to store any additional SNF fragments found in the sludge (Cary 2013) that remains in the K-West basin.

4.3.2 Proposed Actions That Would Affect Spent Nuclear Fuel Management

As part of the Tri-Party Agreement's milestone M-036-01, DOE provided a high-level description (DOE 2012b) of the disposition path for Hanford SNF. DOE's lifecycle reports (DOE 2012b, 2015b) identify facilities that will be needed to prepare the SNF for transport to a repository. DOE will transport SNF that is in the Canister Storage Building in MCOs and Shippingport Spent Fuel Canisters to a planned Hanford shipping facility (Figure 4-7; DeLeon 2011), place the canisters in transportation casks, and transport the casks to a repository (DOE 2012b). DOE planned to repackage SNF at the 200 Area Interim Storage Area into DOE standardized canisters at a planned hot cell facility (McCormack 2010, 2013; Figure 4-7) and subsequently transport the standardized canisters to a planned Hanford shipping facility, place the canisters in transportation casks, and transport the casks to a repository (DOE 2012b).

The current interim storage baseline concludes that supplemental technology is not needed for the first 40 years of storage (McCormack 2010); however, beyond 40 years, DOE needs supplemental technology for extended interim storage and may need technology development for SNF disposal (McCormack 2010). Future technology needs depend on the timing of and requirements for final disposal.

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[117] After drying the SNF under vacuum at approximately 50°C (120°F) and flooding the MCOs with inert gas, conditioning referred to "heating the SNF in a vacuum to about 300°C (570°F) to remove water that is chemically bound to the SNF and canister corrosion products, and to dissociate, to the extent practicable, any reactive uranium hydride present" (DOE 1996d). DOE did not implement the conditioning process; instead, it only cold-vacuum dried the SNF prior to storage (Figure 4-4B).

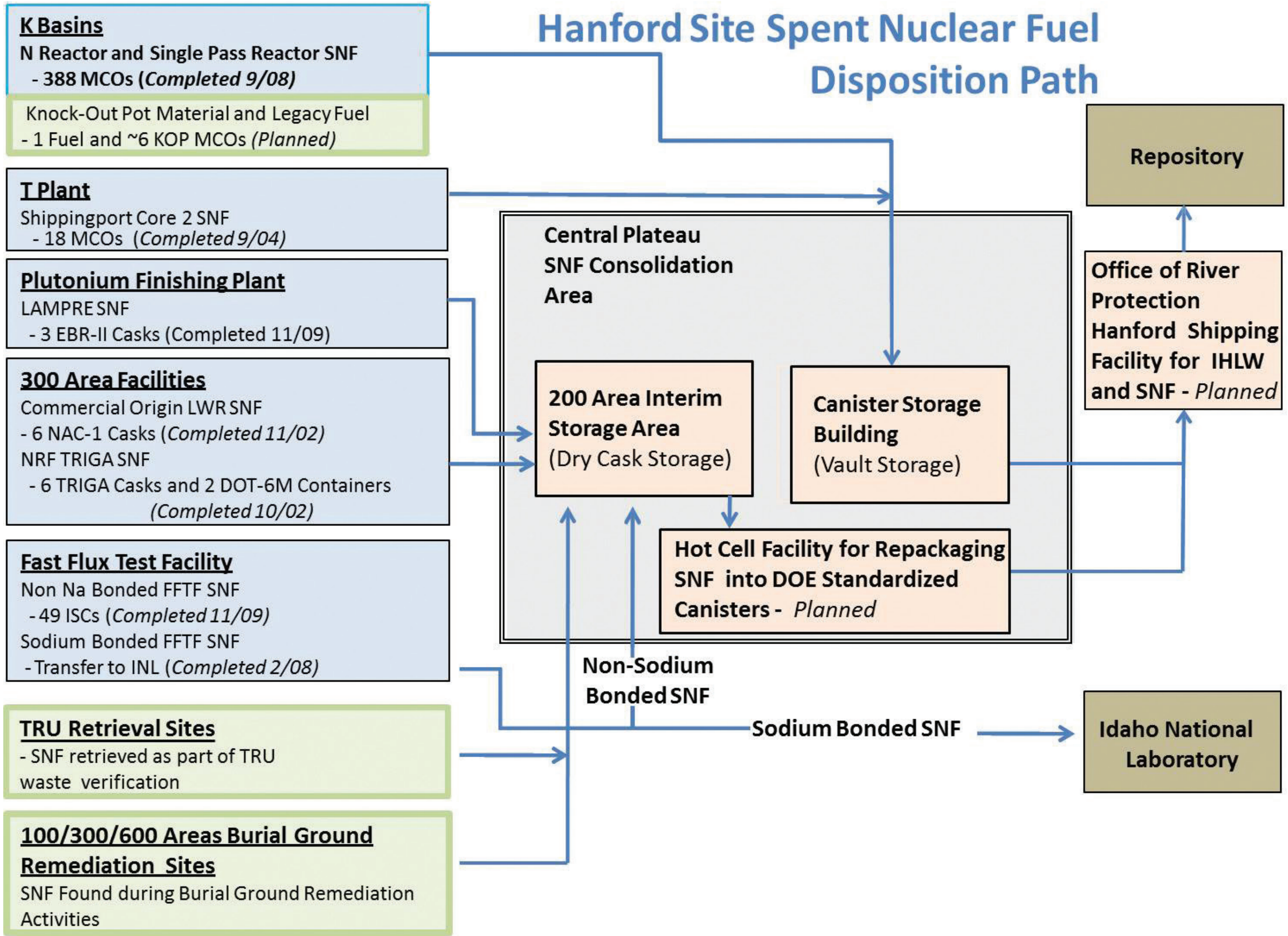

Figure 4-7. The Hanford spent nuclear fuel disposition path.

The light green boxes with heavy borders signify potential sources of additional SNF that would be stored at the 200 Area Interim Storage Area and Canister Storage Building. The blue boxes with black borders identify locations where SNF was previously stored (e.g., K Basins), storage containers used for the SNF stored at the 200 Area Interim Storage Area and Canister Storage Building (e.g., 388 MCOs for N Reactor and Single Pass Reactor SNF), and the dates that DOE completed transfers of the SNF to consolidated storage facilities (e.g., September 2008). The salmon boxes are facilities for SNF storage or for preparing SNF for off-site transport to a repository [e.g., a shipping facility for SNF and immobilized high-level radioactive waste (*i.e.*, HLW solidified by vitrification)]. (Source: DeLeon 2011).

For extended storage, it may be necessary "to better identify and predict the End of Life[118] for credited packaging and facility components" (McCormack 2010). Also, if DOE standardized canisters are used for final disposal, "remote welding technology will be required" (McCormack 2010). The Board previously noted (Ewing 2014a) the importance of retaining records and preserving knowledge from past waste management activities that will be needed decades in the future when packaging and shipping could occur.

4.3.3 Existing Requirements That Would Affect Spent Nuclear Fuel Management

DOE's policy for SNF management facilities at Hanford is to "achieve nuclear safety equivalence for the design and construction of new facilities comparable to facilities licensed by NRC" (Garvin 2002a). DOE designed and constructed the Canister Storage Building and 200 Area Interim Storage Area as part of the Hanford SNF Project in the late 1990s. At that time, NRC regulations specified an initial license period of 20 years for independent spent fuel storage installations. DOE focused on ensuring that safety requirements were applied and evaluated[119] for the proposed 40-year lifetime of both facilities (Carrell 2002). Subsequently, NRC revised its regulation for independent spent fuel storage installations based on safety findings (NRC 2011a). NRC changed the initial license period for such facilities to 40 years or less, with renewal periods not to exceed 40 years. NRC's revised storage regulation includes requirements for extended operations to address safety-related issues associated with aging structures, systems, and components.

DOE's waste acceptance technical requirements (DOE 2008a) affect the disposition path for DOE SNF at Hanford. DOE will need to package SNF in a DOE standardized canister or MCO prior to the material being accepted for disposal at a repository. DOE (2008a) requires that the waste form not cause the repository or transportation system to fail to meet applicable NRC performance requirements or any conditions of an operating license or certificate of compliance. For example, during its certification review of transport casks containing an MCO, NRC will consider formation of a combustible gas mixture inside sealed MCOs as a result of continued reactions of SNF with water to assess whether the concentration of gas is less than NRC's acceptance criterion (Section 3.3.2). DOE (2008a) also requires that a canister and its contents shall not cause a fire or explosion at the repository's receiving facility during normal handling operations and following a canister drop. This requires evaluation of factors considered in the waste form requirements plus requirements with respect to gas generation, thermal effects, particulate concentrations, and internal corrosion of the canister and the contained material.

The waste acceptance document (DOE 2008a) includes requirements for limiting the potential for pre-closure and post-closure criticality. DOE will need to add supplemental neutron absorbers during packaging of some DOE SNF, for example in packages containing TRIGA® SNF, to control the potential for criticality. The post-closure criticality requirement (DOE 2008a) specifies that "the methodology described in the Disposal Criticality Analysis Methodology Topical Report [DOE 2003] shall be used to demonstrate that the total probability of criticality for all DOE SNF canisters shall not cause the total probability of criticality for all waste forms to exceed one chance in 10,000 over the first 10,000 years after permanent closure of the repository."[120] This general methodology is based on 10 CFR Part 63 and the degradation scenarios DOE evaluated were based on features, events, and processes (both engineered and natural) that are specific to the proposed Yucca Mountain repository.

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[118] The current authorization basis was developed for 40 years of storage. Use of the Canister Storage Building and MCOs beyond 40 years will require analysis to determine how much longer the current facility components and packaging can be used. That analysis would need to identify each component relied on for safety and determine its end of lifetime (*i.e.*, how much longer could it be safely used).

[119] DOE does not authorize storage for 40 years; rather, it completes annual reviews and updates of documented safety analyses for operating facilities. The 40-year period reflected in Carrell (2002) relates to the minimum period that was analyzed. Those analyses would need to be modified or new analyses performed to justify additional storage beyond 40 years.

[120] The total probability of criticality for all waste forms includes the contributions to potential criticality from naval SNF, commercial SNF, and DOE SNF. Together, the probability for criticality of these disposed waste forms needs to have less than one chance in 100,000,000 per year of occurring.

4.4 Key Observations on the Management and Disposal of Hanford Spent Nuclear Fuel

1. DOE removed approximately 2,105 MTHM of corroding, low-enriched (less than 1.25% uranium-235), chemically-reactive, metallic uranium SNF from storage in water-filled basins, dried the SNF, packaged it in MCOs, and transferred it to a dry storage facility. DOE determined drying process requirements by modeling the SNF and various sources of bound water (*e.g.*, aluminum hydroxide cladding film that arose from storage of some of the SNF in aluminum canisters) rather than relying on drying experiments. DOE's model projects that, after 40 years of storage, the concentration of hydrogen could be two times below to more than six times above the NRC transport package acceptance criterion concentration limit of 4%. DOE completed packaging MCOs in 2012.

2. DOE monitors temperature, pressure, and gas composition in 15 of the 394 MCOs during storage. Monitoring results are crucial to demonstrate that the concentration of hydrogen is not larger than the NRC acceptance criterion and to support DOE's projections that challenges to MCO integrity from internal reactions are limited during storage. Monitoring results indicate hydrogen concentrations are lower than predicted and seem to be decreasing with time. The results are consistent with hydrogen uptake by reactions with SNF, a process that DOE, conservatively, did not include in its model.

3. DOE designed the MCOs for on-site storage at the Hanford Site, and transportation to and disposal of at Yucca Mountain. The MCOs have a design life of 40 years and serve as the radionuclide confinement barrier during storage, transportation, and pre-closure operations at a repository. Given DOE's current strategy for SNF management and disposal, the MCOs likely will be in service, prior to disposal, for more than a decade beyond their design life. Additional MCO system design is required to provide transportation features such as impact limiters within the transportation cask. NRC approval for MCOs will be required before DOE can use them to transport Hanford SNF off site to an interim storage facility or geologic repository. DOE needs to complete additional analyses to confirm that the MCOs can be safely received and handled at a repository during pre-closure operations.

4. DOE plans to build a new facility to repackage approximately 12 MTHM of higher-enriched SNF that is stored at 200 Area Interim Storage Area before it is transported to a repository. DOE planned to repackage the SNF into approximately 140 DOE standardized canisters that were designed for storage, transportation, and disposal at Yucca Mountain. DOE will need to use supplemental neutron absorber materials in some of the standardized canisters to provide criticality control.

5. Because decades will pass before SNF currently in dry storage at Hanford will be repackaged or transported and disposed of, retaining records and preserving knowledge from past waste management activities will be a key consideration for future waste management and disposal activities.

5. Spent Nuclear Fuel at the Idaho National Laboratory

The Idaho National Laboratory (INL) occupies an 889-square-mile site in the southeastern part of the state of Idaho. INL is approximately 30 miles west of the city of Idaho Falls. More than 50 nuclear reactors were built, operated, and tested at INL, which currently stores spent nuclear fuel[121] (SNF) from a large variety of commercial, research, test, and naval reactors. The SNF inventory at INL—totaling approximately 325 metric tons of heavy metal[122] (MTHM)—is being stored in nine facilities under both wet and dry conditions at the Idaho Nuclear Technology and Engineering Center, the Materials and Fuels Complex, and the Naval Reactors Facility (Figure 5-1). In addition, SNF is temporarily held for cooling purposes in a water-filled canal at the Advanced Test Reactor once the SNF is removed from the reactor.

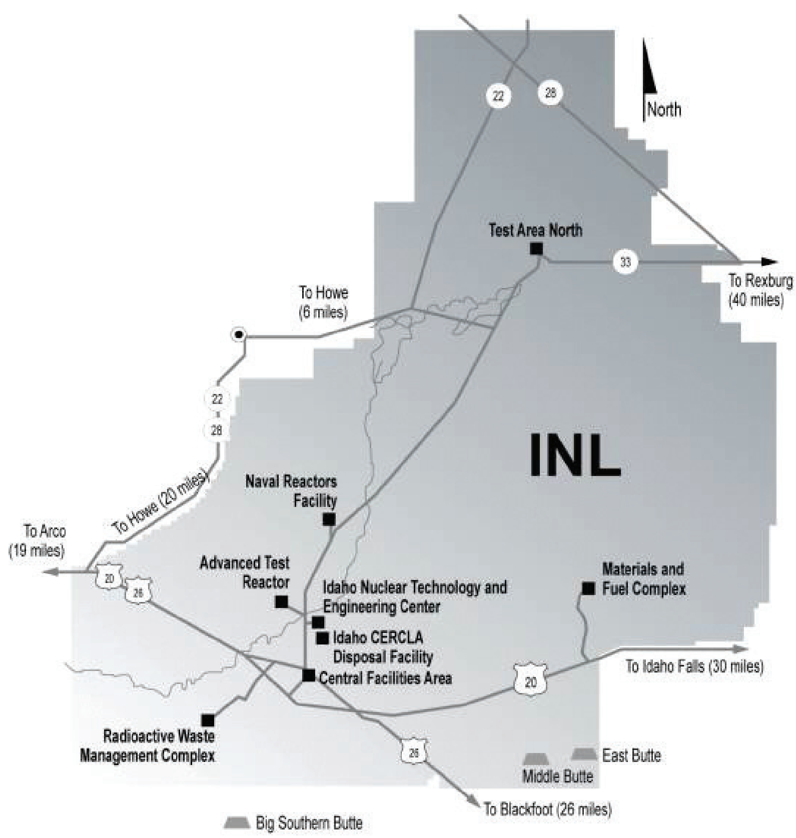

Figure 5-1. Idaho National Laboratory map. Principal facilities at Idaho National Laboratory. (Source: INLCAB 2014).

121 Upon first use in this chapter, underlined terms and phrases are explained in the Glossary (Chapter 11) and abbreviations are introduced.

122 Metric ton of heavy metal is a commonly used measure of the mass of "heavy metal" initially present in nuclear fuel. Heavy metal refers to elements with an atomic number greater than 89 (*e.g.*, thorium, uranium, and plutonium). The mass of other constituents of the fuel, such as cladding, alloy materials, and structural materials, are not included.

5.1 Spent Nuclear Fuel Storage Facilities and Stored Spent Nuclear Fuel

The SNF storage infrastructure includes five facilities at Idaho Nuclear Technology and Engineering Center, two facilities at Materials and Fuels Complex, two facilities at Naval Reactors Facility, and the Advanced Test Reactor where SNF is managed. The five Idaho Nuclear Technology and Engineering Center facilities are identified as CPP-1774, CPP-603 Irradiated Fuel Storage Facility, CPP-749, CPP-666, and CPP-2707, which now includes the West Valley, New York rail casks[123] (Figure 5-2).

The two facilities at the Materials and Fuel Complex are the Hot Fuel Examination Facility and the Radioactive Scrap and Waste Facility. The two naval reactor facilities are the Expended Core Facility and the Overpack Storage Building. DOE manages fuel from the Advanced Test Reactor in its fuel canal[124] (Lacroix 2014a).

The U.S. Nuclear Regulatory Commission (NRC) licensed CPP-1774 (NRC License SNM-2508) and an unbuilt storage facility (Idaho Spent Fuel Facility; NRC License SNM-2512). Except for the NRC-licensed facility, definitive information on SNF storage and management facilities, such as safety analysis reports, is not publicly available. Thus, some of the details provided in this report for other storage facilities [*e.g.*, design lifetimes for facilities at Hanford and Fort St. Vrain (FSV)] are not available for INL. Similarly, detailed information about the characteristics of stored SNF is not available for all storage facilities at INL.

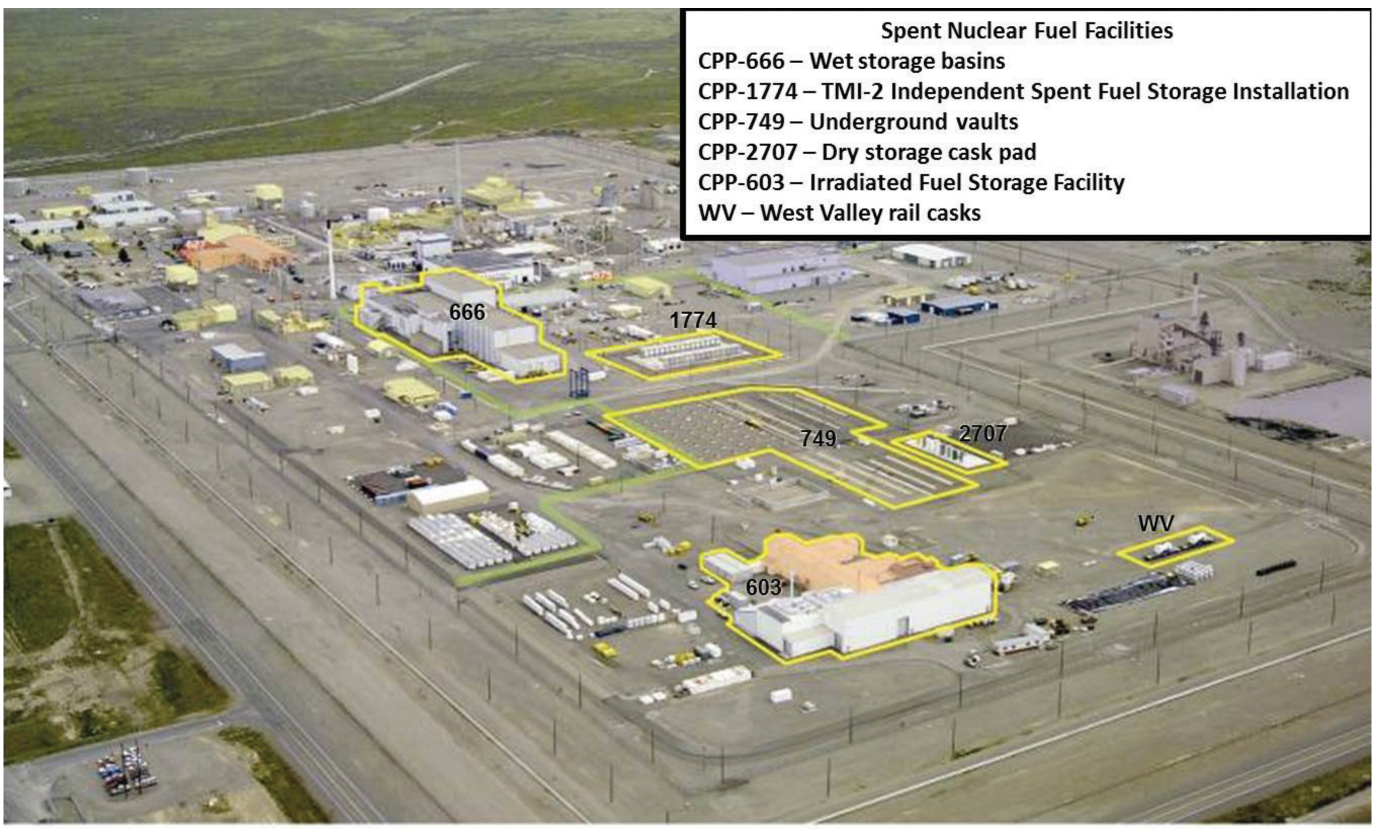

Figure 5-2. Aerial view of storage facilities at the Idaho Nuclear Technology and Engineering Center.
At the time this photo was taken, U.S. Department of Energy (DOE) stored the West Valley rail casks along an abandoned rail spur. DOE moved the West Valley rail casks to CPP-2707 in 2015. (Source: Beller 2013).

[123] DOE moved the West Valley rail casks to CPP-2707 in 2015.

[124] The canal temporarily stores completed experiments and used fuel. It also has facilities to conduct underwater operations such as experiment examination or removal.

Table 5-1 provides summary information about SNF storage facilities at INL, including whether SNF will need to be repackaged for transport to a repository or off-site storage facility. DOE stores more than 75% by mass of the SNF inventory at the Idaho Nuclear Technology and Engineering Center facilities, primarily in dry storage. Table 5-2 summarizes the publicly available characteristics of the stored SNF. The table provides a brief description of the SNF that is consistent with DOE's (2009a) system for grouping fuels (see Appendix 1, Table A1-1). The SNF inventory includes more than 250 types of commercial, research, and defense fuels (Hill and Fillmore 2005). No single fuel form predominates at INL; about one-third of the inventory by mass was fabricated using high-enriched uranium fuel. About half is damaged SNF (either intact or disrupted) of commercial origin. Commercial-origin SNF constitutes 70% of the mass that is stored. Because so many different types of SNF are stored at some facilities, Table 5-2 includes only those fuel types that account for most of the inventory by mass.

Table 5-1. Characteristics of Idaho National Laboratory spent nuclear fuel storage facilities[125]

Storage Facility	Type of Storage	Storage Containers and Arrangement	Need to Repackage to Transport	Storage Capacity	Currently in Storage or in Use	Design Life of Facility or Year of Construction or First Use	Authorized Storage Ends in Calendar Year
CPP-1774 (1; see Notes)	Dry cask system	NUHOMS–12T (vented shielded carbon steel canister in vented modular horizontal concrete storage vault)	Yes	30 canisters	29 canisters	50-year designed service life, licensed for 20 years	2019
CPP-603 (2)	Dry vault in building	Vertical storage tubes inside shielded vault	Yes	636 storage tubes	~580 in use	First use in 1974	2035 (3)
CPP-749 (4)	Dry vaults outside	Carbon steel pipes with shield plugs, installed below-grade as individual vaults; three types built between 1971 and 1985	Yes	218 vaults	128 in use	First use in 1971	2035 (3)
CPP-666 (5)	Pool system inside building	Six stainless steel–lined pools with lidded racks	Yes	2,911 storage positions (5)	~870 in use	Operational in 1984, 40 years	2035 (3)
	Dry cask	Cans in Nu-Pac 125B casks	Yes	–	208 cans in 2 casks		2035 (3)
CPP-2707 (6)	Dry cask outside on pad	Commercial casks (REA 2023, VSC-17, TN-24P, CASTOR® V/21, Nu-Pac 125B, MC-10) on concrete pad	Yes	20 casks	6 casks	Pad constructed in 2003, 40 years	2035 (3)
	Dry cask outside on rail cars (7)	TN-BRP and TN-REG transportation casks on separate rail cars	Yes	2 casks	2 casks	20 years, renewed in 2000	2035 (3)
Radioactive Scrap and Waste Facility (8)	Dry, silos outside below-grade	Inner and outer container within carbon steel liners	No	~1,350 silos	–	Built in 1965	2035 (3)
Hot Fuel Examination Facility (9)	Dry, hot cell inside building	–	No	–	–	Began operations in 1975	2035 (3)

continued on page 78

[125] A dash in the table is used to indicate that the information is not publicly available.

Table 5-1. Characteristics of Idaho National Laboratory spent nuclear fuel storage facilities (continued from page 77)

Storage Facility	Type of Storage	Storage Containers and Arrangement	Need to Repackage to Transport	Storage Capacity	Currently in Storage or in Use	Design Life of Facility or Year of Construction or First Use	Authorized Storage Ends in Calendar Year
Expended Core Facility (10)	Pool system inside building	Four water pools with stainless steel storage racks	Yes	–	–	Constructed in 1957	2035 (3)
Overpack Storage Building and Expansions (11)	Dry cask inside buildings	Multi-purpose stainless steel canisters in concrete overpacks stored vertically in one building with two expansions	No	>200	100	- (building and first expansion); second expansion completed in 2014	2035 (3)

Notes
(1) NRC (1999a); Whitman (2011); and Beller (2014a).
(2) Bohachek *et al.* (2013); Fluor Idaho (2016); and Beller (2014a).
(3) The year 2035 does not reflect the end of authorized storage; rather, it is the deadline established under the 1995 Agreement (Idaho *et al.* 1995) to remove all SNF from Idaho. The deadline to place all SNF in dry storage is 2023. The 2008 Addendum to the Agreement (Idaho *et al.* 2008) allows continued use of the water pool at the Naval Reactors Facility beyond 2023 and continued management of a limited in-process inventory of naval SNF at the Naval Reactors Facility in Idaho beyond 2035.
(4) Lewis and Wilkinson (1998); DOE (2010c); and Beller (2014a).
(5) BRC (2010); Beller (2010); and DOE (2010c). The storage capacity is uncertain as the cited references use three different values, from 2,911 to 4,538 positions. According to Beller (2014a), 30% of the storage positions are filled, 60% of the filled positions contain naval SNF, 10% of the positions contain Advanced Test Reactor SNF, and the remaining 30% of the filled positions contain Experimental Breeder Reactor 2 SNF (Beller 2014a). NRC previously certified Nu-Pac 125B casks for transportation of Three Mile Island Unit 2 (TMI-2) SNF to INL. The certificate of compliance authorizing use of these casks expired and was not renewed. Because DOE (2008a) requires its SNF to be in a DOE st andardized canister or multi-canister overpack (MCO) for transport and disposal, this stored SNF would need to be repackaged.
(6) Hain (2010a) and Birk (2013). Because DOE (2008a) requires its SNF to be in a DOE standardized canister or MCO for transport and disposal, this stored SNF would need to be repackaged.
(7) Hain (2010a) and Williams (2004). NRC previously certified the TN-BRP and TN-REG casks for transportation of SNF from West Valley, New York to INL. The certificates of compliance authorizing use of these casks expired and were not renewed. Because DOE (2008a) requires its SNF to be in a DOE standardized canister or MCO for transport and disposal, this stored SNF would need to be repackaged.
(8) Hill and Fillmore (2005) and Smith *et al.* (2001). The SNF does not need to be repackaged because it will be processed at INL (details are provided in Section 5.3.1).
(9) BRC (2010) and Adams (2013). The SNF does not need to be repackaged because it will be processed at INL (details are provided in the discussion of the Hot Fuel Examination Facility in Section 5.1.2.2).
(10) DOE (1994) and McKenzie (2010a). The floors and walls of the pool were coated with a thermo-setting plastic coating (DOE 1994).
(11) McKenzie (2010a, 2010b) and DOE (2012c). As of August 2014, 100 canisters were in storage. The canisters were designed for storage, transportation, and disposal.

Figure 5-3 depicts the total mass of SNF, which includes fuel from 29 of the 34 groups[126] defined by DOE (2009a). Figure 5-3 also shows the number of multi-purpose canisters (DOE standardized canisters[127] and naval canisters), by fuel group (DOE 2009a), estimated to be needed to transport the SNF off site.

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[126] See also Appendix 1, Table A1-1.

[127] The different sizes and eight internal basket designs of the DOE standardized canisters (Figure 2-10) accommodate the wide dimensional variability of DOE SNF.

Table 5-2. Characteristics of stored spent nuclear fuel[128]

SNF Source	Description (1; see Notes)	Amount MTHM	Initial Enrichment, Percent U-235	Burnup, MWd/ MTHM (1)	Storage System
CPP-1774 TMI-2 Commercial Reactor Core Debris (2) – Group 13	Disrupted Zirc-clad uranium oxide	~81.6	2–3	1,000–6,000	12 stainless steel canisters per carbon steel dry storage canister
CPP-603 FSV (744 fuel handling units) (3) – Group 19	Th/U carbides in graphite matrix	~8.6	93.5	Max 52,000	186 clamped carbon steel canisters containing an ambient air environment
20 fuel types (6,831 fuel handling units) including domestic and foreign research reactor (4)	Various	~3.3	–	–	Unsealed stainless or carbon steel canisters containing an ambient air environment
CPP-749 Shippingport Light Water Breeder Reactor (5) – Group 25	Zirc-clad, oxide fuel (1%–5% U oxide, balance Th oxide)	~42.6	98.23 enriched with U-233, a fissile material	3,600–53,400	39 modules, 7 containers of intact fuel rods, and 1 container of cut fuel rods in 47 vertical vaults
Fermi-1 blanket fuel (6) – Group 31	Sodium-bonded stainless steel–clad U-Mo alloy	~34.2	0.35	–	Within 14 vertical vaults
Peach Bottom Unit 1 Core 1 (7) – Group 20	Th/U carbides in graphite matrix	~1.6	70–93	30,795	21 types of fuel canisters loaded in baskets within ~46 vertical vaults
CPP-666 Advanced Test Reactor fuel post–fiscal year 2005, about 2,000 fuel handling units (8) – Group 16	Aluminum clad	~1.6	93	Various	In pool in a changing number of storage positions
21 fuel types (3,186 fuel handling units) transferred from CPP-666 pool, including all Advanced Test Reactor fuels prior to fiscal year 2006 (4)	Various	~6.7	–	–	Dry interim storage of 208 cans inside 2 Nu-Pac 125B transportation casks (9)
Naval Reactors (10) – Group 32	–	~14	93–97	–	–
CPP-2707 (11) Commercial light water reactor	Zirc- or stainless steel–clad uranium oxide	~38.4	2–3	20,000–40,000	VSC-17, TN-24P, CASTOR® V/21, MC-10 dry storage casks
14 types including Loss-Of-Fluid-Test experiments and epoxied fuel (12)	Various	~3.7	–	–	REA 2023 and Nu-Pac 125B dry storage casks
Big Rock Point and Robert E. Ginna commercial reactors, transported from the West Valley, New York, reprocessing facility (13) – Group 7	Zirc-clad uranium oxide	~26.3	2–3	20,000–40,000	2 rail casks (TN-BRP and TN REG)

continued on page 80

[128] A dash in the table is used to indicate that the information is not publicly available.

Table 5-2. Characteristics of stored spent nuclear fuel (continued from page 79)

SNF Source	Description (1; see Notes)	Amount MTHM	Initial Enrichment, Percent U-235	Burnup, MWd/ MTHM (1)	Storage System
Radioactive Scrap and Waste Facility (14) EBR-II driver assemblies – Group 31	Stainless steel–clad sodium-bonded uranium-Zr alloy	~2.3	67–78	1,000–200,000	–
EBR-II blanket assemblies – Group 31	Depleted uranium metal with 1% plutonium	~19.2	0.3	–	Inner and outer container within carbon steel liners
Hot Fuel Examination Facility Hanford Fast Flux Test Facility driver assemblies (15) – Group 31	Sodium-bonded uranium-plutonium alloy	~0.01	0.2 and 0.7	–	In shielded hot cell
Naval Reactors Facility (10) Naval Reactors – Group 32	–	~14	93–97	–	Stainless steel multi-purpose (storage, transportation, and disposal) canisters in concrete overpacks

Notes
(1) Descriptions are from DOE (2009a) and use the same terminology. Megawatt-day (MWd) per metric ton of heavy metal (MTHM).
(2) Three Mile Island Unit 2 (TMI-2); Beller (2010) and Taylor (2003). The description of the storage system is from Taylor (2003). The DOE SNF group number is provided. A more detailed description of the fuel in the group is in Table A1-1.
(3) Thorium (Th) and uranium (U); Lotts *et al.* (1992); Beller (2010); DOE (2005); and NRC (1991). DOE (2005) uses the term "fuel handling unit" in describing its inventory.
(4) Beller (2010); New South Associates (2012); and DOE (2005). Because there are numerous types of fuel and no particular fuel types dominate, no information is provided other than amount and storage system used.
(5) Uranium (U) and thorium (Th); DOE (2005); Taylor and Loo (1999); Lewis and Wilkinson (1998); and Olson *et al.* (2002). This fuel used U-233, not U-235, as the fissile isotope of uranium.
(6) Uranium (U) and molybdenum (Mo); DOE (2005); Lewis and Wilkinson (1998); and Toews *et al.* (2002).
(7) Thorium (Th) and uranium (U); DOE (2005); Kingrey (2003); and Lewis and Wilkinson (1998).
(8) Hain (2010a) and Hill and Fillmore (2005). Although naval reactor fuel and Experimental Breeder Reactor 2 (EBR-II) fuel are stored in CPP-666 pools, both types of fuel are being transported to the Overpack Storage Building and the Materials and Fuels Complex facilities, respectively, and those fuels are described in those location entries later in the table. The amount includes 45 casks of Advanced Test Reactor SNF that was to be shipped from the reactor to CPP-666 prior to September 30, 2015, which is managed by the U.S. Department of Energy Office of Nuclear Energy (Cooper 2013).
(9) DOE planned to move the Nu-Pac 125B casks to CPP-2707 by 2012 (Hain 2010b), but that has not yet happened.
(10) Total amount at INL is approximately 28 MTHM and is a rough estimate based on Carter *et al.* (2012). Donald (2012) noted that about a third of naval SNF was stored dry. As of August 2014, half is now in dry storage at the Overpack Storage Building and Expansions and the rest is stored in the CPP-666 water pool and the Expended Core Facility pool at the Naval Reactors Facility.
(11) Bare and Torgerson (2001); Beller (2010); Bohachek *et al.* (2013); DOE (2005); and Hain (2010a).
(12) Because there are numerous types of fuel, and no particular fuel types dominate, no information is provided other than amount and storage system used.
(13) DOE (2005); Hunter (2004); and Williams (2004).
(14) Experimental Breeder Reactor 2 (EBR-II). Zirconium (Zr); Hain (2010a); and Simpson (2010). The total of approximately 2.3 MTHM of driver fuel listed here is for all INL facilities as the exact amount at each facility is not known. About 2 MTHM of EBR-II driver SNF was in about 3,600 containers in the CPP-666 pool in 2002 (Pahl 2002). The SNF in CPP-666 is in the process of being transported in 227 shipments (Gonzales-Stoller Surveillance LLC 2012) to the Materials and Fuels Complex; however, where the fuel will be stored at Materials and Fuels Complex is not known. The storage systems used for EBR-II fuel at INL have not been described in public documents. However, the EBR-II storage and transportation cask used at Hanford is described by Hess (1994).
(15) Bergsman (1994) and Simpson (2010). DOE processed all but 13.6 kilograms of an inventory of 0.25 MTHM. The remainder is held for research purposes.

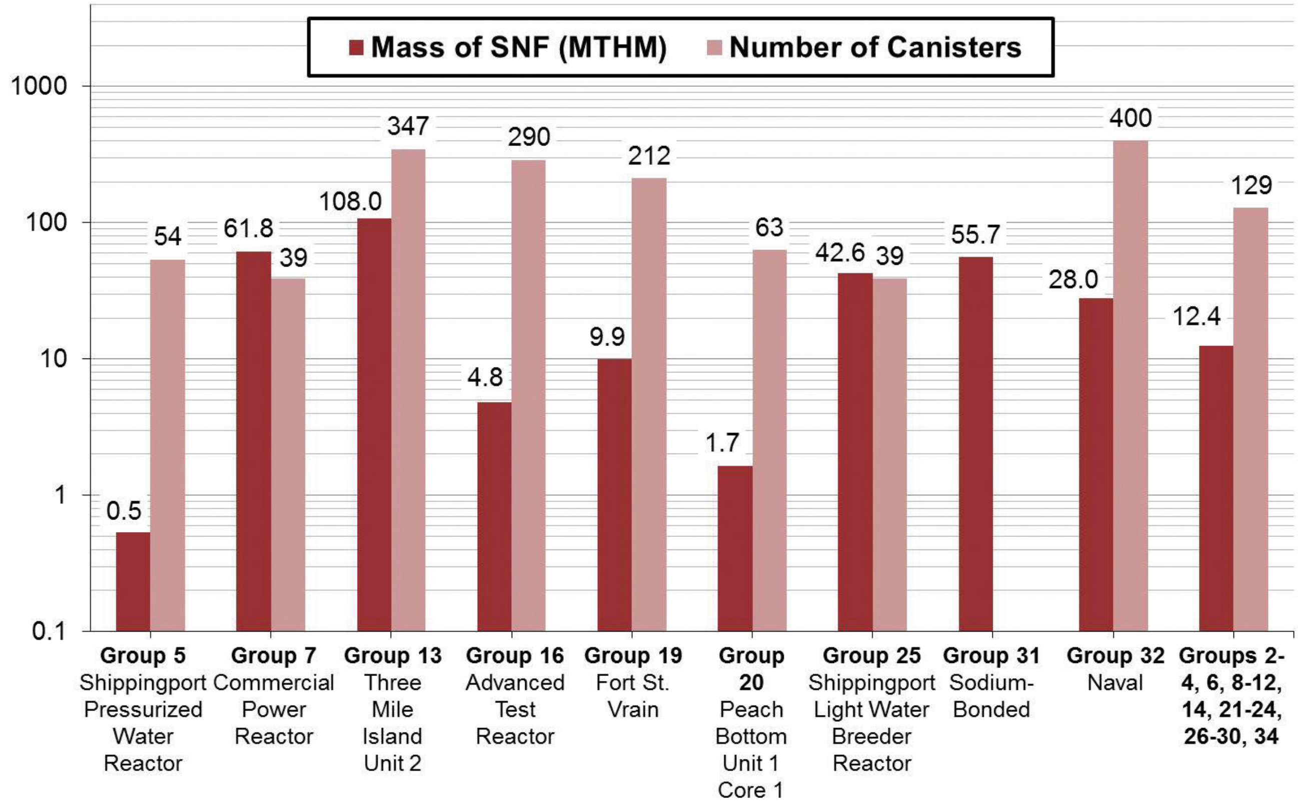

Figure 5-3. Mass of spent nuclear fuel at Idaho National Laboratory by spent nuclear fuel group and estimated number of multi-purpose canisters to be transported to a repository.
Mass of DOE SNF in MTHM and estimated number of DOE standardized canisters by DOE SNF group. Naval SNF (Group 32) would be transported in naval canisters and not in DOE standardized canisters. DOE is treating SNF in Group 31; it will not be disposed of as SNF. Dominant SNF source or fuel type in Groups 5, 7, 13, 16, 19, 20, 25, 31 and 32 is listed.

The diversity of SNF characteristics leads to diversity in the number of multi-purpose canisters[129] planned for packaging. DOE projected that INL SNF bound for a repository could be packaged in as many as 1,173 DOE standardized canisters, 400 naval canisters (containing 65 MTHM of naval SNF), and an unspecified number of NRC-certified bare fuel transportation casks. DOE has packaged only about 14 MTHM of the approximately 325 MTHM of INL SNF in containers of a type that can be used for off-site transport. All of this packaged SNF is of naval origin; it is contained in 100 naval canisters.

[129] A large mass of SNF in a DOE fuel group does not necessarily require a large number of DOE standardized canisters. DOE SNF Group 13 includes debris from a commercial reactor core. This group accounts for the largest mass of stored SNF. Group 13 SNF would also require the largest number of DOE standardized canisters. About 20% of the mass of DOE SNF in Group 13 consists of 116 fuel assemblies that could be transported off site in NRC-certified bare fuel transportation casks. Each of the next three largest DOE SNF groups, in terms of mass of SNF, does not correspond, for different reasons, to comparable numbers of DOE standardized canisters. DOE projected that only 39 DOE standardized canisters would be required to package approximately 62 MTHM of commercial power reactor SNF in Group 7. The undamaged nature of some of the SNF in this group would allow DOE to ship approximately 17 MTHM in NRC-certified bare fuel transportation casks. The approximately 56 MTHM of sodium-bonded SNF in Group 31 will be processed into two solid forms of high-level radioactive waste and will not be transported as SNF. Thus, no DOE standardized canisters are needed for Group 31 SNF. DOE projects that only 39 standardized canisters will be needed to package the approximately 43 MTHM of Shippingport SNF in Group 25. See also Table A1-2. DOE would package a small mass of SNF from some DOE fuel groups in a large number of DOE standardized canisters. For example, the large-diameter FSV fuel (Figure 2-3) consists of fuel particles containing high-enriched uranium in a low-density graphite matrix. Packaging approximately 8.6 MTHM of this SNF would require over 200 DOE standardized canisters. Similarly, Advanced Test Reactor SNF, which totals approximately 5 MTHM, consists of fuel particles containing high-enriched uranium in an aluminum matrix. The size and shape of individual fuel elements (Figure 2-3) and the large number of fuel elements (on the order of 4,000) would require 290 DOE standardized canisters.

5.1.1 Idaho Nuclear Technology and Engineering Center

5.1.1.1 CPP-1774

CPP-1774 is a rectangular facility that covers about 65,000 square feet. The facility consists of a boundary fence with gate, perimeter lighting, and a concrete pad that serves as a base mat for aboveground horizontal dry storage cask modules[130] (Figure 5-4A). The facility stores radioactive material from the Three Mile Island Unit 2 (TMI-2) reactor core, which was damaged in the reactor accident of March 28, 1979. NRC issued a 20-year license for this facility, also known as the TMI-2 independent spent fuel storage installation (NRC 1999a), on March 19, 1999, and DOE is the licensee.

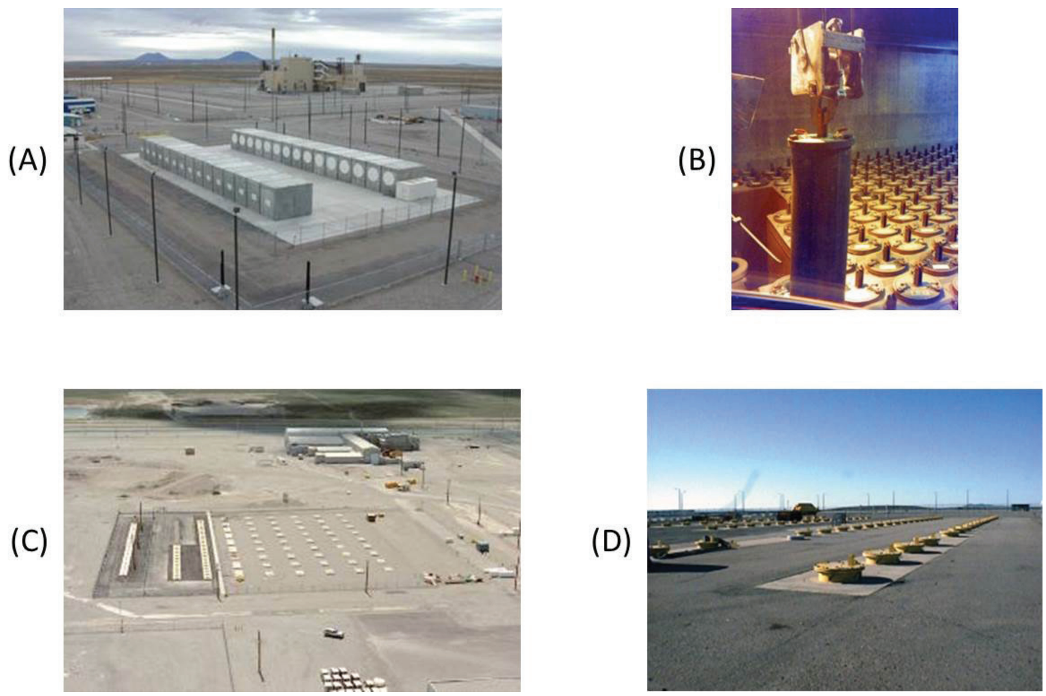

Figure 5-4. CPP-1774, CPP-603, and CPP-749 storage facilities.
A. Aerial view of CPP-1774, the TMI-2 independent spent fuel storage installation. (Source: Beller 2013). B. Remote handling of a storage cask in the CPP-603 vault. (Source: Davis 2009). C. Aerial view of first-generation CPP-749 underground vaults. (Source: Beller 2013). D. Second-generation underground vaults at CPP-749. (Source: Davis 2009).

The dry cask storage system authorized for use at this facility is the NUHOMS®-12T. The concrete horizontal storage system has a "designed service life of 50 years" (Whitman 2011). There are 30 NUHOMS®-12T modules at CPP-1774. Together, 29 of the modules currently store approximately 81.6 MTHM of SNF (Taylor 2003). This stored material includes "the remains of 177 Babcock and Wilcox 15x15 fuel assemblies, 61 control rod assemblies, and miscellaneous irradiated core and core basket material" (NRC 1999a). The material is contained within the storage modules in 344 stainless steel, bolted, cylindrical canisters that include "265 fuel canisters, 12 knockout canisters, and 67 filter canisters that are used to confine the TMI-2 core debris in the absence of intact fuel assembly cladding" (NRC 1999a). Beller (2014b) describes the three canister types and the fuel drying activities used to prepare the TMI-2 core debris for dry storage. The average thermal output of the canisters is 29 watts (Beller 2014b).

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130 Although the storage system is often referred to as a horizontal storage module, NRC certifies the system as an SNF storage cask under its Title 10, Code of Federal Regulations (CFR), Part 72 regulation (10 CFR 72).

Both the knockout and filter canisters are vented[131] to prevent any generated hydrogen from pressurizing the canisters (Taylor 2003). The horizontal storage modules are also vented to prevent any hydrogen accumulation. Maintenance and surveillance requirements for the facility, including air sampling for hydrogen in the horizontal modules, are set out in the license (Hain 2010b; Beller 2014b). Degradation of the concrete in the base mat and the horizontal storage modules (Whitman 2011) prompted DOE to complete repairs to the concrete in 2011 (Cooper 2011). DOE completed the repairs as part of a program to manage age-related degradation of the facility (Beller 2014c). DOE planned to package the SNF into 347 DOE standardized canisters for off-site transport.

5.1.1.2 CPP-603

The CPP-603 building complex occupies approximately 40,800 square feet (DOE 2012c). It was constructed in 1952 for the "interim storage of SNF" (Bohachek *et al.* 2013) prior to reprocessing. The facility originally consisted of two unlined concrete underwater basins with a hanger system for holding the SNF. A third unlined concrete basin with conventional rack storage was added in 1958 (BRC 2010). All SNF was removed from these basins in 2000 (BRC 2010). By 2008, the sludge debris in the basins had also been removed, and the basins were filled with grout and decommissioned.

The CPP-603 Irradiated Fuel Storage Facility[132] was built in 1974 as an addition to the CPP-603 basin storage facility. DOE built the dry storage facility to store irradiated graphite fuel from the FSV high-temperature gas-cooled reactor. The facility includes a cask receiving area, fuel handling cave, fuel storage area, truck bay areas, crane maintenance area, and other support areas (Bohachek *et al.* 2013; Beller 2014c). The facility depends on forced ventilation to ensure decay heat removal. The fuel storage area and the fuel handling cave are served by the same ventilation system, which is equipped with high-efficiency exhaust filters. The authorization basis for this facility assumes operation through 2035 (Hain 2010a). However, Hain (2010a) noted that its "mechanical systems need to be upgraded to maintain minimum safe storage and to support retrieval of SNF." These upgrades have not yet been completed, although the aging facility has had some repairs. For example, the storage array relies on moderator (*e.g.*, water) exclusion to meet criticality control requirements. This system was compromised by a roof leak in the winter of 2010 (Hain 2010a). DOE subsequently completed repairs to address the leak and now conducts annual preventive maintenance checks on the roof (Beller 2014c).

The CPP-603 SNF storage facility includes a fuel conditioning station that uses the crane maintenance area, fuel handling cave, and part of a truck bay area (Beller 2014b). Prior to placing SNF in the fuel storage area, DOE uses a heated vacuum system to passivate potentially reactive fuels by drying them in their storage container at 175°C (Beller 2014b). DOE has used this method to dry Training, Research, Isotopes, General Atomics (TRIGA®) fuel, uranium alloy fuels, Advanced Test Reactor fuel, and other aluminum test reactor fuels (Beller 2014b) stored at this facility (DOE 2005).

The fuel storage area (Figure 5-4B) is a shielded cell containing 636 vertical tube storage positions (DOE 2010c) that was about 90% full as of 2013. SNF is handled remotely and stored in 18-inch-diameter cylindrical stainless steel canisters. The facility can handle Advanced Test Reactor, FSV, and Peach Bottom cask types (Bohachek *et al.* 2013). Generally, the facility receives intact SNF. Compromised SNF received at the facility "must be canned and these cans are not welded" (Hain 2010a).

DOE designed the facility primarily to store all the SNF from the FSV reactor in Colorado. DOE had only shipped about one-third of the FSV SNF to the facility when further shipments were stopped as the result of a lawsuit. The 1995 Settlement Agreement fully resolved the issues in the lawsuit (Idaho *et al.* 1995). Because much of the FSV SNF remains in storage in Colorado, the CPP-603 storage facility is now used to store fuels from domestic and foreign research reactors

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[131] A vent assembly with High-Efficiency Particulate Air (HEPA) filters is installed on these canisters, with access through a small vented door in the rear of the horizontal storage module (NRC 1999b). DOE developed the design features, operations, surveillance, and maintenance plans to ensure the system can be tested and monitored for gas accumulation in the canisters. "Although no release of radioactive gases or particulate is anticipated," DOE monitors air and gases vented through the HEPA filters as part of its surveillance and maintenance plans (NRC 1999b).

[132] Hereafter the Irradiated Fuel Storage Facility portion of CPP-603 is referred to as CPP-603 SNF storage facility.

and to consolidate and store (dry) other INL fuels. The facility stores more than 20 types of fuel totaling approximately 11.9 MTHM (DOE 2005).

INL evaluated the CPP-603 storage facility for possible use in its high-burnup commercial SNF cask demonstration program (Bohachek *et al*. 2013). Bohachek *et al*. (2013) concluded that "facility operations can be readily modified to handle a heavier, commercial fuel cask (such as the TN-32 or TN-40HT) with the use of a portable gantry crane operated by an experienced heavy-haul subcontractor."

5.1.1.3 CPP-749

The CPP-749 storage facility occupies a 260,050-square-foot fenced area (Figure 5-4C). DOE stores approximately 78.4 MTHM of SNF at CPP-749, which includes SNF from Peach Bottom Unit 1 Core 1, SNF from the Shippingport Light Water Breeder Reactor, and Fermi-1 blanket SNF (DOE 2005). The facility consists of 218 underground vaults that were constructed between 1971 and 1985, in two generations of designs, to store SNF and un-irradiated fuel[133] (Birk 2013; Lewis and Wilkinson 1998). Three types of vaults were constructed, each consisting of carbon steel pipes with shield plugs and grouted bottoms (Hain 2010a) that were emplaced in wells with mild steel casings (Lewis and Wilkinson 1998).

The first generation of storage vaults consists of 61 steel-lined, below-grade, individual vaults that were built to store Peach Bottom Unit 1 SNF (Figure 2-3) (Hill and Fillmore 2005; Beller 2014c). DOE first loaded the vaults with SNF in September 1971, but "accelerated corrosion of stored fuels occurred as a result of moisture intrusion" (DOE 2010c; Beller 2014c). DOE subsequently moved some stored SNF[134] from the first-generation vaults to second-generation vaults (Kingrey 2003; Beller 2014c). Some of the first-generation vaults remain unusable because they are located in an area where water from past fire-suppression system leaks had collected in a perched water zone[135] (Hain 2010a; Birk 2013). Kingrey (2003) provides a description of Peach Bottom Unit 1 Core 1 SNF, including information about how this SNF was packaged and stored. He concludes that the SNF was placed in 21 types of fuel packages and was likely stored in carbon steel–lined (not stainless steel–lined), double O-ring sealed aluminum canisters.

Two types of second-generation vaults were built in 1984 and 1985: one to store un-irradiated Shippingport Light Water Breeder Reactor fuel and another to store Shippingport SNF (Figure 2-3). All 157 of these vaults are in 30-inch-diameter carbon steel–lined wells. The top of the well is embedded in a concrete slab (Figure 5-4D) that extends above grade to prevent surface water from entering the vault (Beller 2014c). The vault design includes a stainless steel tube into the top of the vault for taking gas samples to test whether the atmosphere within the vault remains free of oxygen. Another tube extends to the lowest point in the vault to remove water from the vault sump, should that become necessary (Lewis and Wilkinson 1998). These tubes can also be used to pressurize the vault to test for leaks, purge the vault with a dry gas, and take liquid samples. The storage vaults are under cathodic protection to minimize corrosion damage to metallic components exposed to the soil. The vault liner is bonded to both the cathodic protection system and the well casing. Olson *et al.* (2002) provides additional details on Shippingport Light Water Breeder Reactor SNF and its storage.

Limited information is available on the Fermi-1 blanket SNF (Toews *et al*. 2002). No information is publicly available on how it is being stored.

The CPP-749 vaults are subject to routine surveillance, gas (hydrogen) monitoring, and corrosion monitoring (Hain 2010a; Beller 2014c). The authorization basis for CPP-749 assumes this facility will operate through 2035 (Hain 2010a).

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[133] The high-enriched un-irradiated uranium-233 stored consists of fabricated fuel materials, scrap, and waste that were generated during the development of the Shippingport Light Water Breeder Reactor program during the 1970s (Lewis and Wilkinson 1998).

[134] The timing of when the accelerated corrosion occurred is uncertain, but Kingrey (2003) indicates that during monitoring in 1987, the presence of krypton and hydrogen in several of the gas samples led to further investigation of stored materials. These studies indicated that corrosion of the storage canisters had occurred. Between 1997 and 2000, DOE transferred the contents of six vaults containing Peach Bottom SNF to second-generation vaults (Beller 2014c).

[135] A perched water zone is a zone of unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone.

5.1.1.4 CPP-666

The CPP-666 building occupies an area of 131,942 square feet. It includes a hot cell and a 79,000-square-foot SNF storage facility (Hain 2010a). DOE uses the hot cell as a remote-handling transuranic waste packaging facility (Birk 2013). The CPP-666 SNF storage facility became operational in 1984 and shares safety-significant systems (such as the ventilation system) with the adjacent hot cell (Birk 2013). CPP-666 includes a truck receiving area, a cask receiving and decontamination area, and two unloading pools interconnected with six storage basins via gates and a transfer canal (Figure 5-5A), as well as areas for supporting functions (Beller 2014c). The unloading pools (Figure 5-5B) provide "the capability for cask unloading and transfer of commercial-length fuels" (DOE 2010c).

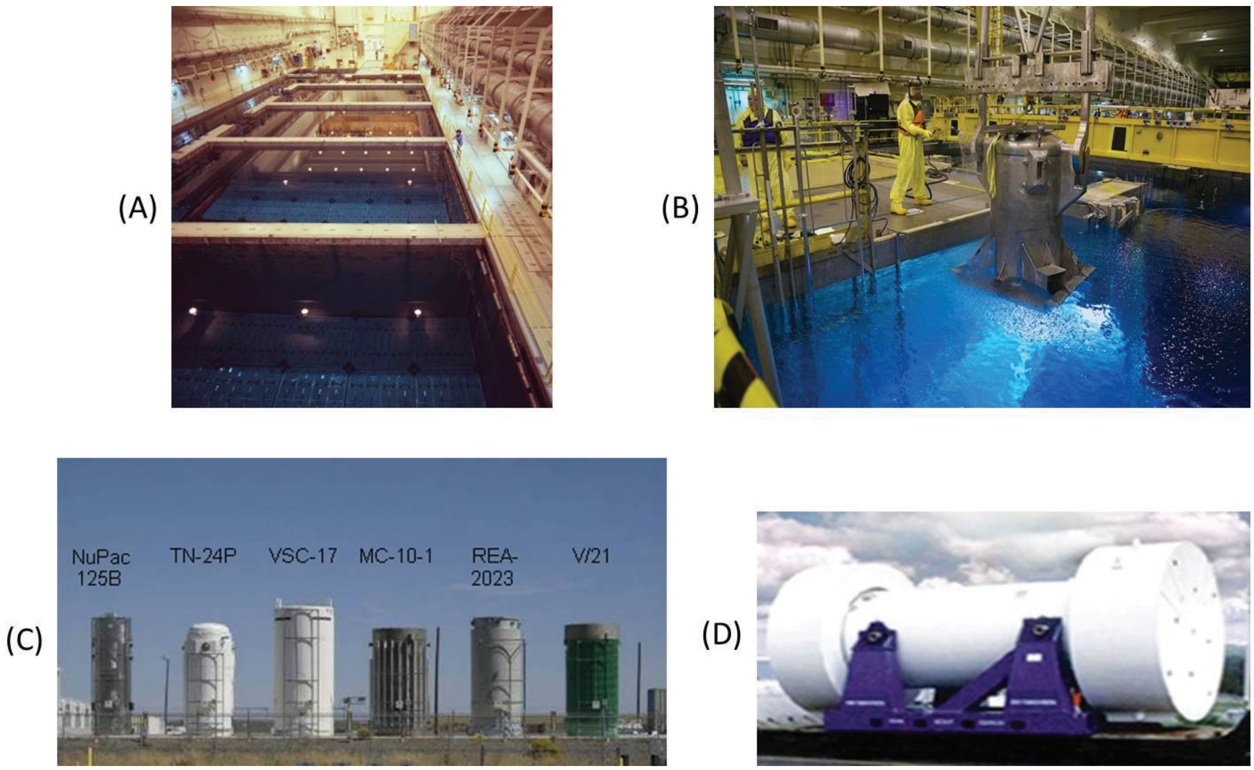

Figure 5-5. CPP-666 and CPP-2707 storage facilities.
A. Five of the six interconnected CPP-666 storage basins. Each basin's gate and the transfer canal are on the left in the image. (Source: Beller 2013). B. Removing an Advanced Test Reactor cask from a CPP-666 unloading pool in January 2014. (Source: Cooper 2014). C. Six types of dry storage casks on the CPP-2707 concrete pad. (Source: Beller 2013). D. One of two West Valley rail casks stored at CPP-2707. (Source: Beller 2013).

The facility also includes a fuel cutting pool that can be isolated from the main pool system; however, this pool has never been used (BRC 2010). The six basins and canal are stainless steel–lined concrete and have leak detection and water purification systems. The basins collectively hold 3.5 million gallons of demineralized water (Beller 2014c). Four basins are 31 feet deep and two are 41 feet deep (Hain 2010a). SNF is stored in lidded stainless steel racks. The storage capacity of the basins has been described variously as "2,911 fuel storage ports of 5 different sizes" (DOE 2010c), "3,800 storage positions" (BRC 2010), and "4,538 positions" (Beller 2010).

As of August 2014, the pools were approximately 30% full (Beller 2014a). The storage basins have a 40-year design life and the "authorization basis assumes operation through 2035" (Hain 2010a; Birk 2013). Continuous routine surveillance and monitoring is required (Hain 2010a). On a monthly basis, DOE analyzes pool water samples for chloride, specific conductivity, and pH to ensure they remain within specified limits (Beller 2014c). DOE also checks the data for trends to determine when the demineralizer should be replaced (Beller 2014c) and monitors aluminum and stainless steel elements in the pool for corrosion (Beller 2014c). In addition to the pool storage, DOE stores two Nu-Pac 125B casks in dry storage at CPP-666 (Beller 2010). DOE monitors the Nu-Pac 125B casks for hydrogen (Beller 2014c).

The three organizations that store SNF at CPP-666 are the DOE Office of Environmental Management (DOE-EM), the DOE Office of Nuclear Energy (DOE-NE), and the Naval Nuclear Propulsion Program. The inventory of SNF stored at CPP-666 is changing over time as some Advanced Test Reactor SNF is moved into the pools (Figure 5-5B) while other SNF, from that reactor and from other sources, is moved to different INL dry storage facilities.

DOE-EM transferred its SNF from CPP-666 pools to dry storage in 14 campaigns between May 2005 and June 2010 (Beller 2010). These transfers included 3,186 SNF handling units, representing some 21 types of SNF (New South Associates 2012). The transfers completed movement of all DOE-EM SNF from wet storage to dry storage (Hain 2010a; Birk 2013). The SNF includes all Advanced Test Reactor SNF discharged prior to fiscal year 2006 that DOE-NE had managed, but transferred to DOE-EM. DOE-EM stores 208 cans of miscellaneous fuels within two Nu-Pac 125B storage casks (Beller 2010). These casks were slated to be moved to CPP-603 by the end of 2012 (Hain 2010b), but they had not been moved as of August 2014 (Beller 2014a).

DOE-NE stores some of its Experimental Breeder Reactor 2 (EBR-II) driver SNF (sodium-bonded; Box 2-2) and Advanced Test Reactor SNF (post–fiscal year 2005) in CPP-666 pools. In 2002, Pahl (2002) indicated that approximately 2 MTHM of EBR-II driver SNF was stored in about 3,600 containers in CPP-666. DOE is in the process of retrieving the EBR-II fuel and transferring it in 227 shipments to the Materials and Fuels Complex (Gonzales-Stoller Surveillance 2012; Hain 2010a). The remaining shipments of EBR-II SNF to the Materials and Fuels Complex are scheduled to be completed by fiscal year 2022. This will allow DOE to meet the December 31, 2023, deadline—established as part of the 1995 Settlement Agreement—for removing all SNF at INL from wet storage (Cooper 2013; Beller 2014a).

The Advanced Test Reactor uses aluminum-clad, highly enriched (93% uranium-235) fuel. Following discharge from the reactor core, DOE stores the SNF in the reactor canal until it is cool enough to be transported and placed in the CPP-666 storage basins (Hain 2010b; Lacroix 2014b), where it is cooled—on average—for an additional five years (Lacroix 2014b). There are about 4,000 items of Advanced Test Reactor fuel at INL—the largest population of any fuel type, by piece count, at INL; however, the total mass of SNF is only about 3.2 MTHM. The disposition path for Advanced Test Reactor SNF currently in the CPP-666 storage basins is not clear; however, Hain (2010b) indicated that the SNF is being considered as a candidate for processing at the Savannah River Site's H Canyon because it is aluminum-clad, small, highly enriched, and easily transported. According to Hain (2010b), there are "two commercial casks that can transport the fuel where the fuel is currently in the licenses." DOE is conducting a study to assess all the disposition options for Advanced Test Reactor SNF (Lacroix 2014a, 2014b).

DOE is moving SNF from the Naval Nuclear Propulsion Program that is in the CPP-666 storage basins to the Naval Reactors Facility for dry storage in canisters (Beller 2010). Transfers of naval SNF from CPP-666 are scheduled to be completed in fiscal year 2017 (Cooper 2013).

5.1.1.5 CPP-2707

The CPP-2707 facility occupies a fenced, 36,150-square-foot area (DOE 2012d; Beller 2014c). It consists of a gravel pad where miscellaneous equipment is stored and a concrete pad (approximately 7,000 square feet) that supports six aboveground, vertical dry storage casks. These casks contain SNF that was previously stored at INL's Test Area North[136] fuel examination facility (Hain 2010a). The cask pad was constructed in 2003. It has 20 cask storage positions, and its authorization basis assumes operation through 2035 (Hain 2010a). The six storage casks (Figure 5-5C) are of different designs: Nu-Pac 125B; TN-24P; VSC-17; MC-10; Ridihalgh, Eggers, and Associates, REA-2023; and Gesellschaft für Nuklear

[136] DOE decommissioned the Test Area North fuel examination facility in 2008.

Service CASTOR® V/21 (Beller 2010). DOE also used the MC-10, CASTOR® V/21, and TN-24P casks in a dry cask storage testing program during the mid- to late 1980s.

About 42.1 MTHM of SNF (comprising 20 different fuel types, including epoxied SNF) is stored at CPP-2707 (Beller 2010; DOE 2005). The Nu-Pac 125B at CPP-2707 stores a variety of SNF (DOE 2005). Currently, the TN-24P and VSC-17 casks store canisters of consolidated SNF rods from the Surry and Turkey Point pressurized water reactors (DOE 2005; Mullen *et al.* 1988). The MC-10 cask stores pressurized water reactor SNF assemblies from the Surry and Turkey Point reactors (DOE 2005). The REA-2023 cask is a cylindrical double containment design that consists of an outer shell, an inner containment vessel, lead gamma shielding, and a neutron moderator. Most of the material stored in the REA-2023 cask is damaged fuel and post-irradiation examination specimens from the Loss-Of-Fluid-Test experimental reactor (including epoxied remains). The stored material is held in a variety of containers, including baskets and canisters. A single Surry fuel storage basket that holds nine Surry fuel rods is also stored in the REA-2023 cask (Bohachek *et al.* 2013). The CASTOR® V/21 cask has a cylindrical cavity that holds a fuel basket designed to accommodate up to 21 pressurized water reactor SNF assemblies. Since 1985, the CASTOR® V/21 has continuously stored 21 pressurized water reactor SNF assemblies from the Surry plant (Bare and Torgerson 2001; DOE 2005). As part of the dry cask storage characterization project, DOE reopened the CASTOR® V/21 cask in 1999—the cask had previously been opened in 1985 as part of the dry cask storage testing program—and visibly inspected the stored fuel (Electric Power Research Institute 2000). DOE samples each of the casks for hydrogen at a frequency that is determined by the previously-measured hydrogen concentration and the inspection history (Beller 2014c). DOE also measures and tracks trends in cask pressure and temperature (Beller 2014c).

Two rail casks—the TN-REG and TN-BRP—are also stored at the CP-2707 facility. Prior to 2015, DOE had stored the SNF from the West Valley, New York, reprocessing facility at INL in these casks on two rail cars parked on an unmaintained railroad spur (Figure 5-2), but in 2015, DOE moved the West Valley rail casks (Figure 5-5D) to CPP-2707. In 2003, DOE used the TN-REG and TN-BRP rail casks (Hunter 2004) to transport 125 assemblies of commercial SNF from the New York reprocessing facility to INL. Before the SNF was transported to INL, it had been stored at West Valley since the reprocessing facility was shut down in 1972[137] (Williams 2004; Hain 2010a). The two casks store about 26.3 MTHM of SNF (DOE 2005) from the Big Rock Point boiling water reactor and the Robert E. Ginna pressurized water reactor. Gas sampling that DOE performed on these casks, which occurs every five years, found krypton-85, indicating defective fuel (Beller 2014c).

5.1.2 Materials and Fuels Complex

5.1.2.1 Radioactive Scrap and Waste Facility

The Radioactive Scrap and Waste Facility at the Materials and Fuel Complex (Figure 5-1) is a fenced, outdoor compound of approximately 174,000 square feet (Figure 5-6A; Adams 2013). This facility began operations in 1964 and stores SNF and a variety of other types[138] of radioactive waste. The facility is regulated under a Resource Conservation and Recovery Act (RCRA) hazardous waste storage permit (Gonzales-Stoller Surveillance 2012) and DOE orders. This facility, which contains about 1,350 below-ground, silo-type storage locations, provides the bulk of interim SNF storage at the Materials and Fuels Complex. The carbon steel–lined silos are 2 feet in diameter and 12 feet long (Smith *et al.* 2001; Gonzales-Stoller Surveillance 2012). Figure 5-6A depicts the materials and geometry of the SNF storage containers in the silos. The silos are cathodically protected from corrosion and have concrete or steel shield plugs inserted into their tops to protect workers from radiation and to prevent water intrusion (Gonzales-Stoller Surveillance 2012).

DOE stores about 19.2 MTHM of EBR-II blanket fuel at the facility (Table 5-2; Simpson 2010). In 2011, DOE started moving the sodium-bonded EBR-II driver fuel that is stored in the CPP-666 basins to the Radioactive Scrap and Waste

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[137] The West Valley commercial reprocessing facility operated from 1966 to 1972. When it stopped operations, there was commercial SNF still at the facility awaiting reprocessing. In 1980, Congress passed the West Valley Demonstration Project Act, which directed DOE to conduct a high-level waste solidification and decommissioning demonstration project, in cooperation with New York State. Shipping the SNF that remained at West Valley to INL was part of the decommissioning project.

[138] The facility stores four types of remote-handled (higher radioactivity) wastes. The facility stores transuranic waste, mixed (hazardous chemical) transuranic, low-level waste, and mixed (hazardous chemical) low-level waste (Adams 2013).

facility (Gonzales-Stoller Surveillance 2012; Cooper 2013) and plans to complete shipments by 2023. DOE plans to continue treatment of the driver SNF at the Fuel Conditioning Facility that is located at the Materials and Fuels Complex, and evaluate possible interim dry storage of this SNF (Lacroix 2014a, 2014b). In developing its plans, DOE is considering whether the driver fuel is suitable for treatment. For fuel that may not be suitable for treatment, "that will have to be further investigated" (Lacroix 2014b). Other considerations include shipping schedules, processing rates at the Fuel Conditioning Facility, funding, and receipt and storage capabilities (Lacroix 2014a, 2014b). Kula (2010) indicates that non-EBR-II sodium-bonded SNF stored at the Radioactive Scrap and Waste Facility includes sodium debris bed material[139] from Sandia National Laboratories.

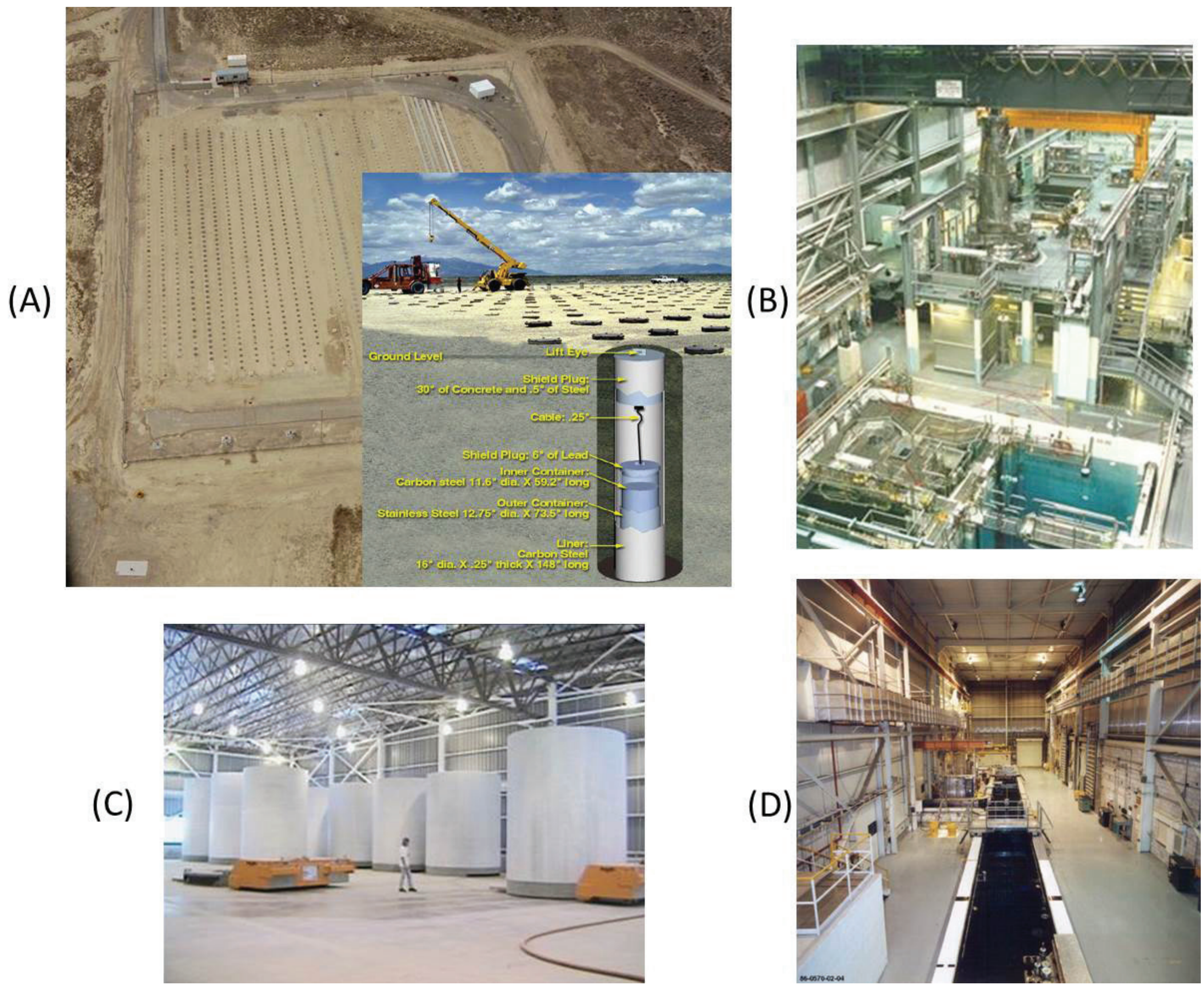

Figure 5-6. Radioactive Scrap and Waste Facility, Naval Reactors Facility spent nuclear fuel facilities, and Advanced Test Reactor fuel canal.
A. In the background is an aerial view of the Radioactive Scrap and Waste Facility, and in the foreground, is a ground-level photo of the facility with a schematic cutaway of an underground storage vault and container. (Source: Adams 2013). B. Expended Core Facility. (Source: McKenzie 2010a). C. Naval SNF storage in concrete overpacks in the Overpack Storage Building. (Source: McKenzie 2010a). D. SNF removed from the Advanced Test Reactor is temporarily maintained in the reactor canal. (Source: Hain 2010a).

[139] This material was formed in experiments that used crucibles containing high-enriched uranium dioxide (93% U-235) that were immersed in sodium.

5.1.2.2 Hot Fuel Examination Facility

DOE designed the Hot Fuel Examination Facility to be the front end of INL's post-irradiation examination capability (DOE 2012c). Commissioned in 1975, the facility consists of a multi-program hot cell system with two adjacent shielded hot cells (one with an air environment and the other in an argon environment; BRC 2010). The facility "can receive and handle kilograms to hundreds of kilograms of nuclear fuel and material in almost any type of cask" (DOE 2012c). The missions of the Hot Fuel Examination Facility include bench-scale electrochemical separations testing and engineering-scale, waste-form development to support operations in the Fuel Conditioning Facility at the Materials and Fuels Complex (DOE 2012c). All of the 0.25 MTHM of sodium-bonded SNF that DOE transferred from the Fast Flux Test Facility at the Hanford Site was processed, with the exception of 13.6 kilograms that are being held for research purposes at the Hot Fuel Examination Facility (Table 5-2).

5.1.3 Naval Reactors Facility

5.1.3.1 Expended Core Facility

The building that houses the Expended Core Facility is a concrete block structure of approximately 197,000 square feet (DOE 1994, 2013d). The original building was constructed in the mid-1950s and consisted of a water pool and a shielded cell with a connecting transfer canal (Figure 5-6B; DOE 1994). Since then, three more water pools, several shielded cells, and other capabilities were added. The total volume of the water pools in the Expended Core Facility is 3 million gallons (DOE 1994). The water pool surfaces are covered with either a fiberglass or epoxy coating (DOE 2016a). The water pool does not have a liner, creating the potential for water to infiltrate the reinforced concrete structure and the potential for corrosion damage of the reinforcing bar within the structure. The capability to detect and collect small leaks, a common feature in modern water pools, is not present for this water pool (DOE 2016a).

Naval SNF is transported to INL and examined at the facility. These activities are part of a program to verify the performance of current naval nuclear fuel and support efforts to design naval fuel with longer lifetimes [U.S. Department of Defense (DOD) and DOE 1997]. The Expended Core Facility has two major capabilities: (1) to receive, unload, prepare, and package naval SNF, and (2) to conduct naval SNF examinations (DOE 2013d). Large roll-up doors allow rail car and truck entry to the facility to receive and ship large containers. Storage racks in the pools are required because fuel is, at times, received into the facility faster than fuel can be prepared and shipped out of the facility (DOE 1994). Racks are also used to store the small amounts of naval SNF that are retained as library specimens for future reference and study. The basic configuration of these fuel storage racks is a rectangular structural array of storage ports. Each port has a square opening, but its depth is variable. All storage ports are stainless steel.

5.1.3.2 Overpack Storage Building and Expansions

The purpose of Naval Reactors Facility Overpack Storage Building is to provide dry storage, in multi-purpose canisters (storage, transportation, and disposal), for naval SNF (Figure 5-6C). The Overpack Storage Building (Figure 5-7) has the capacity to store 54 overpacks that each contain a naval canister. The original building has been augmented by several expansions, but detailed information about how it has been expanded is limited. Overpack Storage Expansion #1 provided capacity for 68 additional overpacks (McKenzie 2010b). Expansions #1 and #2 (Figure 5-7) consisted of adding concrete storage pads with a sheet metal covering on a structural steel frame (DOE 2012e). In 2012, as Overpack Storage Expansion #2 was under construction next to Expansion #1, it collapsed from wind damage and had to be rebuilt (DOE 2012e). Expansion #2 is 40 feet tall (DOE 2012e) and has a floor area of approximately 190 feet by 180 feet.

The Overpack Storage Building and its expansions provide dry storage for naval SNF in vertical, welded, cylindrical, stainless steel multi-purpose canisters placed inside concrete overpacks (Figure 5-6C). The canisters, known as the spent fuel canister system, are approximately 5.5 feet in diameter and 15.5 feet or 17.5 feet long and were designed to meet NRC's transportation, storage, and disposal regulations (Section 3.3; Bechtel Bettis 2008). DOE (2009a) provides additional details on the canisters and the naval SNF.

Figure 5-7. Expended Core Facility and major naval spent nuclear fuel handling support facilities at the Naval Reactors Facility.
As described in Section 5.3.2.2.3, Overpack Storage Expansion #3 is a conceptual facility to be built if needed. (Source: DOE 2016a).

NRC reviewed the safety analysis report[140] for the naval reactor SNF canister system relative to storage requirements in 10 CFR Part 72 (Staab 2009). Current plans assume that the spent fuel canister system will be emplaced directly in a repository (DOE 2009a; Staab 2009). Nonetheless, the canister is capable of being opened, the fuel and baskets can be removed, and the fuel can be repackaged (Bechtel Bettis 2008).

The Navy is planning to use the M-290 transportation cask (Figure 2-13) to transport aircraft carrier SNF from the shipyard where the SNF is removed from the carrier to the Naval Reactors Facility (Miles 2013). The Office of Naval Reactors program developed and procured the M-290 shipping container system, which includes a specialized rail car, over the past seven years to support defueling eight reactors onboard the aircraft carrier Enterprise in early 2015 (Miles 2013). The M-290 transport package (Staab 2009; NRC 2014b) will be used to ship spent fuel canisters by rail to a repository or interim storage site (Bechtel Bettis 2008; McKenzie 2010a). The M-290 cask weighs 260 tons loaded and is about 30 feet long, whereas the Navy's other shipping container, the M-140, weighs 175 tons loaded and is about 16 feet long (Staab 2009). The Navy sought NRC certification to use the M-290 cask as a shipping container under 10 CFR 71 (White 2013). NRC accepted the application for review (White 2013) and subsequently certified the package (Sampson 2014; NRC 2014b).

DOE stores about 28 MTHM of naval SNF at INL (Carter *et al*. 2012). In March 2012, Donald (2012) indicated that about one-third of this SNF was in dry storage, and as of August 2014, about one-half of the naval SNF was in dry storage with the balance stored in the CPP-666 water pool and the Expended Core Facility pool. DOE is responsible for packaging naval SNF that is being moved from the CPP-666 pool to dry storage. DOE's objective is to move all naval SNF that was

140 The Office of Naval Reactors requested that NRC review the safety analysis report and make a determination whether the storage facility provides protection to the public comparable to a facility licensed by NRC under 10 CFR 72.

in pool storage prior to January 1, 2017, out of pool storage by January 1, 2023. In June 2010, there were 32 canisters in dry storage (McKenzie 2010b). This had increased to 50 by March 2012 (Donald 2012) and to 100 by August 2014.[141]

A small percentage of naval SNF that will be stored in the Overpack Storage Building and Expansions has been disassembled for examination in the Expended Core Facility. In most cases, the disassembled naval SNF assemblies have intact cladding; however, in a few cases destructive evaluations of disassembled components resulted in nonintact cladding. Some test specimens have nonintact cladding either because they were tested until the cladding failed or because they were tested with intentionally introduced defects (Carter *et al*. 2012).

5.1.4 Advanced Test Reactor

The Advanced Test Reactor (Figure 5-1) is one of the few reactors in the DOE complex still operating. It is located in Building TRA-670 at the Reactor Technologies Complex and was constructed in 1967. The reactor continues to generate SNF, producing more than 30 SNF assemblies each year (Beller 2010; Hill and Fillmore 2005). During routine reactor maintenance outages, DOE removes SNF assemblies and temporarily places them in underwater racks in the reactor canal (Figure 5-6D). The reactor canal has 600–700 assembly positions. Although the reactor canal is designated as a working facility rather than a storage facility, SNF assemblies are allowed to cool before being transferred to the CPP-666 basins (Hain 2010a). The ultimate disposition path for Advanced Test Reactor SNF may involve recycling at the Savannah River Site's H Canyon (Hain 2010a) or disposal in a repository (Gonzales-Stoller Surveillance 2012). Although Hill and Fillmore (2005) state that the reactor is scheduled to operate through 2025, the reactor's future operating life is still being considered (*e.g.*, DOE 2012c). Details about the reactor's SNF and its transport from the reactor canal to CPP-666 basins are provided in the discussion of the CPP-666 basins in Section 5.1.1.4.

5.2 Legal Agreements and Decisions That Affect Spent Nuclear Fuel Management

5.2.1 Legal Agreements

The three legal agreements that affect how SNF is managed at INL are the 1995 Settlement Agreement, the Addendum to the 1995 Settlement Agreement, and the Memorandum of Agreement Concerning Receipt, Storage, and Handling of Research Quantities of Commercial Spent Nuclear Fuel at the Idaho National Laboratory (hereafter the "Memorandum on Research Quantities of Commercial SNF").

5.2.1.1 1995 Settlement Agreement

An agreement reached in 1995 by the state of Idaho, DOE, and the Department of the Navy (Idaho *et al*. 1995) concerning the management of nuclear waste at INL is known as the 1995 Settlement Agreement. The agreement is codified in a consent order, signed by the parties, with the United States District Courts, District of Idaho. The agreement addresses how high-level radioactive waste (HLW), SNF, transuranic waste, and mixed waste are managed at INL. It includes terms and conditions to fully resolve all issues in two related lawsuits [Public Service Co. of Colorado v. Batt, No. CV 91-0035-S-EJL (D. Id.) and United States v. Batt, No. CV-91-0065-S-EJL (D. Id.)]. The agreement specifies requirements and deadlines for SNF and HLW shipments leaving INL, as well as for shipments of SNF to INL. The agreement also ties DOE's failure to meet certain deadlines (*e.g.*, shipping transuranic waste out of Idaho by a specific date) or requirements (*e.g.*, treating existing waste and transferring SNF out of wet storage at INL) to a suspension of SNF shipments to INL. Separate terms and conditions apply to transporting Navy SNF and DOE SNF (including SNF from foreign research reactors and SNF from FSV) to INL. Finally, the agreement lists eight requirements for INL's SNF program. These requirements mostly relate to funding specific projects and upgrades to INL SNF facilities; however, the agreement includes one program requirement stipulating that DOE shall designate INL the "DOE's lead laboratory for spent fuel." The agreement goes on to specify that "DOE shall direct the research, development and testing of treatment, shipment and disposal

[141] The Board toured this facility as part of a site visit to INL in advance of the Board's public meeting on August 6, 2014 in Idaho Falls, Idaho.

technologies for all DOE spent fuel, and all such DOE activities shall be coordinated and integrated under the direction of the Manager, DOE-Idaho Operations Office." Another program requirement is that "DOE and the Navy shall employ multi-purpose canisters or comparable systems to prepare spent fuel at the Idaho National Engineering Laboratory[142] for shipment and ultimate disposal of such fuel outside Idaho." Additional key elements of the 1995 Settlement Agreement are described in the next section, which discusses the 2008 addendum to the agreement.

5.2.1.2 Addendum to 1995 Settlement Agreement

The addendum (Idaho *et al.* 2008) governs receipt and handling of shipments of naval SNF. It provides for enforceable commitments by the Navy "to assure that naval SNF is stored safely in Idaho and removed from Idaho with reasonable promptness." The addendum "relates only to the receipt and storage of naval SNF at the INL after January 1, 2017 and January 1, 2035." Several elements of the 1995 Settlement Agreement and the Addendum to the 1995 Settlement Agreement (key addendum modifications are denoted by square brackets below) are especially relevant[143] for future SNF management at INL:

- "DOE shall complete the transfer of all spent fuel from wet storage facilities at Idaho National Engineering Laboratory by December 31, 2023" [naval SNF arriving at INL after January 1, 2017, may be kept in wet storage for up to six years].
- "DOE shall remove all spent fuel, including naval spent fuel and Three Mile Island spent fuel from Idaho by January 1, 2035" [no more than 9 MTHM of naval SNF may be kept at INL after January 1, 2035].
- Up to 1,135 shipments of SNF[144] to Idaho National Engineering Laboratory (no more than 575 of which would be Navy shipments) may be made during the period 1995–2035 [no more than 20 shipments/year of naval SNF may be made to INL after January 1, 2035].
- "Shipments of naval spent fuel to Idaho National Engineering Laboratory through 2035 shall not exceed 55 metric tons of spent fuel."
- "After December 31, 2000, DOE may transport shipments of spent fuel to Idaho National Engineering Laboratory constituting a total of no more than 55 metric tons of DOE spent fuel."[145]
- No shipments of SNF shall be made to INL from FSV, Colorado, unless a permanent repository or interim storage facility for SNF "located outside of Idaho, is operating and accepting spent fuel" from INL.
- Exchange of SNF between INL and the Savannah River Site (SRS) is permitted with some restrictions.
- "DOE shall treat all high-level waste currently at Idaho National Engineering Laboratory so that it is ready to be moved out of Idaho for disposal by a target date of 2035."
- "If DOE fails to satisfy the substantive obligation or requirements it has agreed to in this Agreement or fails to meet deadlines for satisfying substantive obligations or requirements, shipments of DOE spent fuel to Idaho National Engineering Laboratory shall be suspended[146] unless or until the parties agree or the Court determines such substantive requirements have been satisfied."

The 1995 Settlement Agreement provides for the federal parties (DOE and Navy jointly) to pay the state of Idaho $60,000 for each day after January 1, 2035, that any SNF remains in Idaho. The 2008 addendum requires the Navy to pay Idaho $60,000 for each day[147] after January 1, 2023, that any naval SNF that was in pool storage prior to January 1, 2017, remains in pool storage.

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[142] The Idaho National Engineering Laboratory subsequently was renamed Idaho National Laboratory.

[143] Only those key HLW requirements in the 1995 Settlement Agreement that affect SNF management are listed.

[144] A shipment is defined as a single shipping container containing SNF.

[145] Navy SNF and DOE SNF are treated separately in the 1995 Settlement Agreement.

[146] The suspension of SNF shipments does not apply to the removal of SNF by 2035 or to treatment of all HLW by 2035.

[147] Both the $60,000/day joint payment for not moving SNF out of Idaho and the $60,000/day Navy payment for not moving SNF from wet storage to dry storage are subject to the availability of advance appropriations.

5.2.1.3 Memorandum on Research Quantities of Commercial Spent Nuclear Fuel

In 2011, DOE signed a Memorandum of Agreement with the state of Idaho (DOE and Idaho 2011) that sets the conditions under which INL may receive limited quantities of commercial SNF for "research and examinations." Although the 1995 Settlement Agreement provides that DOE "will make no shipments of spent fuel from commercial nuclear power plants" to INL, the 2011 memorandum grants a limited waiver to this provision, as allowed under the 1995 Settlement Agreement, for small amounts of commercial SNF to remain at INL (less than 400 kilograms per year) for testing and research purposes. It also retains the 1995 Settlement Agreement's overall 55-MTHM limit on the quantity of DOE SNF that can be shipped to INL. The purpose of the 2011 memorandum is to "provide for efficient and safe development of research capacities at INL related to the next generation of nuclear reactor fuels while continuing to ensure Idaho does not become a *de facto* repository for the Nation's SNF from commercial nuclear power plants."

5.2.2 Records of Decision

5.2.2.1 Programmatic Spent Nuclear Fuel Management

The 1995 DOE decision to consolidate SNF regionally by type is described in its record of decision for the SNF management programmatic environmental impact statement (EIS; DOE 1995b). The decision indicated that, by 2035, INL could receive 1,940 shipments of SNF from generators or current storage sites, including 244 shipments from FSV. INL could also send 114 shipments of SNF, including all existing INL aluminum-clad SNF, to SRS. As described by Hill and Fillmore (2005), under the record of decision, INL would receive sodium-bonded fuel removed from the Fast Flux Test Facility at the Hanford Site for treatment. INL would also receive non-aluminum-clad SNF from generators or current storage sites including "16 universities, 8 domestic sites, 18 foreign sites and 5 DOE sites" (Hill and Fillmore 2005).

In 1996, DOE's record of decision for the SNF management programmatic EIS was amended (DOE 1996a) to reflect the 1995 Settlement Agreement (Idaho *et al.* 1995). That agreement, among other things, limits shipments of SNF to INL (*e.g.*, it stops shipments from FSV until a repository or interim storage facility is receiving SNF from INL). The origin and interim management destination of specific fuels and the potential number of shipments to INL were changed in the 1996 amendment to the record of decision (DOE 1996a). The main change was to reduce shipments from FSV to INL to zero and to reduce the number of SNF shipments from Hanford to INL from 512 to 12. Some actions identified in the amended record of decision (DOE 1996a) have yet to be completed[148] (*e.g.*, shipments of aluminum-clad SNF to SRS).

5.2.2.2 Foreign Research Reactor Spent Nuclear Fuel

DOE's 1996 revised record of decision (DOE 1996b) for a final EIS on a proposed nuclear weapons nonproliferation policy concerning foreign research reactor SNF affects SNF management at INL. The revised record of decision indicated that foreign TRIGA® research reactor SNF (about 1 MTHM) would be transported to and managed at INL in accordance with DOE's record of decision on SNF management (DOE 1995b) and the 1995 Settlement Agreement. DOE revised the 1996 record of decision (DOE 1996b) multiple times and extended the fuel acceptance deadline to 2019 (DOE 2008c). INL had been receiving shipments of foreign research reactor SNF (Beller 2007; Cooper 2012), but those shipments, and all other DOE SNF shipments to INL (*e.g.*, SNF from domestic research reactors), were stopped on January 1, 2013, as required under the 1995 Settlement Agreement because DOE failed to meet a December 31, 2012, deadline for completing treatment of sodium-bearing waste.

5.2.2.3 Dry Storage Container System for Naval Spent Nuclear Fuel Management

Building on the SNF management programmatic EIS (DOE 1995a) and other records of decision, DOD and DOE jointly issued a record of decision for their final EIS for a container system to manage naval SNF (DOD and DOE 1997). DOD and DOE decided that a dual-purpose canister system would be used for "loading, storage, transport, and possible dis-

[148] Under guidelines adopted by DOE, decisions contained in records of decisions that have not been implemented should be reexamined to determine if criteria or other assumptions have changed significantly before proceeding with implementation.

posal of naval SNF following examination of the naval SNF.” They further decided that the “naval SNF which is, or which will be, stored at the CPP[149] will be loaded into dual purpose canisters at the NRF [Naval Reactors Facility]” (DOD and DOE 1997). The Navy and DOE also decided “that all dual purpose canisters loaded with naval SNF will be stored at a site adjacent to the Expended Core Facility” (DOD and DOE 1997). DOD and DOE implemented these decisions as work continues to remove naval SNF from pool storage at CPP-666, package the SNF into dual-purpose canisters at the Naval Reactors Facility, and store the canisters at the Overpack Storage Building and its expansions. Because DOD and DOE intend to dispose of the dual-purpose canisters without repackaging,[150] the naval canisters are now considered triple-purpose, or multi-purpose, canisters.

5.2.2.4 Treatment and Management of Sodium-bonded Spent Nuclear Fuel

In 2000, DOE issued a final EIS and record of decision to manage and treat sodium-bonded SNF, which addressed the issue that “sodium could complicate compliance with the eventual final repository waste acceptance criteria” (DOE 2000a). DOE currently manages about 55.7 MTHM of sodium-bonded SNF and considers and treats the SNF as hazardous waste. Approximately 34.2 MTHM of this inventory consists of blanket fuel from the Fermi-1 reactor; another 19.2 MTHM, approximately, is blanket fuel from the EBR-II reactor. The remaining roughly 2.3 MTHM is driver fuel from the EBR-II reactor (Box 2-2 describes driver and blanket fuel). In addition, DOE manages a small quantity of sodium-bonded material (approximately 50 kilograms) from experiments at the Hanford Site and Sandia National Laboratories.

DOE’s current requirements for accepting waste for disposal (DOE 2008a) in a geologic repository at Yucca Mountain, Nevada, do not allow RCRA-regulated waste to be accepted there. Unless DOE either shows that sodium-bonded SNF is not regulated under RCRA or develops other waste acceptance criteria for alternative disposal options, the disposition pathway for sodium-bonded fuel will need to provide for the physical removal or chemical deactivation of the sodium. Based on fuel characteristics, driver fuel will require some type of chemical treatment because the elemental sodium is infused into the fuel. For blanket fuel, physical separation of the sodium or chemical processes may be considered.

To overcome the waste acceptance obstacle, DOE opted for electrometallurgical treatment for EBR-II driver fuel and small quantities of other miscellaneous sodium-bonded SNF at INL (Figure 5-8). The treatment uses an electrorefiner with a molten salt electrolyte to dissolve the chopped fuel (Hill and Fillmore 2005; Simpson 2010). This chemical treatment process separates the cladding from the fuel and results in the sodium and fission products accumulating in the molten salt, creating two waste streams that are considered HLW. First, the cladding, along with some added metals, is converted into a metallic HLW form in a furnace. Second, once the molten salt reaches its capacity to accumulate radionuclides, the salt and accumulated radionuclides in the salt will be converted into a ceramic HLW form. After the electrometallurgical treatment of the sodium-bonded SNF, the HLW metallic and ceramic forms created will be stored at the Radioactive Scrap and Waste Facility to await geologic disposal (Hill and Fillmore 2005). Alternatively, the salt waste could be stored and disposed of in a repository other than Yucca Mountain.

In contrast to driver SNF, mechanical stripping is an option for blanket SNF cladding, which opens up other treatment alternatives[151] for this type of SNF. Also, “because of the different physical characteristics of the Fermi-1 sodium-bonded blanket SNF,” DOE (2000a) decided to continue to store its inventory of this material while alternative treatments were evaluated. According to DOE’s record of decision, “while EBR–II SNF is undergoing electrometallurgical treatment and the Fermi-1 blanket SNF remains in storage, DOE has approximately four years in which to evaluate the operating experience of electrometallurgical treatment technology and further evaluate other alternatives for the Fermi-1 blanket SNF” (DOE 2000a). The record of decision goes on to state that “after these data are evaluated, DOE will decide whether to

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[149] Chemical Processing Plant, the former name for Idaho Nuclear Technology and Engineering Center.

[150] The naval reactors program required the design of the naval canister to permit the repackaging of naval spent nuclear fuel because, “although remote and undesirable, there is a possibility that fuel which has been loaded into a canister will need to be unloaded and repackaged in a new canister. The possibility of repackaging would most likely be attributed to the uncertainties associated with the repository” (Bechtel Bettis 2008).

[151] For example, DOE (2000a) identified sodium removal and placement in high-integrity cans as one alternative.

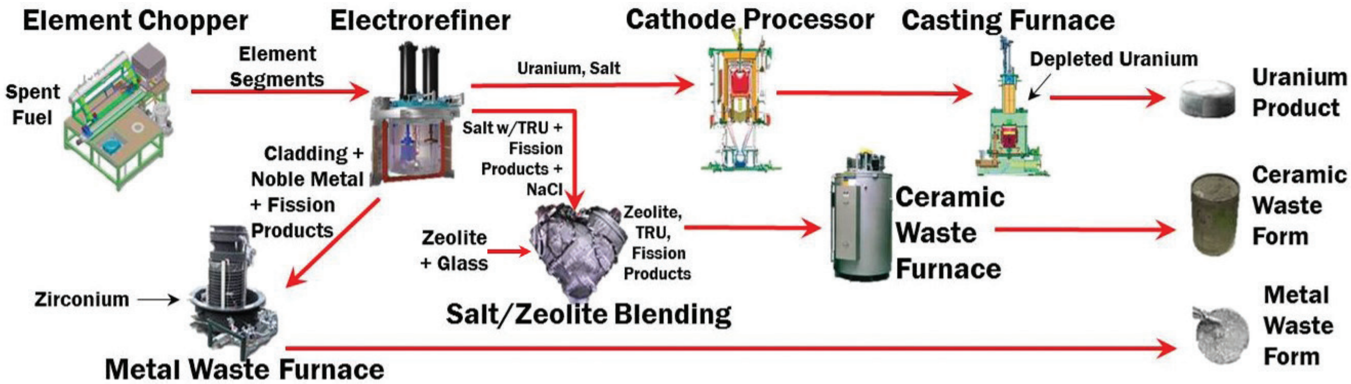

Figure 5-8. Electrometallurgical treatment of sodium-bonded spent nuclear fuel at Idaho National Laboratory. The SNF is chopped into segments before putting it into the electrorefiner to allow the molten salt to react with the fuel. The electrorefiner precipitates uranium from the molten salt, which can then be removed and purified by removing any attached salt in the cathode processor. The purified high-enriched uranium from the driver fuel (Table 5-2) is diluted with depleted uranium in a casting furnace to create a low-enriched uranium product. The SNF cladding, along with metals that don't remain dissolved in the molten salt (noble metals), are removed from the electrorefiner. These materials, and any fission products removed along with the materials, are combined with zirconium in a metal waste furnace to create the metal waste form. The salt with transuranic isotopes (TRU) and fission products from the SNF are removed from the electrorefiner and blended with zeolite and glass. The mixture is added to a ceramic waste furnace that creates the ceramic waste form. (Source: Simpson 2010).

treat the Fermi-1 blanket SNF using electrometallurgical treatment or to use another treatment method and/or disposal technique." As of 2010, about 85% of the EBR-II fuel remained untreated (Simpson 2010), and DOE had not made any decision concerning the treatment of Fermi-1 blanket SNF. Since 1996, DOE has treated approximately 4.5 MTHM of sodium-bonded SNF—less than 10% of the 55.7 MTHM awaiting treatment at INL.

5.2.2.5 Recapitalization of Infrastructure Supporting Naval Spent Nuclear Fuel Handling

In 2016, DOE decided to recapitalize the existing Naval Reactors Facility Expended Core Facility infrastructure (DOE 2016b). DOE began its National Environmental Policy Act of 1969 (U.S. Congress 1969) activities to "ensure the continued availability of the infrastructure needed to support the transfer, handling, examination, and packaging of naval SNF removed from nuclear-powered aircraft carriers and submarines, as well as from land-based prototype reactors for at least the next 40 years" (DOE 2012f). DOE acknowledged that the existing infrastructure and equipment are over 50 years old and do not meet current standards (DOE 2013d, 2016a).

DOE (2016b) decided to construct a new facility in the northeast section of the Naval Reactors Facility site. The new facility will include all current naval SNF handling operations conducted at the Expended Core Facility (DOE 2016b). Also, the facility will include the capability to unload naval SNF from M-290 shipping containers in the water pool and handle aircraft carrier naval SNF assemblies without prior disassembly for preparation and packaging for disposal. That capability does not currently exist within the Expended Core Facility water pools. DOE (2016b) states

> This decision will include recapitalization of the naval SNF handling capabilities described in the EIS including: unloading M-140 and M-290 shipping containers; temporary wet storage of naval SNF; initial examination of naval SNF; resizing and securing nuclear poison in naval SNF modules; transfer of naval SNF for more detailed examination at the examination location; loading naval SNF into naval SNF canisters; transfer of naval SNF into or out of temporary dry storage; and loading waste shipping containers.

DOE did not make a decision regarding the recapitalization of Expended Core Facility infrastructure for examinations (DOE 2016b). In addition to building a new facility, the Naval Nuclear Propulsion Program "will continue to perform limited upgrades as necessary to keep the Expended Core Facility infrastructure in safe working order" (DOE 2016b).

5.3 The Path Forward for Managing and Disposing of Spent Nuclear Fuel

5.3.1 Changes to the Spent Nuclear Fuel Inventory

Potential changes to the inventory of INL SNF, between now and 2035, are constrained by the types and amounts of SNF currently at INL, the 1995 Settlement Agreement, and records of decision that impact future shipments of SNF to INL (DOE 1996a, 1996b) and the processing of SNF at INL (DOE 2000a). The record of decision resulting from the programmatic SNF management EIS (DOE 1996a) indicated that the existing INL SNF inventory (as of 1995) totaled approximately 261 MTHM and that the "existing redistributed [from other sites to INL] and newly generated inventory [by 2035]" could be 381 MTHM. The Board's analysis indicates that the quantity of SNF stored at INL could increase 52 MTHM by 2035, from the current total of approximately 325 MTHM to approximately 377 MTHM.

Table 5-3 provides a breakdown of expected additions to INL's SNF inventory. It includes planned receipt of naval SNF, domestic and foreign research reactor SNF (DOE 1996b), and non-aluminum-clad SNF from SRS (DOE 1996a). Ongoing operations of the Advanced Test Reactor will also add to the inventory of stored SNF.

The Board's estimate of future receipts of domestic and foreign research reactor SNF depends on three factors: (1) the number of shipments, (2) the quantity of SNF per shipment, and (3) the duration of the shipment programs. DOE had planned to receive three shipments of domestic and foreign research reactor SNF between October 1, 2012, and September 30, 2015, and had identified which facilities (foreign and domestic) could ship SNF to INL between 2012 and 2018 (DOE 2011c).

Table 5-3. Potential changes to the inventory of Idaho National Laboratory spent nuclear fuel before 2035

Source of change (1; see Notes)	Amount of SNF (MTHM) added to or removed from inventory
Additions	
Receipt of naval SNF (2)	~37
Receipt of domestic and foreign research reactor SNF (3)	~2
Continued operations of the Advanced Test Reactor (4)	~0.5
Receipt of non-aluminum-clad SNF from SRS (5)	~20
Reductions	
Transfer of aluminum-clad SNF to SRS (5)	~5
Electrometallurgical treatment of sodium-bonded SNF (6)	~2
Net change (addition)	~52

Notes

(1) Assumes no out-of-state transport of INL SNF to a repository or consolidated storage facility.

(2) The amount of naval SNF received under the 1995 Settlement Agreement is 18.22 MTHM (Idaho 2014). The agreement limits naval SNF shipments to 55 MTHM; thus 36.78 MTHM could still be received at INL. The expected total inventory of naval SNF is 65 MTHM (McKenzie 2010a) and the inventory at INL, as of August 2014, is approximately 28 MTHM.

(3) Assumes an average of three shipments per year with an average of 0.03 MTHM per shipment for 20 years starting in 2015. As described in Section 5.2.2.2, shipments of DOE SNF, including domestic and foreign research reactor were halted, but were expected to be allowed after September 30, 2015 (Cooper 2012), although shipments had not started as of October 2017.

(4) Assumes 0.024 MTHM per year (Hill and Fillmore 2005) for 21 years (2014 through 2035). The estimate neglects years in which the reactor is undergoing core change-outs and assumes that the reactor operates through 2035. A decision on length of time that the reactor will operate into the future is pending. Thus, the potential addition of approximately 0.5 MTHM is likely overestimated.

(5) Assumes that INL aluminum-clad SNF is shipped to SRS and non-aluminum-clad SNF at SRS is shipped to INL.

(6) Assumes that the recent average rate of treatment of 0.1 MTHM of SNF per year (DOE 2013e) continues through 2035.

DOE's program for foreign research reactor SNF (Section 5.2.2.2) is scheduled to be complete in 2019 (DOE 2008a). The total quantity of SNF to be shipped to INL under this program is about 1 MTHM of TRIGA® SNF (DOE 1996b). Between 1999 and 2012, INL received between one and five shipments of TRIGA® SNF per year from domestic and foreign reactors. Quantities of SNF per shipment ranged from 0.01 to 0.05 MTHM (DOE 2005). Thus, new shipments of SNF from domestic and foreign research reactors are likely to add less than 2 MTHM to the INL inventory before 2035.

At the same time, future reductions in the current inventory are anticipated as a result of planned shipments of aluminum-clad SNF to SRS (DOE 1996a) and treatment of sodium-bonded SNF (DOE 2000a). Over the 13-year period from 1996 to 2009, DOE used electrometallurgical treatment to remove 4 MTHM of sodium-bonded SNF[152] (Simpson 2010). In recent years, however, the treatment rate of driver fuel has slowed to about 0.1 MTHM of SNF per year (DOE 2013e). Projecting out to 2035, another 2 MTHM of SNF will be removed from the inventory if treatment rates remain at the level of the past few years. Adding to the uncertainty of potential inventory changes, DOE stated that it has been planning to "ramp up our treatment of the fuel" and has the capacity to increase treatment throughput eight-fold (Lacroix 2014b).

In addition to changes in the overall SNF inventory, inventories at specific INL facilities are expected to change as DOE consolidates SNF storage to fewer facilities and moves SNF from pools to dry storage. None of these planned changes will challenge the storage capacity of the affected facilities, which include CPP-603, CPP-666, the Radioactive Scrap and Waste Facility, and the Overpack Storage Building and its expansions. The inventory at CPP-603 (currently about 11.9 MTHM) will increase when DOE moves two Nu-Pac 125B storage casks containing approximately 6.7 MTHM from CPP-666[153] (Hain 2010b). DOE will store SNF from future shipments from foreign and domestic research reactors at CPP-603. Planned inventory changes at CPP-666 reflect several actions: (1) naval SNF will be transferred from pool storage to the Expended Core Facility for packaging and subsequent dry storage at the Overpack Storage Building expansions, (2) EBR-II driver fuel will be removed from storage pools for transport to the Materials and Fuels Complex (six shipments per year; DOE 2013f), (3) two Nu-Pac 125B storage casks that are currently in dry storage could be transferred to CPP-603, and (4) Advanced Test Reactor SNF will be added to pool storage at CPP-666 (approximately 0.1 MTHM per year in 15 casks; DOE 2013f). The fuel transfer from CPP-666 pools means an increase in SNF inventories at the Radioactive Scrap and Waste Facility, and the Overpack Storage Building and expansions.

5.3.2 Proposed Actions That Would Affect Spent Nuclear Fuel Management

5.3.2.1 Proposed Actions at Existing Facilities

5.3.2.1.1 Renewing the License for the Three Mile Island Unit 2 Installation

DOE plans to renew the NRC license for the TMI-2 independent spent fuel storage installation (DOE 2013g) at CPP-1774. In 2012, DOE initiated work and developed a schedule to support submitting the license renewal application by 2017.[154] The application would be "for renewal of the license in 2019" (Beller 2013; Allen 2013) to extend operations for a 20-year period to 2039 (Banovac 2016, Enclosure 3). DOE described to NRC its license application approach and how it planned to manage age-related degradation of the structures, systems, and components of the facility (Allen 2013; Banovac 2016). For example, DOE is considering using hydrogen monitoring of the vented storage canisters[155] to estimate corrosion rates of carbon steel internal canister components (Banovac 2016).

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[152] This included 3.2 MTHM of blanket fuel, which may be treated using other techniques (Box 2-2). For geologic disposal purposes only, DOE accounts for the HLW created by the treatment process as equivalent in terms of MTHM, regardless of its volume, to the quantity of SNF from which it was derived. For example, if 2 MTHM of sodium-bonded SNF were processed, then the physical quantity of SNF that would need to leave Idaho by 2035 would be reduced by 2 MTHM; however, under the 1995 Settlement Agreement, the HLW created from the processing would still need to be ready to be moved out of Idaho for disposal by the target date of 2035.

[153] DOE had not moved the storage casks as of August 2014 (Beller 2014a), and DOE has not indicated that plans for these casks have changed.

[154] On March 6, 2017, DOE submitted an application for the renewal of its license; however, the Board has not reviewed the contents of the application or subsequent documents associated with DOE's renewal application.

[155] DOE's hydrogen monitoring results indicate that radiolysis is not the primary process producing hydrogen; rather, hydrogen generation is "related to corrosion actions with the canisters" (Banovac 2016, Enclosure 3, Slide 40).

NRC staff (Banovac 2016) noted that additional degradation mechanisms are applicable to concrete and encouraged DOE to review the *Managing Aging Processes in Storage (MAPS) Report* (NRC 2016c) and other sources of operating experience information[156] in DOE's review of aging management. Based on discussions with DOE, NRC noted "that for development of the aging management programs, the method or technique for detection of aging effects should be demonstrated to be capable of evaluating the condition of the structure, system, and component against the acceptance criteria for the specific aging mechanism or effect being monitored or inspected" (Banovac 2016).

5.3.2.1.2 Removing Spent Nuclear Fuel from Pool Storage Facilities

Consistent with its commitments in the 1995 Settlement Agreement, the Navy is in the process of moving its SNF from the CPP-666 pools into dry storage (McKenzie 2010b). DOE stated that it is on track to have all SNF, including naval SNF, now stored at CPP-666 basins transferred from wet to dry storage by 2023 (DOE 2013h); however, the rate of transfer of EBR-II driver SNF from pools to the Materials and Fuels Complex is "dependent on maintaining the naval SNF returns schedule [removal of naval SNF and transfer to Naval Reactors Facility] and the ability of the receipt facility at Materials and Fuels Complex to receive the EBR-II driver SNF" (DOE 2013f). Lacroix (2014a) lists funding, processing rates at the Materials and Fuels Complex, suitable receipt and storage capability, shipping schedule, and suitability of the SNF for treatment as considerations in meeting the 2023 deadline. According to Lacroix (2014a, 2014b), DOE plans to move all EBR-II SNF from the basins by 2023, with continued Materials and Fuels Complex treatment and possible interim dry storage.

Whether DOE meets the 2023 milestone for removing SNF from CPP-666 pools will also depend on how much longer the Advanced Test Reactor continues to operate. As long as the reactor operates, DOE will continue to discharge additional SNF that requires cooling in pools. Currently, the reactor SNF is removed from the reactor, temporarily cooled in the reactor canal, and then transferred to CPP-666 basins for five additional years of cooling before it is placed in dry storage (Lacroix 2014a). DOE views the Advanced Test Reactor operation as part of INL's continuing mission and plans to continue operating the reactor beyond 2023 (Lacroix 2014b). DOE is studying disposition options[157] for the reactor's SNF (Lacroix 2014a, 2014b).

5.3.2.1.3 Surveillance, Monitoring, and Maintenance at Storage Facilities

The authorization basis for all DOE-regulated SNF facilities supports their use through 2035 with appropriate surveillance and maintenance (Hain 2010a; Beller 2014c). DOE directed its previous Idaho Cleanup Project contractor, CH2M-WG Idaho, to provide surveillance and monitoring, and implement a comprehensive preventative maintenance program for all Idaho Nuclear Technology and Engineering Center SNF storage facilities through the duration of its contract, which was slated to end September 30, 2015[158] (DOE 2013f). Beller (2014c) describes monitoring and surveillance and activities for those storage facilities. Because some systems and facilities are at the end of their service lives or are obsolete, DOE (2012g) identified a prioritized list of systems and facilities in CPP-666 and CPP-603 that could be refurbished if funds became available (DOE 2013g). At CPP-603, mechanical systems need to be upgraded to "maintain minimum safe storage and to support retrieval of SNF" (Hain 2010a).

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156 DOE is "evaluating participation in the independent spent fuel storage installation aging management Institute of Nuclear Power Operations database (AMID) via AREVA-TN" (Banovac 2016, Enclosure 3, Slide 15).

157 DOE's Advanced Test Reactor SNF option study is evaluating reduced cooling requirements for dry storage, dry storage needs and existing capabilities, funding profiles, and the potential continued need for wet cooling operations post-2023.

158 On February 4, 2016, DOE awarded Fluor Idaho the Idaho Cleanup Project Core Contract with a 90-day transition period from the old to new contractor. The new contract, and its modifications (DOE 2017), prescribes DOE SNF management activities, including surveillance and monitoring, including activities at the Radioactive Scrap and Waste Facility. The contract includes details on receipt and storage of foreign and domestic research reactor SNF and EBR-II transfer activities. The contract also addresses receipts of Advanced Test Reactor SNF at CPP-666 and transfer of 1,000 Advanced Test Reactor SNF elements from the facility into dry storage at Idaho Nuclear Technology and Engineering Center.

5.3.2.1.4 Potentially Exchange Spent Nuclear Fuel with Savannah River Site

In its record of decision for the programmatic EIS, DOE (1995b) indicated that it would transfer aluminum-clad SNF from INL to SRS and non-aluminum-clad SNF from SRS to INL. DOE (2007b) subsequently indicated that it planned to implement these exchanges between fiscal years 2008 and 2016; however, the exchanges have not yet occurred and the decision to conduct these transfers is on hold (DeLeon 2011). Furthermore, because these transfers are not funded in the current environmental liability baseline (Beller 2014a), it is not clear when or whether an exchange of INL SNF and SRS SNF will occur.

5.3.2.1.5 Continue Treating Sodium-bonded Spent Nuclear Fuel

DOE continues to treat sodium-bonded SNF in the Fuel Conditioning Facility at the Materials and Fuels Complex. In fiscal year 2013, DOE treated approximately 170 kilograms (DOE 2013e). DOE planned to treat 76 kilograms in fiscal year 2014 (DOE 2013e) and to continue treatments[159] into the future.

5.3.2.2 Proposed Actions for Potential Future Facilities and Programs

5.3.2.2.1 Spent Nuclear Fuel Management Alternatives

In response to the Obama Administration's decision in 2010 to stop work on a repository at Yucca Mountain, DOE-Idaho developed several SNF management alternatives that address storing SNF for extended periods. DOE-Idaho submitted these alternative management plans to DOE headquarters and the Government Accountability Office (Hain 2010a). The plans include increasing cask pad storage (for example, by using the available storage space at CPP-2707) or adding modular storage, like the NUHOMS® system used at CPP-1774, at the Idaho Nuclear Technology and Engineering Center (Hain 2010a). DOE is reviewing these management alternatives and others, such as identifying technical needs and funding research and development to ensure safe extended storage (Birk 2013). Birk (2013) also indicates that "INL SNF management may change as a result of responses to recommendations from the BRC [Blue Ribbon Commission on America's Nuclear Future] and Idaho's LINE [Leadership in Nuclear Energy] Commission."

5.3.2.2.2 A Facility to Prepare Spent Nuclear Fuel for Off-site Transport

DOE recognizes that INL will need a facility to prepare all its SNF, with the exception of naval SNF, for transportation out of Idaho by the January 1, 2035, deadline stipulated in the 1995 Settlement Agreement. DOE's plans for that facility have evolved over time. From the late 1990s until 2006, DOE's proposed approach was to construct and operate a storage-only facility, called the Idaho Spent Fuel Facility. From 2006 until DOE closed its Yucca Mountain repository program in 2010 (DOE 2010b), DOE's plans—as embodied in the Idaho Spent Fuel Facility Project—focused on using the new Idaho Spent Fuel Facility, or reusing an existing facility, to first condition, characterize,[160] and package SNF for off-site transport, and then store the packaged SNF. After terminating the Yucca Mountain repository program, DOE suspended the Idaho Spent Fuel Facility Project and only recently described plans for a facility to prepare INL SNF for off-site transport (Beller 2014a). DOE's past plans illustrate potential challenges for a future facility.

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[159] The proposed and actual rates of treatment from 2014 forward are not recorded in DOE budget request documents.

[160] The terms "characterization" and "conditioning" are defined in the Memorandum of Agreement for Acceptance of Spent Nuclear Fuel and High Level Radioactive Waste (DOE 1998, 2007a). Characterization refers to the activities (*e.g.*, data collection, testing, inspection, document preparation, and analysis) needed to describe SNF and HLW adequately for acceptance, transportation, and disposal (including pre-closure and post-closure performance in the repository). Conditioning is defined as "any process which prepares or treats SNF or HLW for transportation or disposal in accordance with regulatory requirements and Office of Civilian Radioactive Waste Management acceptance criteria. This includes processing (*e.g.*, vitrification) of HLW and passivation of SNF."

Idaho Spent Fuel Facility (Late 1990s to 2006)

In response to the 1995 Settlement Agreement,[161] DOE pursued plans to construct a new dry storage facility at INL. In 2001, Foster Wheeler Environmental Corporation, a DOE contractor, applied to NRC for a 10 CFR Part 72 license to operate the proposed Idaho Spent Fuel Facility as an independent spent fuel storage installation (Rodgers 2001). The application described a vault storage facility (Figure 5-9).

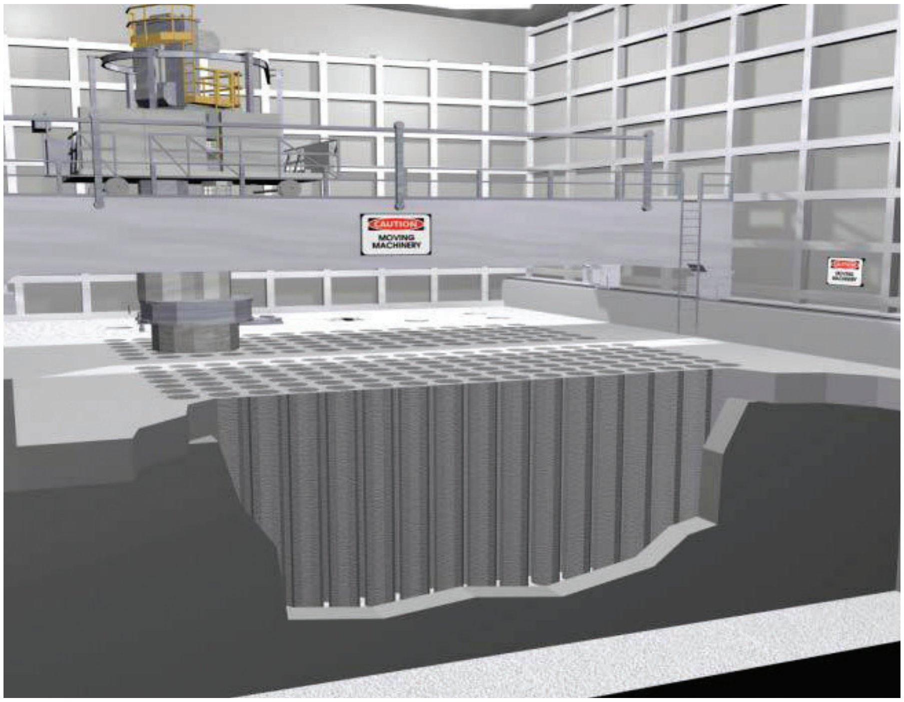

Figure 5-9. Schematic of the modular storage vault configuration for the proposed Idaho Spent Fuel Facility. The modular vault dry storage system shown in the schematic is similar to the vaults used in CPP-603 (Figure 5-4B) and at FSV (Figure 7-2 and Figure 7-3). The schematic depicts a cutaway through the concrete vault wall showing an array of vertical storage tubes, each of which would contain a fuel storage canister. At this facility, DOE planned to use an early version of the DOE standardized canister, known as the "ISF canister" as the fuel storage canister. At the back of the vault, the canister handling machine extends above the array of storage tubes (see Figure 7-3 for a comparable container handling machine and array of storage positions). (Source: Hain 2010c).

The facility would be used to store SNF and associated radioactive material from the first and second cores of the Peach Bottom 1 reactor (2.95 MTHM), fuel from the Shippingport Light Water Breeder Reactor (18.95 MTHM), and a portion of the INL TRIGA® SNF[162] (0.32 MTHM). As described in the license application, upon arrival at the proposed Idaho Spent Fuel Facility, SNF would be removed from the containers in which it was stored, visually inspected, inventoried, then placed into new storage containers that would be welded, vacuum-dried, backfilled with helium, and placed into interim storage. According to the application, "the storage containers are intended to be packaged for transportation and shipped to a repository when it becomes available" (Rodgers 2001).

In 2004, NRC issued a license[163] that allowed the proposed facility to operate until November 30, 2024. Responding to a DOE request, NRC subsequently transferred the license from Foster Wheeler Environmental Corporation to DOE (NRC 2009). Until 2015, DOE was paying NRC a license fee of approximately $200,000 per year for this storage facility, which had not been built. Since then, NRC allows DOE to maintain the license without fee payment.

Idaho Spent Fuel Facility Project (2006 to 2010)

In 2006, before starting to construct the Idaho Spent Fuel Facility, DOE modified its contract with Foster Wheeler Environmental Corporation to delete constructing the facility from the scope of the project (DOE 2007b). DOE also

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161 Section F.2 of the 1995 Settlement Agreement required DOE to seek appropriations for fiscal year 1998 "to initiate the procurement of dry storage at Idaho National Engineering Laboratory to replace wet, below ground facilities."

162 The license application anticipated that slightly more than two-thirds of the TRIGA® spent fuel inventory—about 1,100 elements out of a total of 1,600 elements—would be moved to the new facility.

163 NRC reviewed and approved an early version of the DOE standardized canister, known as the "ISF canister" (Rodgers 2001), for storage at INL (Carlsen 2014a).

tasked the contractor with developing an alternate solution for SNF conditioning and characterization—that is, capabilities beyond just storage—that would involve reusing existing facilities rather than constructing a new one (DOE 2007b).

In a feasibility level report to DOE, the contractor described a method for repackaging fuel using existing INL facilities. That information serves as a baseline to develop the conceptual design of the future facility—either reusing an existing facility or building a new one—under DOE's project management framework. After terminating its contract for the Idaho Spent Fuel Facility, in 2007, as part of its project management responsibilities, DOE completed a mission need statement[164] for the Idaho Spent Fuel Facility Project (DOE 2007b), which relied on the baseline information. The mission need statement acknowledged that aging SNF facilities at INL are at or nearing the end of their storage capacities and design lives. These facilities lack the capability to characterize, condition, and package SNF in DOE standardized canisters; to provide interim storage for packaged SNF; and to load SNF onto the transportation system for shipment to a repository by January 1, 2035.

In its 2007 mission need statement, DOE scheduled 12 years (from 2007 to 2019) to complete all critical decisions related to the facility—from approving the mission need to approving the start of operations (DOE 2007b). The mission need statement assumed that a geologic repository would begin accepting SNF from the Idaho Spent Fuel Facility by 2020 and would continue to receive Idaho SNF until 2035. Consistent with this assumption, DeLeon (2011) depicted a potential disposition pathway for INL SNF that envisioned the flow of all non-naval INL SNF through the Idaho Spent Fuel Facility (Figure 5-10). Because DOE has not proceeded with efforts for either the facility or a repository, the mission need statement schedules for developing and operating the packaging facility to allow off-site transport of all INL SNF by 2035 are not viable.

Idaho Spent Fuel Facility (2010 to 2017)

Since the mission need statement was approved in 2007, DOE has continued to rely on the Idaho Spent Fuel Facility Project as its basis for planning future management of DOE SNF at INL. For example, DOE's 10-year site plan for INL for the period 2014–2023 includes a lifecycle schedule for the Idaho Cleanup Project[165] (DOE 2012c, Figure C-1) that relies on the Idaho Spent Fuel Facility Project.

Meanwhile, the latter project has been suspended (*i.e.*, "in project management space it is not active in various reporting systems and is not currently funded"),[166] but not cancelled, and the mission need statement remains in place. This means that "there is formal agreement between the DOE Idaho Operations Office and DOE Headquarters that there is a need in Idaho that will require a capital investment in the future so that the SNF currently in Idaho will be out of the state as required by the 1995 Settlement Agreement date of January 1, 2035."[167]

The next phase of the project, when funding is available, involves analyzing alternatives for performing the SNF management functions that the Spent Fuel Facility was intended to provide. This could include reviewing the complete design for a stand-alone packaging facility and comparing it to options for renovating and reusing existing on-site facilities. According to Beller (2014a), DOE will develop and evaluate alternate fuel disposition recommendations and plans to reuse existing facilities.

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[164] DOE Order 413.3B ("Program and Project Management for the Acquisition of Capital Assets") defines the project management process, including the development of a mission need statement, and describes a number of critical decisions that must be scheduled in a project.

[165] The Idaho Cleanup Project is DOE's effort to cleanup the INL site. The lifecycle schedule for this project is similar to the schedules provided in Hanford's 2013 Lifecycle Report (DOE 2012b).

[166] *Source:* Barbara Beller, in an e-mail message to Bret Leslie, NWTRB staff, August 30, 2013, describing the status, path forward, and future planning assumptions for the Idaho Spent Fuel Facility Project.

[167] Ibid.

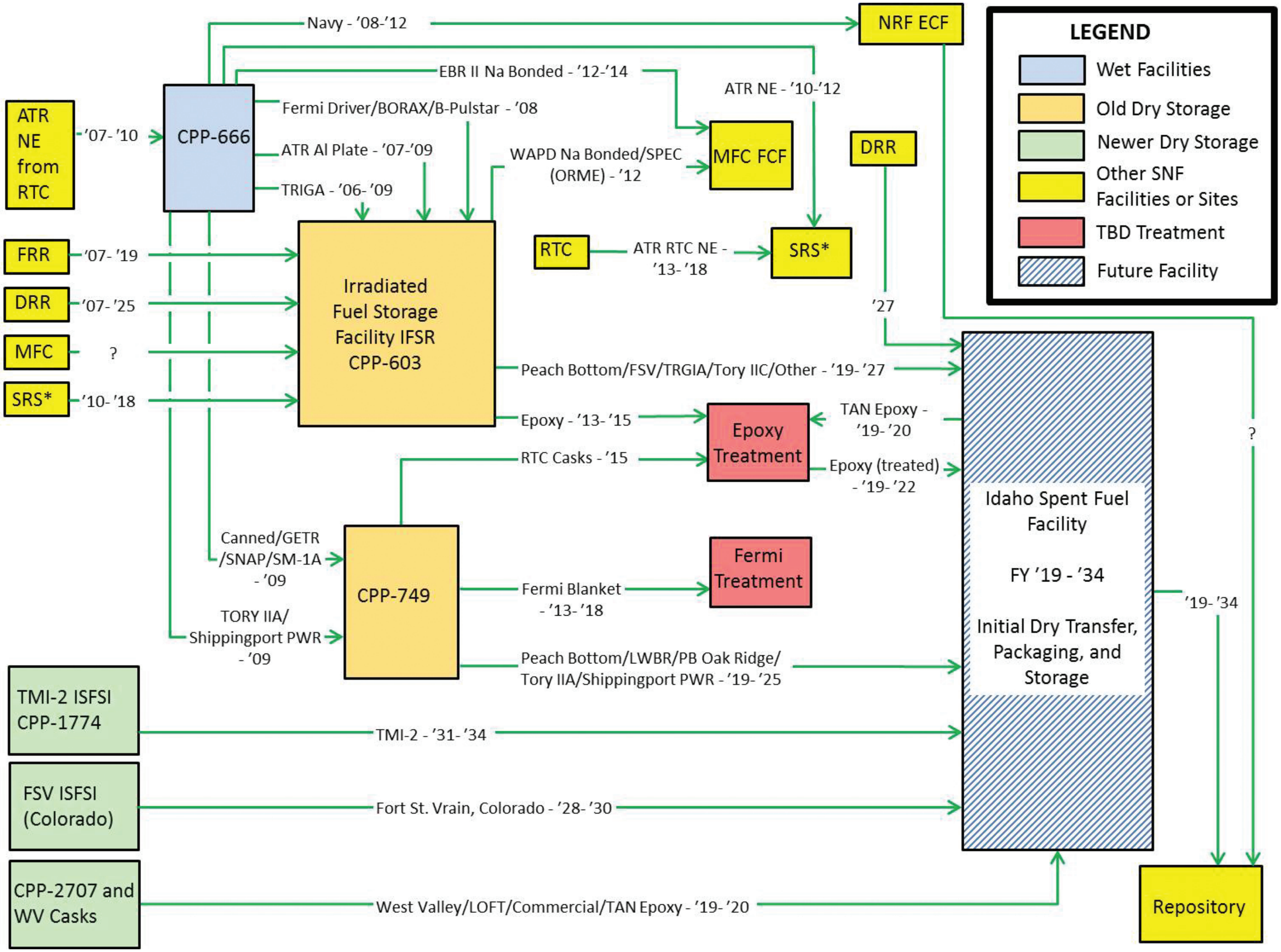

Figure 5-10. A previous disposition path for Idaho National Laboratory spent nuclear fuel.
The timing (years are denoted by two digits preceded by an apostrophe) and movement of various SNF types (abbreviations were not defined in the source document) into and out of the Idaho Spent Fuel Facility (box with diagonal blue hatches) are illustrated by segmented arrows between facilities (e.g., TMI-2 SNF from CPP-1774 would be transferred to the Idaho Spent Fuel Facility between 2031 and 2034). (Source: DeLeon 2011). The treatment method for Epoxy and Fermi is to be determined.

This effort was projected to start in 2017,[168] with the aim of completing a design report—including a cost estimate and schedule—by 2019. DOE anticipates that approval to begin construction will be granted in 2023 and that the plan to retrieve SNF for packaging will begin in 2025 (Beller 2014a). The capabilities to be provided are documented in the mission need statement and include receiving SNF from on-site facilities, fuel characterization and stabilization, packaging in DOE standardized canisters, standardized canister storage (limited to approximately 300 positions), and a load-out capability for both rail and truck transportation casks, with the casks provided by DOE-NE (Beller 2014a).

DOE Challenges for the Facility

The schedules and some of the assumptions and constraints in the mission need statement for the Idaho Spent Fuel Facility Project (DOE 2007b) are no longer valid; however, the mission need statement nonetheless illustrates the challenges DOE faces in completing a facility and transferring all SNF out of Idaho by 2035. It is no longer realistic to expect that shipments of SNF to facilities outside Idaho will commence by 2020 or 2025 and end by 2035. Such a schedule would require DOE to have either a repository or an interim storage facility outside Idaho operating in time and have a rate of SNF acceptance at a repository adequate to meet the 2035 deadline. To meet the 2035 deadline would also require that the packaging facility be able to prepare all the SNF for transport in less than nine years, compared with the original DOE (2007b) estimate of 15 years of operation. One set of operational constraints that DOE (2007b) identified for the Idaho Spent Fuel Facility in 2007 remains pertinent for any future facility and its ability to process SNF: as DOE noted in the mission need statement (2007b), "the throughput capability of the facility is dependent on the ability to retrieve fuel from existing onsite storage locations, the drying time required for the wide range of fuel types and the repository opening date."

DOE's assumption has been, and continues to be, that all fuel will be packaged in DOE standardized canisters (DOE 2007b; Beller 2014a), which haven't yet been fully developed or deployed. Furthermore, an important factor that will affect the schedule and cost for building a future facility is the availability of the neutron absorber alloy that is integral to the design of the standardized canisters (Carlsen 2014a),[169] but DOE terminated the program to develop and make advanced neutron absorber alloy prior to completing the task (Carlsen 2014a). Another assumption that will also affect the planned facility is that NRC will grant a moderator exclusion exemption for seal-welded DOE standardized canisters during transportation. This assumption may or may not be correct. In addition to these project constraints and assumptions, DOE (2007b) identified a number of factors, both internal to DOE and external to DOE, that affect the project's timing, scope, cost, and schedule. Whether the INL Spent Fuel Facility would be self-regulated by DOE or be regulated by NRC under 10 CFR Part 72 is another factor that could affect the schedule for the facility. Given plans to package SNF assemblies at the Spent Fuel Facility into DOE standardized canisters and NRC-certified transportation casks, some level of NRC oversight would be expected.

5.3.2.2.3 Constructing the Naval Reactor Facility Overpack Storage Expansion 3

As the Navy continues to ship its SNF to INL, additional dry storage capacity may be needed. DOE (2013d) plans estimated needing three years to construct the proposed Overpack Storage Expansion 3 (from fiscal years 2015 to 2018); however, to date DOE has not pursued the project and has only indicated that a third expansion may be necessary if there is no interim storage facility or geologic repository able to receive naval spent nuclear fuel by 2020 (DOE 2015b).

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[168] DOE did not request funds in fiscal year 2017 to analyze alternatives and the schedule outlined by Beller (2014a) will extend into the future.

[169] To address criticality after disposal in a repository, DOE can demonstrate that the probability of its occurrence is less than the regulatory limit or demonstrate that consequences of criticality do not affect the magnitude or time of the dose from radionuclides released from a repository (Section 3.3.3). The former approach is known as a probability approach, while the latter is a consequence approach. To date DOE has focused on limiting probability—through design requirements such as use of advanced neutron absorbers—to be less than the regulatory limit. If DOE continues to use a probability approach to address disposal criticality, then the neutron absorber alloy will be needed for any repository other than a repository in salt to ensure that regulatory limits on the probability of post-closure criticality, for a mode in which the SNF is fully degraded and the waste package is flooded, are met.

5.3.2.3 Existing Requirements That Would Affect Spent Nuclear Fuel Management

5.3.2.3.1 U.S. Department of Energy Waste Acceptance Criteria

As described in Section 3.4.1, DOE continues to rely on technical requirements detailed in the "Waste Acceptance System Requirements Document" (DOE 2008a) to manage its SNF. Because of the diversity of SNF types at INL (Hill and Fillmore 2005), meeting waste acceptance requirements (DOE 2008a) at INL will be more challenging than at other DOE sites. The following examples illustrate the challenge.

DOE will need to determine that each type of SNF meets criticality limits for repository operations (*i.e.*, pre-closure limits) and for underground disposal (*i.e.*, post-closure limits). If disposal occurs in a non-salt repository, DOE will need to package about 18% (by mass) of non-naval SNF at INL in approximately 400 DOE standardized canisters with advanced neutron absorber materials.

Some small amounts of the INL SNF contain epoxy in the form of sample mounts for metallurgical examination (Hill and Fillmore 2005). As Hill and Fillmore observed in 2005, the presence of organic material[170] in the repository was, at that time, an unanalyzed potential problem (Hill and Fillmore 2005). Beller (2007) acknowledged the need to treat SNF in an organic epoxy matrix and stated that DOE could define a procedure (*e.g.*, define a *de minimus* quantity) to ensure that epoxy-coated fuel could be accepted at the repository or otherwise define the level of treatment required. As depicted in Figure 5-10, treatment of the epoxied fuel will be necessary prior to repository disposal, [171] although the process to be used to treat this fuel has not yet been defined (DeLeon 2011).

Both the waste form and canister content requirements listed in Section 3.7 of DOE (2008a) are important considerations. For example, limiting gas generation is part of the "Waste Acceptance System Requirements Document" (DOE 2008a) canister content requirements. As described in Section 2.3.1, properly drying SNF is the critical step in determining gas generation within a sealed canister. The diversity of non-naval SNF, including about 4,000 assemblies of aluminum-based Advanced Test Reactor SNF, and the degraded nature of the TMI-2 SNF will complicate drying and packaging.

DOE did not include sodium-bonded SNF in the Yucca Mountain license application (DOE 2009a; Group 31). This SNF does not meet the waste acceptance technical requirements[172] (DOE 2008a). Unless the sodium-bonded SNF can be shown to not be regulated under the RCRA, sodium-bonded SNF disposal options need to include either physical removal or chemical deactivation of the sodium (DOE 2006). Classifying ceramic and metallic waste products from the electrochemical treatment of sodium-bonded SNF (Figure 5-8) as HLW and disposing of these wastes in a geologic repository (Simpson 2010) will require action to ensure that the waste products meet waste acceptance requirements (DOE 2008a). These waste forms may need their own DOE waste acceptance product specification, comparable to the specification for vitrified HLW forms (DOE 2012h).

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170 For example, the presence of organic materials in a repository can influence degradation of repository materials. Also, degradation of organic materials could potentially generate combustible gases, or change the chemistry of the water that contacts waste forms in ways that would affect the solubility and release of radionuclides from the waste forms. DOE analyzed these features, events, and processes and their potential impact on repository performance in 2008 (Sandia National Laboratories 2008). DOE excluded those features, events, and processes associated with organic materials by requiring that organic materials, other than trace amounts, will not be included in the sealed waste form canisters (Sandia National Laboratories 2008).

171 NRC staff accepted DOE's exclusion of those features, events, and processes associated with organic materials from the performance assessment of a volcanic tuff repository. "Furthermore, the NRC staff finds acceptable the applicant's use of repository design and controlled parameters to limit the scope of features, events and processes, as well as to define the initial states or boundary conditions of systems analyzed in the performance assessment" (NRC 2014a, p. 2-11).

172 The "Waste Acceptance System Requirements Document" (DOE 2008a) states, "The Civilian Radioactive Waste Management System shall only accept HLW and/or SNF that is not subject to regulation as hazardous waste under the Resource Conservation and Recovery Act (RCRA 1976) Subtitle C for disposal in the first geologic repository licensed by NRC under the Nuclear Waste Policy Act. Prior to acceptance for disposal, Federal Waste Custodians must determine and document that RCRA-regulated wastes are not present, and develop appropriate data to assure relevant state and/or U.S. Environmental Protection Agency (EPA) RCRA requirements are addressed."

5.3.2.3.2 U.S. Nuclear Regulatory Commission Regulations

Some of the primary regulatory requirements that DOE uses to define its waste acceptance technical criteria (DOE 2008a) are set out in applicable provisions of 10 CFR Part 63, "Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada." The definition of HLW in 10 CFR Part 63 includes a clause stating that HLW means "other highly radioactive material that the Commission, consistent with current law, determines by rule requires permanent isolation." Thus, the ceramic and metallic waste generated from sodium-bonded SNF treatment may need to be disposed of in a geologic repository.

NRC regulations for packaging and transporting radioactive material (under 10 CFR Part 71) also affect the management of DOE SNF at INL. Certificates of compliance for the TN-REG and TN-BRP rail transportation casks that store West Valley, New York SNF have expired. Systems for transporting SNF off site in the standardized DOE canister will need to be certified by NRC via 10 CFR Part 71.

NRC SNF storage regulations affect DOE SNF management at two INL facilities. First, as described in Section 5.3.2.1.1, DOE's application for NRC license renewal for the TMI-2 independent spent fuel storage installation will need to address the effects of aging on the facility and its structures, systems, and components as they relate to the safety performance of the facility. The NRC requires that these aging effects must be assessed over the current license period and over the period covered by the license renewal. To approve the renewal, NRC will require DOE to implement an aging management program that considers aging effects, prevents or mitigates aging effects, and detects aging effects through condition monitoring (*e.g.*, visual inspection of concrete structures for cracking) and performance monitoring (*e.g.*, periodic radiation monitoring). Because NRC regulations also require that the storage system must be designed to allow ready retrieval[173] of SNF for further processing or disposal, DOE will need to address retrievability of stored SNF during the period of extended operation.

Second, NRC's storage regulation, 10 CFR Part 72, also affects the Idaho Spent Fuel Facility Project. Activities that currently require an NRC license under 10 CFR Part 72 and that were identified for the Idaho Spent Fuel Facility include "repackaging of SNF into sealed canisters" and storage, but not SNF conditioning (Rodgers 2001). DOE (2007b) acknowledges that regulatory authority (DOE or NRC) for DOE SNF will be determined as the project progresses through the critical decision process; however, it is not clear that the conditioning needed to prepare INL SNF for transportation off site could be licensed under 10 CFR Part 72 requirements, which are focused on storage (Lombard 2014). Conditioning SNF—especially conditioning certain SNF types, such as epoxied SNF—is comparable to activities regulated under 10 CFR Part 70, "Domestic Licensing of Special Nuclear Material," and not 10 CFR Part 72. Clarifying which, if any, NRC regulation would apply to the Idaho Spent Fuel Facility Project is important as the approach for demonstrating compliance is substantially different between the two regulations.

5.4 Key Observations on the Management and Disposal of Idaho National Laboratory Spent Nuclear Fuel

1. DOE is required by the 1995 Settlement Agreement with the state of Idaho to remove SNF from wet storage by 2023, use multi-purpose canisters to prepare SNF for shipment and ultimate disposal outside Idaho, and remove SNF from Idaho by 2035.

2. DOE will need to build a new facility or reuse an existing one to repackage non-naval SNF into NRC-approved multipurpose canisters to meet the 2035 deadline for removing INL SNF from Idaho. The throughput capability of the

[173] NRC defines "ready retrieval as 'the ability to safely remove the spent fuel from storage for further processing or disposal.' In order to demonstrate the ability for ready retrieval, a licensee should demonstrate it has the ability to perform any of the three options below. These options may be utilized individually or in any combination or sequence, as appropriate. A. remove individual or canned spent fuel assemblies from wet or dry storage, B. remove a canister loaded with spent fuel assemblies from a storage cask/overpack, C. remove a cask loaded with spent fuel assemblies from the storage location" (NRC 2016a).

packaging facility is dependent on the ability to retrieve fuel from existing on-site storage locations; the drying time required for the wide range of fuel types, which increases as degradation of the SNF increases; the opening date for a repository or consolidated interim storage facility; and the acceptance rate of the receiving facility.

3. Managing aging SNF and SNF storage facilities is a common challenge. Both DOE-EM and the Navy identified a need for new facilities, either because existing facilities are at the end of their service lives or because existing capabilities are not sufficient to receive SNF and prepare it for off-site transport. The NRC-licensed dry storage facility at INL, which stores TMI-2 SNF, is subject to a formal program to manage age-related degradation. Other aging management programs focus mainly on storage facility aging and, in general, do not address the effects of aging SNF or the implications of SNF aging for future packaging, storage, transportation, and disposal systems.

4. DOE is not implementing a multi-purpose canister approach for non-naval SNF and needs to complete development of the DOE standardized canister. The Navy continues to remove naval SNF from wet storage, and dry and package it into the naval canisters that were designed for disposal in the Yucca Mountain repository. In contrast, DOE has stopped developing the DOE standardized canister to store, transport, and dispose of SNF at Yucca Mountain. DOE planned to use this multi-purpose canister at the Hanford Site, INL, and SRS to package all remaining non-naval disposable SNF. DOE will need to finish developing a number of standardized canister components and fabrication methods.

5. DOE-NE treats sodium-bonded driver SNF by dissolving it in a molten salt medium. This process creates two waste streams (metallic and salt) that are both considered HLW. Because DOE-NE is not a "waste custodian" and, hence, is not subject to the waste acceptance system requirements that apply to all SNF and HLW that will be disposed in a repository, the fate of these waste streams is uncertain.

6. Spent Nuclear Fuel at the Savannah River Site

The 310-square-mile Savannah River Site (SRS) is in western South Carolina, 20 miles southeast of Augusta, Georgia, and is bound by the Savannah River on its southwestern edge (Figure 6-1). In the early 1950s, SRS began producing tritium and plutonium for nuclear weapons (Savannah River Nuclear Solutions 2011a). Five reactors were used to produce these materials until they ended operations in the late 1980s. Each reactor area contained an underwater storage[174] facility known as a disassembly basin. Support facilities included two chemical separations plants and a nuclear fuel and target[175] fabrication facility. The two chemical separations plants, including one in the H area that is still operating, chemically processed spent nuclear fuel (SNF) and irradiated target assemblies to separate useful products from waste materials. These chemical separations facilities are known as "canyons."

SRS now stores approximately 30 metric tons of heavy metal[176] (MTHM) of SNF that was shipped from domestic and foreign

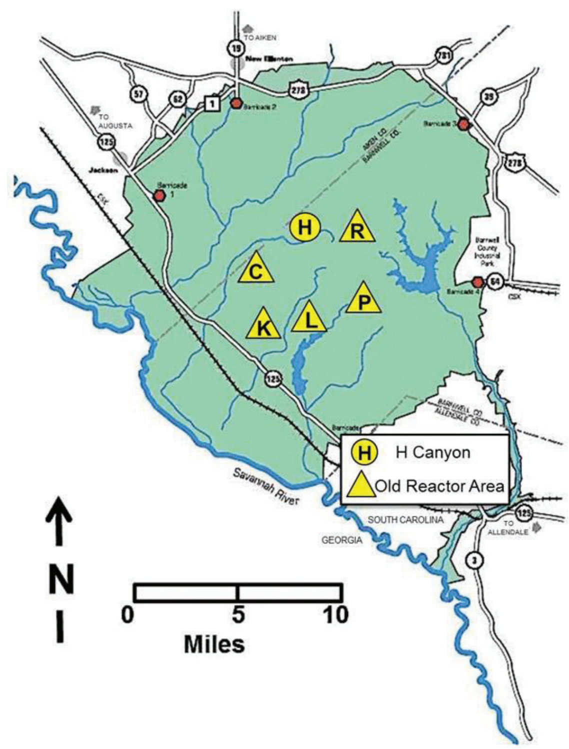

Figure 6-1. Savannah River Site map.
The L Basin SNF storage facility is at the L reactor area. The H Canyon facility processes some aluminum-based SNF that has been stored in the L Basin storage facility (Source: Savannah River Nuclear Solutions 2011a).

[174] Upon first use in this chapter, underlined terms and phrases are explained in the Glossary (Chapter 11) and abbreviations are introduced.

[175] At SRS, these targets are aluminum-clad plutonium oxide that contain significant quantities of americium and curium, which react under neutron irradiation to produce even higher atomic number elements such as californium.

[176] Metric ton of heavy metal is a commonly used measure of the mass of "heavy metal" initially present in nuclear fuel. Heavy metal refers to elements with an atomic number greater than 89 (e.g., thorium, uranium, and plutonium). The mass of other constituents of the fuel, such as cladding, alloy materials, and structural materials, are not included.

research and test reactors. The site continues to receive, inspect, and store SNF from domestic and foreign research reactors. All SNF at SRS is stored in the 105-L Basin building, which contains the L Basin (Figure 6-1). The H Canyon chemical separations plant recently completed a campaign to process "vulnerable"[177] SNF in 2014. In that campaign, the H Canyon plant processed 36 bundles of SNF from the Sodium Reactor Experiment, along with some high-aluminum, low-uranium SNF that was used to mitigate viscosity issues of the thorium-based Sodium Reactor Experiment fuel in caustic solution (Gunter 2013).

6.1 Spent Nuclear Fuel Storage Facility and Stored Spent Nuclear Fuel

6.1.1 L Basin Storage Facility

Detailed information on the L Basin facility, such as the facility's documented safety analysis, is not publicly available. Thus, some of the details provided in Chapters 4 and 5 for SNF and SNF storage facilities are not available for this chapter. Table 6-1 summarizes information about the characteristics of the L Basin storage facility, including whether the SNF will need to be repackaged for transport to a repository or an off-site storage facility. Unavailable information is depicted by a dash.

Most of the SNF at the L Basin building is stored underwater in the L Basin (Figure 6-2 and Figure 6-3) (Savannah River Nuclear Solutions 2011b). The remaining SNF is stored in two small dry storage areas in the L Basin building (Gillas 2011). Dry Storage Area 1 is in the southwest corner of the L Basin—a walled-off section of the basin—and Dry Storage Area 2 is outside the L Basin, but within the L Basin building (Gillas 2011).

Table 6-1. Characteristics of the L Basin storage facility

Type of Storage (1; see Notes)	Storage Containers and Arrangement	Need to Repackage	Storage Capacity (1)	Currently in Storage	Design Life of Facility and Package	Authorized Storage Ends in Calendar Year
Dry Storage Area 1 (1)	Metallic barrels placed on floor	Yes	27	23	–	Reviewed each year
Dry Storage Area 2 (1)	Metallic barrels placed on floor	Yes	16	16	–	Reviewed each year
Dry Cave in L Basin (wet) (1)	None	Yes	150	0	–	Reviewed each year
Vertical bundle storage (wet) (2)	Aluminum tube (bundle); one tube per rack position	Yes	3,650 rack positions	3,165	–	Reviewed each year
High Flux Isotope Reactor racks (wet) (2)	Full cores contained in metallic racks	Yes	120	120	–	Reviewed each year
Bucket storage (wet) (3)	Variety of stainless steel containers open at the top	Yes	50	14	–	Reviewed each year
Oversized can racks (wet) (3)(4)	Cans within aluminum oversized isolation cans	Yes	42	23	–; most inner cans are 50 years old	Reviewed each year

Notes
(1) Gillas (2011).
(2) Maxted (2012) updates the capacity and Maxted (2013a) presents the inventory as of September 30, 2013.
(3) Gillas (2011) describes capacity and Sindelar and Deible (2011) provide details of storage containers.
(4) Winokur (2013) describes both the variety and the design details of cans of stored uranium and thorium metal SNF.

[177] Vulnerable SNF is that SNF at SRS that is deemed less likely to resist degradation in long-term, wet storage. For example, vulnerable fuel is bare metal fuel with a sealed can providing a single barrier from basin water (Rose 2013).

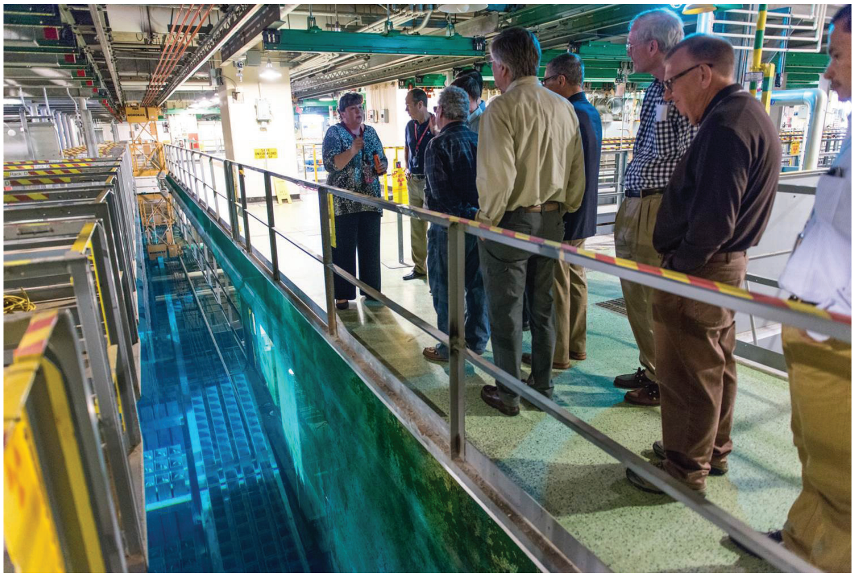

Figure 6-2. L Basin storage facility.
U.S. Nuclear Waste Technical Review Board (Board) members and staff, along with U.S. Department of Energy (DOE) and SRS staff, tour the L Basin facility. Degraded vinyl sealer along the inside wall of the pool and vertical tube storage racks containing bundles of SNF are visible in the unlined concrete basin as well as the ceiling-mounted rail system (along the length of the pool and the red-tipped rails to the left) used to move SNF through the L Basin.

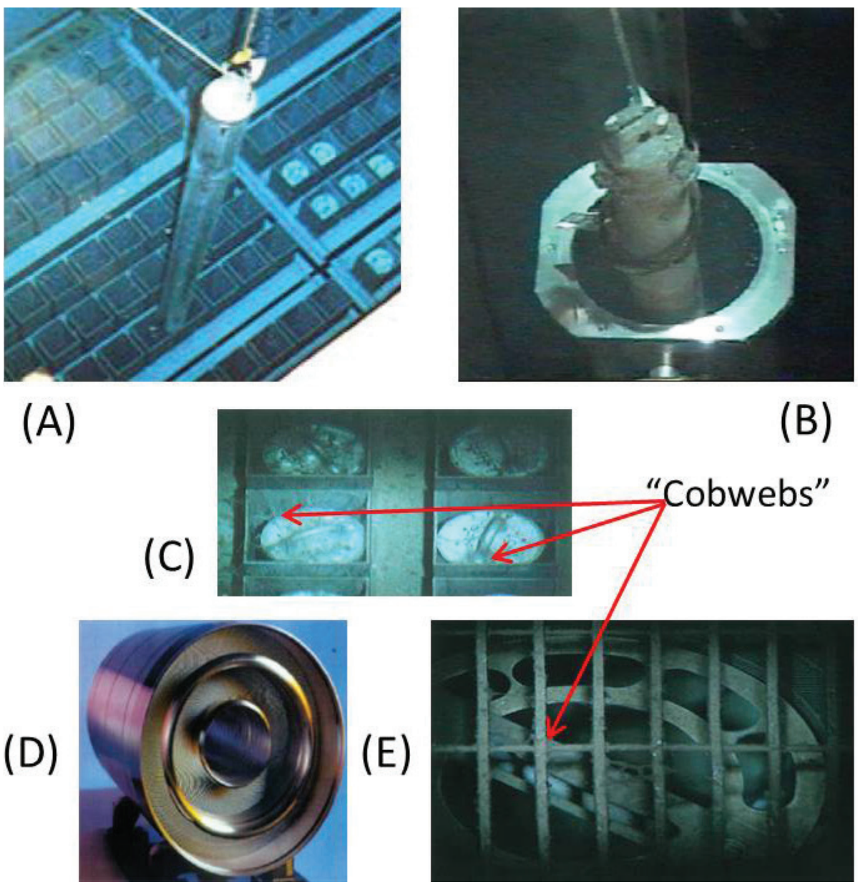

Figure 6-3. L Basin spent nuclear fuel storage.
A. Bundle of SNF assemblies being inserted into a vertical tube storage rack. (Source: Maxted and Eisele 2013). B. Inner fuel can is placed in an oversized L isolation can. (Source: Maxted and Eisele 2013). C. "Cobwebs" of bacterial growth on top of fuel bundles. (Source: Maxted and Eisele 2013). D. Core (length 31.5 inches) of High Flux Isotope Reactor fuel. (Source: Maxted and Eisele 2013). E. Web-like structures at the High Flux Isotope Reactor SNF storage location. (Source: Maxted 2012).

L Basin is a reinforced concrete structure, 160 feet by 130 feet (according to its plan dimensions), with walls that are 2.5 to 7 feet thick (Maxted 2014a). It holds a water volume of 3,375,000 gallons (Sindelar and Deible 2011). The basin is divided into seven interconnected sections from 17 to 50 feet deep that are configured for SNF storage (Sindelar and Deible 2011). The structure is also divided into an upper (North) and lower (South) basin. Most of the upper basin is 30 feet deep and includes the vertical tube storage (Figure 6-2 and Figure 6-3A), dry cave basin, machine basin, and emergency basin areas (Sindelar and Deible 2011). The vertical tube storage area stores bundles of SNF. Most of the lower basin is 17 feet deep and includes the horizontal bundle and bucket storage, monitor basin, and transfer bay areas (Sindelar and Deible 2011). Three storage arrangements in the horizontal bundle and bucket storage area accommodate High Flux Isotope Reactor racks, bucket storage, and oversized can racks.

The L Basin is not lined with stainless steel that could serve as a barrier to leaks, and it does not have a leak detection system. SNF from the L Reactor, which operated from the mid-1950s to the early 1980s, was discharged to the L Basin for cooling prior to shipment to one of the two SRS chemical separations facilities.

The L Basin was drained, inspected, and resealed with a vinyl sealer painted on the basin's inside surface in the 1980s (Sindelar and Deible 2011) to prevent concrete degradation. In 2004, the sealer showed evidence of blisters, peeling, and decomposition, and contractors determined that it was degraded beyond its useful life (Sindelar and Deible 2011). Visual inspection of the external surfaces of the basin walls shows that water historically has migrated through the walls in several locations (Sindelar and Deible 2011).

Soluble salts dissolved in the water (from radioactive materials such as cesium-137 in the basin water and chemical constituents leached from the concrete) left salt deposits on the exterior surfaces of the walls, which take the form of evaporative salts or stalactite-type formations (Sindelar and Deible 2011). The rate of water dripping from the stalactites has continually decreased since dripping was initially recorded in 2005 (Sindelar and Deible 2011).

Sindelar and Deible (2011) evaluated the condition of SNF storage in the L Basin, including the structures, systems, and components necessary for safe SNF wet storage, as well as present programs and storage practices for SNF management that would allow an additional 50 years of storage. Sindelar and Deible (2011) determined that characteristics of the SNF itself (*e.g.*, corrosion rates) and of the systems used to store the SNF are essential for extended safe SNF storage. They also found that the water chemistry control system, further described by Rose (2014a), and the basin structure are essential for safe storage in the L Basin. Sindelar and Deible (2011) identified activities necessary to validate the technical bases for, and verify the condition of, the SNF and the structures, systems, and components under long-term wet storage. Their conclusion in 2011 was that "the fuel can be stored in L Basin, meeting general safety functions for fuel storage, for an additional 50 years and possibly beyond contingent upon continuation of existing fuel management activities and several augmented program activities" (Sindelar and Deible 2011).

6.1.2 Stored Spent Nuclear Fuel

"Test SNF from SRS and commercial domestic reactors" (Sindelar and Deible 2011), research SNF from foreign and domestic reactors, and targets are stored in the L Basin facility (Table 6-2; Maxted 2014a). DOE (2000c) sorted the SNF types into two groups ("aluminum-based SNF" and "non-aluminum-based SNF") and assessed the technologies that could be used to treat these groups. Because there are more than 30 types of SNF in each group, Table 6-2 describes only those fuel types that account for the largest quantities of stored SNF within each group. The current SNF inventory at the L Basin facility includes 23 of the 34 fuel groups defined by DOE (Figure 6-4 and Appendix 1). Figure 6-4 also depicts the number of DOE standardized canisters[178] needed to package DOE SNF in for the depicted fuel groups. Approximately 10 of the 30 MTHM of SRS SNF are of commercial origin.

DOE uses the term "aluminum-based SNF" for aluminum-clad, uranium oxide SNF, aluminum-clad, uranium-aluminum alloy SNF, and declad fuel stored in aluminum cans. The aluminum-based fuels primarily consist of fuel assemblies from material test reactors (DOE 2000c). These assemblies come to SRS from more than 10 countries[179] under the foreign research reactor program and from more than 10 research reactors in the United States under the domestic research reactor program

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[178] The Board adopts the DOE's nomenclature for this canister even though it is not standard by any conventional definition. The DOE standardized canister is a canister system that consists of four cylindrical stainless steel canisters with two different diameters (18 inches and 24 inches) and two different lengths (10 feet and 15 feet; Figure 2-9). The different sizes and eight internal basket designs of the multi-purpose canisters accommodate the wide dimensional variability of non-naval DOE SNF.

[179] Approximately 4,500 foreign material test reactor assemblies (totaling approximately 5 MTHM) have been received at SRS and Idaho National Laboratory (INL) from 32 countries. Aluminum-based SNF assemblies are received at SRS and remaining assemblies are sent to INL.

(DOE 1996b). Aluminum-based SNF comes in various configurations, including rods, plates, and rings (Triay 2011). The length of the rods varies from 3 to 10 feet. There are approximately 13,000 assemblies of aluminum-based SNF at SRS.

Table 6-2. Characteristics of stored spent nuclear fuel and targets

SNF Source	Description (1; see Notes)	Amount MTHM	Initial Enrichment, Percent U-235	Burnup, MWd/ MTHM (2)	Storage System
Foreign and domestic research reactors; test reactors; and other reactors	Al-based; Al-clad uranium oxide, Al-clad uranium-aluminum (3)	~10 (4)	Up to 93 (5)	Up to 300,000	4 or 5 material test reactor assemblies per aluminum tube in vertical tube storage (bundle); ~13,000 assemblies
Research and test reactors (1)	Non-Al-based; Zirc-clad, stainless steel–clad, and declad thorium and uranium oxide, uranium-zirconium (3)	~20	Various; including depleted (<0.717) and natural (0.717)	Various	Various, including oversized isolation cans; ~2,000 assemblies
Higher actinide targets	Al-clad, plutonium oxide (3)	<0.1	Not applicable	Some irradiated, some un-irradiated	Wet (unknown storage container type); 200 targets

Notes
(1) Rose (2013) and DOE (2000b).
(2) Megawatt-day (MWd) per metric ton of heavy metal (MTHM).
(3) Aluminum (Al).
(4) Aluminum-clad SNF being processed in H Canyon is not included in the amount column.
(5) The enrichment of the uranium ranges from 5% to 93% with an average of approximately 50% (Triay 2011).

SRS stores more than 30 types of "non-aluminum-based SNF" (Sindelar and Deible 2011; DOE 2000c, Appendix C), which includes approximately 2,000 assemblies of non-aluminum-clad SNF. The non-aluminum-based SNF includes zirconium-clad and stainless steel–clad SNF. Zirconium-clad test assemblies from the Heavy Water Components Test Reactor account for about one-third of the non-aluminum-based SNF. The uranium in the Heavy Water Components Test Reactor SNF was primarily un-enriched and the fuel was uranium metal, uranium-zirconium, uranium oxide, or uranium-molybdenum (Andes and Spieker 2003).

In the late 1950s and early 1960s, DOE cut most of the Heavy Water Components Test Reactor fuel assemblies into pieces as part of its post-irradiation examination process (Winokur 2013). The fuel pieces were initially placed in sealed aluminum cans and subsequently stored at four separate wet storage locations, and sometimes repackaged into new types of storage containers at their new location: until 1964, the fuel pieces were stored in the R Basin; from 1964 to 1969–1970,[180] they were stored in the P Basin; from 1969–1970 to 1997–2003, they were stored in the Receiving Basin for Offsite Fuel; and most recently, they have been stored in the L Basin.

In the P Basin, observers noticed gas bubbles[181] being released from vented cans and increases in basin radioactivity as storage of vented cans continued (Andes and Spieker 2003). Gas bubbles continued to be released even after repackaging the cans into oversized cans at the Receiving Basin for Offsite Fuel (Winokur 2013).

DOE observed cracked inner cans and corrosion products in the bottom of oversized cans when the SNF was repackaged again to prepare for shipment to the L Basin (Winokur 2013). Gas bubbles continued to be released after the repackaged

[180] Transfers from one pool facility to another occurred over multiple years.

[181] Water can react with metal fuel to form an oxide and release hydrogen gas, and radiolysis of water can generate hydrogen.

oversized isolation cans[182] were moved into the L Basin (Rose 2013), suggesting that this type of SNF has been corroding since the mid-1960s[183] (Andes and Spieker 2003).

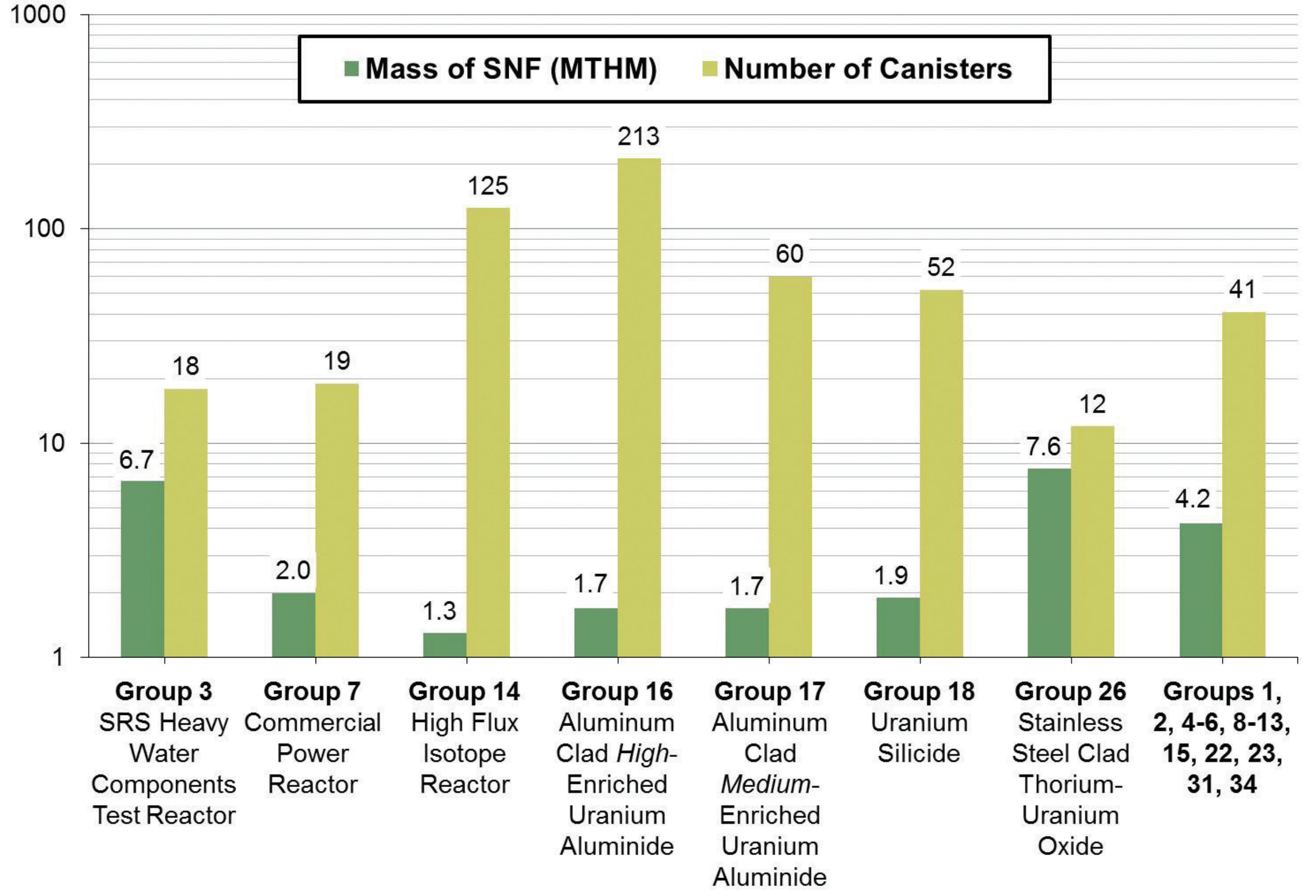

Figure 6-4. Mass of spent nuclear fuel at Savannah River Site by spent nuclear fuel group and estimated number of multi-purpose canisters to be transported to a repository.
Mass of DOE SNF in MTHM and estimated number of needed DOE standardized canisters by DOE SNF group (Table A1-1 and Table A1-2). Dominant SNF source or fuel type at SRS in fuel Groups 3, 7, 14, 16, 17, 18, and 26 is listed.

6.2 Agreements and Decisions That Affect Spent Nuclear fuel Management

6.2.1 Agreements

Unlike Hanford, INL, and Fort St. Vrain, SRS is not subject to any legal agreements that affect SNF management. Nonetheless, DOE has a 1980 agreement with the state of South Carolina that addresses SNF shipments.

The 1980 agreement between the state of South Carolina and DOE comprises the "Principles of Understanding" (Maxted 2013a) and acknowledges the need for mutual cooperation to safely transport radioactive waste. The "Principles of

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182 The oversized isolation cans are designed with a "J" vent to prevent radionuclide releases to the basin.

183 In 2015, the Defense Nuclear Facilities Safety Board followed up its previous report (Winkour 2013). It noted that "beyond the processing of the Sodium Reactor Experiment spent nuclear fuel (completed in 2014), no significant actions have been taken by Savannah River Site personnel to address the reactive metal fuels stored in L Basin" (Connery 2015). As described in Winkour (2013), "these fuels are not stored in a robust configuration and continue to degrade" (Connery 2015). The fundamental conclusion of Winkour (2013) remains valid: "Further attention to the disposition of the other vulnerable fuel types remaining in the L Basin is warranted" (Connery 2015).

Understanding is the mechanism that notifies South Carolina Department of Health and Environmental Control of the wastes and SNF … coming into and out of SRS" (Maxted 2013a). The 1980 agreement applies to all shipments of radioactive waste (including SNF), by or for DOE, and to or from any waste disposal or storage site located in South Carolina. DOE reports annually to the South Carolina Department of Health and Environmental Control on its shipments.

6.2.2 Records of Decision

Four records of decision arising from three DOE National Environmental Policy Act (U.S. Congress 1969) efforts affect SNF management at SRS. The first record of decision is associated with the programmatic SNF environmental impact statement (EIS; DOE 1995a). The second record of decision is associated with a proposed nuclear weapons nonproliferation policy on foreign research reactor SNF EIS (DOE 1996e). The third and fourth records of decision address the SRS SNF management EIS (DOE 2000c), which evaluates alternatives for storage and disposition of the SNF and target material that SRS manages.

6.2.2.1 Programmatic Spent Nuclear Fuel Management

DOE's record of decision (DOE 1995b) for the SNF management programmatic EIS was to consolidate SNF regionally by type. The record of decision indicated that SRS would store all aluminum-clad SNF, and that it could receive a total of 1,715 shipments of aluminum-clad SNF by 2035, including 400 shipments from universities and over 800 shipments from foreign research reactors (DOE 1995b, Table 3.1). Under this record of decision, SRS would send 121 shipments of SNF, including all existing SRS non-aluminum-clad SNF, to INL (DOE 1995b). Conversely, INL would send all its aluminum-clad SNF to SRS in 114 shipments (DOE 1995b). DOE's 1995 record of decision was amended in 1996 (DOE 1996a) to reflect the limitations of the 1995 Settlement Agreement (Idaho *et al.* 1995).

6.2.2.2 Foreign Research Reactor Spent Nuclear Fuel

DOE's revised record of decision for a proposed nuclear weapons nonproliferation policy concerning foreign research reactor SNF (DOE 1996b) also affects SNF management at SRS. In 1996, the policy applied only to aluminum-based and TRIGA® (Training, Research, Isotopes, General Atomics) foreign research reactor SNF as well as target material containing uranium enriched in the United States. Under this policy, aluminum-based foreign research reactor SNF (totaling approximately 18.2 MTHM) and target material (totaling approximately 0.6 MTHM) would be transported to and managed at SRS. DOE revised the 1996 record of decision multiple times, extending the deadline for fuel acceptance to its current deadline of 2019 (DOE 2008c). DOE then amended its policy to allow the United States to transport up to 1 MTHM of Gap Material SNF[184] from foreign research reactor locations to the United States. The Gap Material SNF was to be stored at SRS pending disposition (DOE 2009b). Under the amended policy, DOE is to bring the material to SRS "if the material poses a threat to national security, is susceptible for use in an improvised nuclear device, presents a high risk of terrorist threat, and has no other reasonable pathway to assure security from theft or diversion" (DOE 2009b).

6.2.2.3 Spent Nuclear Fuel Management at Savannah River Site

In 2000, DOE issued a final EIS and record of decision on managing 48 MTHM of aluminum-based SNF and 20 MTHM of non-aluminum-based SNF at SRS (DOE 2000b, 2000c). The decision also reflected projections of the amount of SNF that SRS could receive in the future. DOE (2000c) divided all the SRS SNF into groups and identified treatment options for each type of SNF within each group. DOE expected to dispose of its aluminum-based SNF in a geologic repository after treatment or packaging. Three specific decisions are contained in DOE's record of decision (DOE 2000b), which

[184] The U.S. National Nuclear Security Administration defined the term "Gap Material SNF" (DOE 2009b) as "a category of material currently in foreign countries that presents a potential threat to nonproliferation goals and may not have adequate safe and secure management options; it is referred to as Gap Material SNF consisting of SNF containing non-U.S.-origin highly-enriched uranium and SNF containing U.S.-origin highly-enriched uranium that was not addressed in the proposed nuclear weapons nonproliferation policy concerning foreign research reactor SNF EIS." Gap Material SNF is expected to consist of aluminum-based fuel configured as plates, concentric tubes, pins, rods, annular designs, or other forms.

address managing aluminum-based SNF (Section 6.2.2.3.1), conventional processing of unstable SNF (Section 6.2.2.3.2), and managing higher actinide targets (Section 6.2.2.3.3). In reaching these decisions, DOE considered numerous factors, including “the paramount goal that the processes and facilities used to prepare aluminum-based SNF for disposal in a geologic repository be cost-effective and present only low risks to workers and the public” (DOE 2000b).

6.2.2.3.1 Aluminum-based Spent Nuclear Fuel Management

To support its EIS, DOE completed a technical assessment of “melt-and-dilute”[185] preparation for direct disposal technologies (Westinghouse Savannah River Company 1998). Based on its EIS (DOE 2000c), DOE decided (DOE 2000b) to develop and demonstrate a melt-and-dilute technology to manage approximately 28.6 MTHM of aluminum-based SNF. For the remaining mass of aluminum-based SNF, DOE decided to use conventional aqueous processing (that is, make use of the existing canyons; Section 6.2.2.3.2). DOE stated that it would ensure conventional processing facilities[186] are continuously available at SRS until the melt-and-dilute technology is implemented. As a back-up to melt-and-dilute, DOE stated it will also continue to evaluate the new packaging treatment technology’s “prepare for direct disposal/direct co-disposal” option[187] and will pursue implementation of this option if melt-and-dilute is not feasible (DOE 2000b). DOE defined the outcome for both the melt-and-dilute and the new technology options as having SNF in a road-ready condition[188] for transportation off site (DOE 2000c).

6.2.2.3.2 Conventional Processing of Unstable Spent Nuclear Fuel

Conventional processing (Figure 6-5) is a chemical separations process that involves dissolving SNF in nitric acid and separating fission products from uranium using solvent extraction. Most SNF (*e.g.*, commercial SNF) has cladding that does not dissolve, which requires that SNF elements are chopped into pieces to allow the SNF inside the cladding to react with the acid. H Canyon was designed to process aluminum-clad SNF (Savannah River Nuclear Solutions 2012) without the use of a chopper because the aluminum cladding and aluminum-based fuel dissolves. Instead, the aluminum-based SNF is placed directly into a dissolver.

DOE (2000b) decided to use conventional aqueous chemical processing to stabilize the remaining aluminum-based SNF (12.4 MTHM) before a new treatment facility (such as a melt-and-dilute facility) was in place. The liquid HLW from processing is then converted into a glass waste form that remains stable during storage. This decision allowed DOE to stabilize materials of a form or of a type that posed a heightened probability of releasing fission products in wet storage, including SNF from the Sodium Reactor Experiment.

6.2.2.3.3 Management of Higher Actinide Targets

DOE evaluated treatment options for higher actinide targets and decided to continue storing the higher actinide targets in pools until a determination is reached concerning their final disposition.

6.2.2.3.4 Shipment of Spent Nuclear Fuel to Idaho National Laboratory

DOE (2000b) also reaffirmed its previous decision (DOE 1996a) to ship 20 MTHM of non-aluminum-based SNF to INL; however, the decision to ship this SNF to INL is on hold (DeLeon 2011).

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185 In the melt-and-dilute option, fuel assemblies would be melted and diluted with depleted uranium, with the resulting ingots placed in a disposable canister. This option addressed disposal criticality concerns, which existed at that time, for high-enriched aluminum-based SNF.

186 Conventional processing at SRS could treat all aluminum-based SNF, but the rate of treatment has been slow. At SRS, conventional processing dissolves the aluminum-based SNF and creates liquid high-level radioactive waste (HLW; Figure 6-5).

187 In 2000, the technology that would be needed to address disposal criticality associated with the direct disposal of high-enriched SNF in a geologic repository was not available. Subsequent technology development led to advanced neutron absorbers (Section 2.3.2) that would allow direct disposal of high-enriched SNF.

188 The term “road ready” was not tied to a date, but it was tied to the availability of a geologic repository for disposal (DOE 2000c). The EIS evaluated management alternatives through 2035; for example, it calculated the number of road-ready canisters that would be needed from 1998 to 2035.

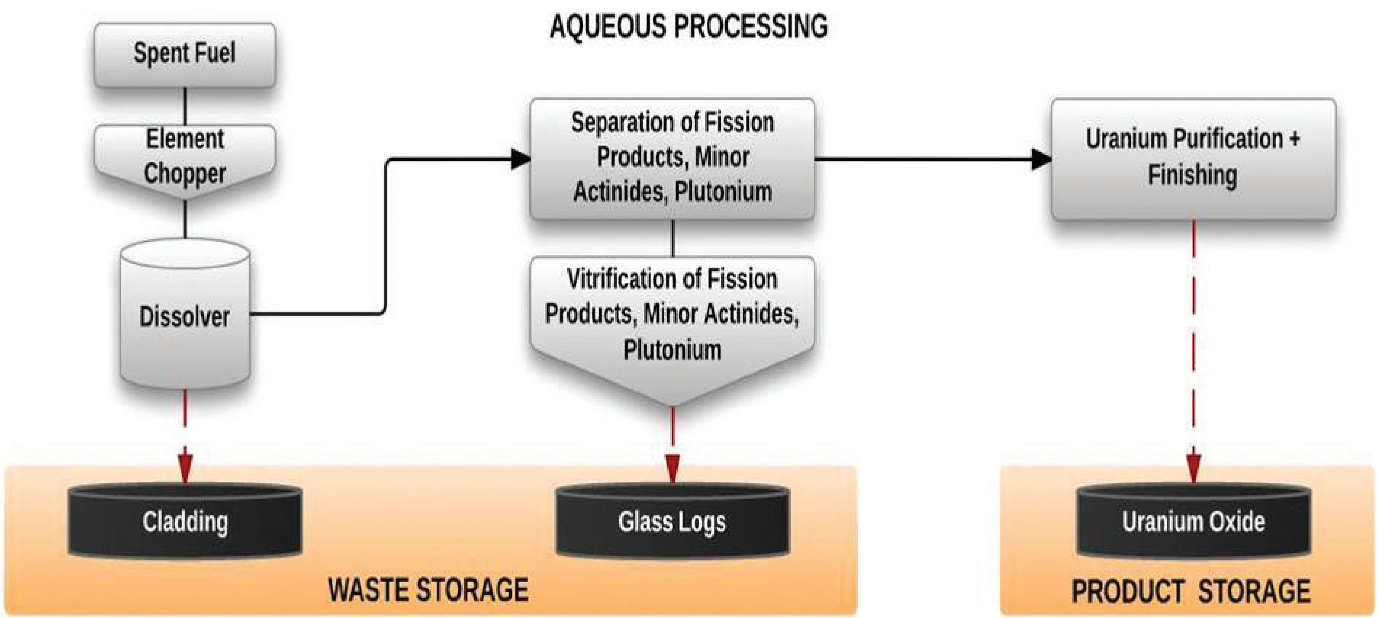

Figure 6-5. Conventional aqueous processing of spent nuclear fuel.
In conventional aqueous processing, a chopper is used to cut the fuel so that the fuel inside the cladding is exposed to the solution in the dissolver. Conventional aqueous processing has been applied to commercial SNF, in which case the cladding (*e.g.*, zirconium-based alloys; Table 2-1) does not dissolve. In the aqueous process used at SRS, there is no SNF element chopper because the aluminum cladding and fuel are dissolved, so there is no cladding materials storage. To process non-aluminum-based SNF in the H Canyon facility, DOE would need to add an element chopper to the facility, which would be a major design and facility change.

6.2.2.3.5 Amended Record of Decision

In 2013, DOE amended its previous record of decision for managing SNF at SRS (DOE 2000b), indicating that it did not implement the melt-and-dilute option due to technical issues involving the off-gas system and funding constraints (DOE 2013i). In the amended record of decision, DOE (2013i) revised its approach to use conventional processing at the H Canyon facility to manage 3.3 MTHM of the projected 28.6 MTHM of aluminum-clad SNF that was previously designated for treatment using the melt-and-dilute technology (DOE 2013i).

According to DOE, "3.3 MTHM is the minimum amount of SNF necessary to avoid the need for costly modifications to the L Basin[189] that would allow DOE to accommodate expected receipts of SNF for the foreseeable future" (DOE 2013i). This amount includes up to 200 High Flux Isotope Reactor cores generated at Oak Ridge National Laboratory and approximately 1,000 bundles of aluminum-clad SNF that currently are being stored at SRS, as well as target processing residue materials containing enriched uranium. DOE anticipated that processing this SNF and target residue material would begin as early as 2014, following Sodium Reactor Experiment SNF processing, and continue for approximately four years (DOE 2013i). The anticipated processing time was based, in part, on the HLW system being able to accept 300,000 gallons of waste per year. Due to reductions in funding for the HLW system, the amount of waste that can be accepted has been reduced, and SNF processing is expected to take longer than the previously anticipated four years (Gunter 2014). High-enriched uranium recovered during processing will be down-blended to produce low-enriched uranium suitable for use by commercial reactors.

[189] DOE would need to build new racks and rerack a large fraction of the pool to be able to accommodate the large volume of High Flux Isotope Reactor cores and the anticipated shipments of materials test assemblies.

6.3 The Path Forward for Managing and Disposing of Spent Nuclear Fuel

6.3.1 Changes to the Spent Nuclear Fuel Inventory

The inventory of SNF stored at SRS is expected to increase as material continues to be received by the facility through five anticipated mechanisms (Figure 6-6). First, DOE plans to process 3.3 MTHM of aluminum-based SNF from the L Basin in H Canyon, which it anticipated would occur between 2014 and about 2018 (DOE 2013i; Rose 2014b; Section 6.2.2.3.5).

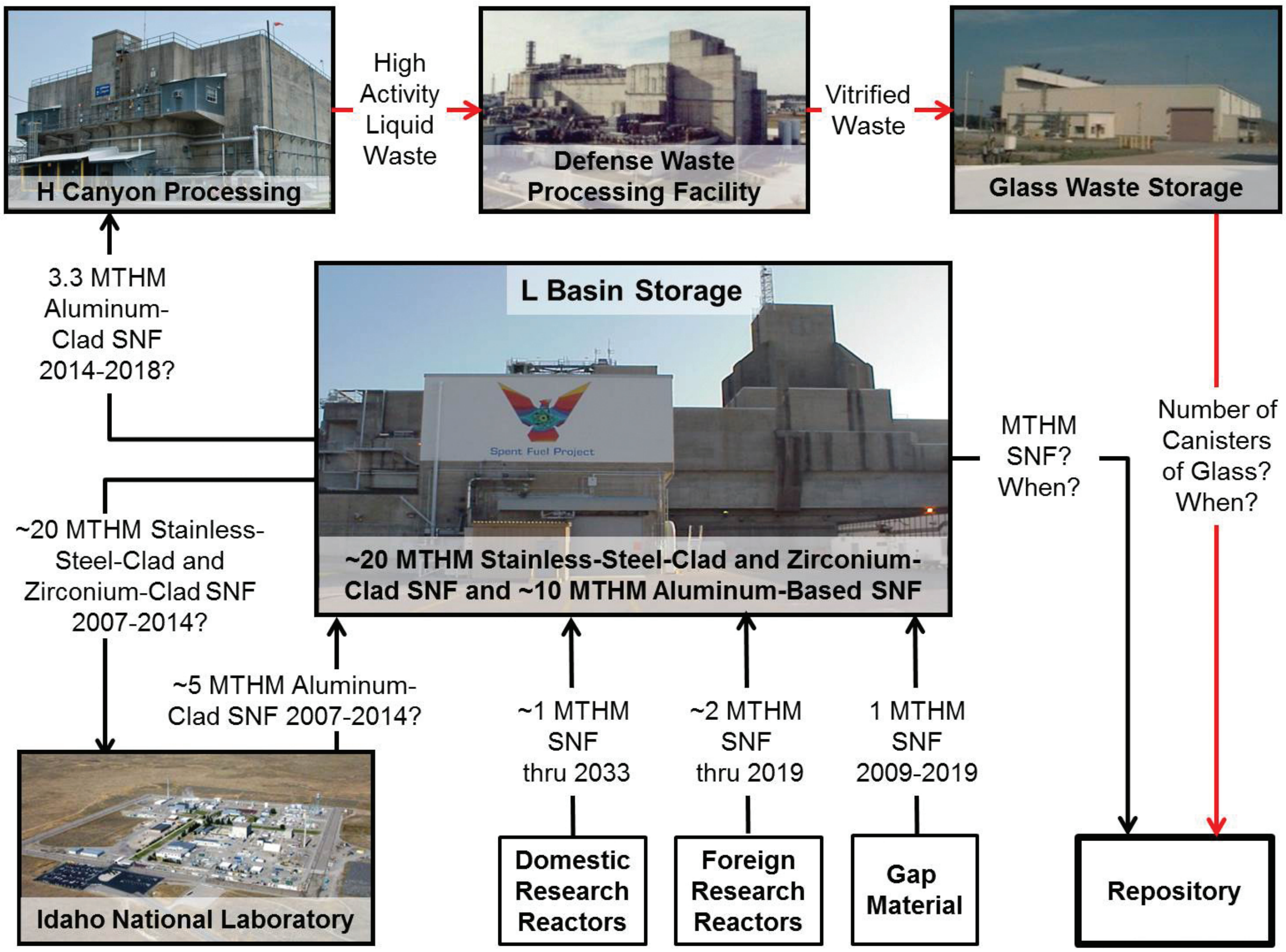

Figure 6-6. Planned changes in the inventory of spent nuclear fuel at Savannah River Site.
Black arrows denote movement of SNF between facilities, while red arrows denote movement of HLW between facilities. Question marks associated with movement between facilities of SNF or HLW reflect uncertainties in the dates of planned transfers of SNF between INL and SRS, the duration of the processing campaign in H Canyon for 3.3 MTHM of aluminum-clad SNF, and the dates and amounts of SNF and HLW canisters that will be sent to a repository. The amount of SRS SNF that is sent to a repository is a function of how much more processing of aluminum-based SNF DOE conducts at H Canyon and whether DOE's planned exchange of SNF with INL occurs.

Second, SRS anticipates receiving 400 domestic research reactor assemblies between February 2013 and May 2019 (Rose 2013), with a total of 1,067 assemblies to be received prior to 2033 (Rose 2014b). These receipts would increase the inventory in the L Basin by about 1 MTHM. Third, SRS anticipates receiving 2,121 assemblies from foreign research reactors through May 2019 (Rose 2014b; DOE 2008c). These additions are expected to increase the inventory in the L Basin by about 2 MTHM. Fourth, SRS could receive about 1 MTHM of Gap Material SNF in the L Basin prior to 2019. This material includes assemblies from the Canadian National Research Universal and National Research Experimental reactors

(Rose 2014b; DOE 2009b). Finally, in 1996, DOE (1996a) decided to ship 20 MTHM of non-aluminum-clad SNF to INL, while INL would ship about 5 MTHM of aluminum-clad SNF to SRS. While DOE originally planned for the shipments to occur between 2007 and 2014 (DOE 2000c), the transfers have not been implemented. Further, DOE placed the planned shipments on hold until after the President's Blue Ribbon Commission on America's Nuclear Future issued its recommendations on disposition (DeLeon 2011). DOE's decision to implement the exchange is still on hold and DOE plans to store non-aluminum-clad SNF in the L Basin indefinitely (DOE 2013h).

6.3.2 Proposed Actions That Would Affect Spent Nuclear Fuel Management

6.3.2.1. H Canyon Operations

In accordance with the National Defense Authorization for fiscal year 2001 (U.S. Congress 2000), the Secretary of Energy is required by law to "continue operations and maintain a high state of readiness" at the H Canyon facility. In September 2014, DOE began processing 3.3 MTHM of aluminum-based SNF from the L Basin in H Canyon; DOE plans to continue processing this material for up to eight years (Gunter 2014). DOE will install a third dissolver in H Canyon "in order to cost effectively use H Canyon and expeditiously complete the mission" (DOE 2013i). Processing the approximately 3.3 MTHM of SNF and target residue materials in H Canyon will result in plutonium-bearing HLW. This waste will be vitrified in the Defense Waste Processing Facility at SRS. Processing 3.3 MTHM of SNF will create up to about 24 canisters of vitrified HLW (DOE 2013i).

6.3.2.2 Foreign and Domestic Research Reactor Spent Nuclear Fuel and Gap Material Spent Nuclear Fuel Programs

SRS will continue to accept foreign and domestic research reactor SNF and gap material SNF. The programs for foreign research reactor and gap material SNF expire in 2019 (DOE 2008c, 2009b). The program for accepting domestic research reactor SNF at SRS extends through 2035 (DOE 1996a). DOE will modify L Basin facilities to accommodate receiving SNF from the Canadian National Research Universal and National Research Experimental reactors (Rose 2014b).

DOE analyzed the number of vertical tube storage positions that would be filled each year out to 2033, taking into account expected receipts from the domestic and foreign research reactor programs and processing 3.3 MTHM of SNF in H Canyon (Maxted 2013a). In the most probable scenario, there will be a maximum of about 800 unfilled vertical tube storage positions in the L Basin. To accommodate planned shipments of aluminum-clad SNF from INL, additional vertical tube storage racks would need to be placed in the L Basin or additional quantities of aluminum-clad SNF would need to be processed in H Canyon (Maxted 2013a) to remove SNF that is now in L Basin. DOE also assessed the availability of storage space in the L Basin for High Flux Isotope Reactor cores (Rovira 2014). DOE expects the High Flux Isotope Reactor to produce a total of 240 cores (Rovira 2014), and that DOE will need to process at least 120 cores in its new processing campaign to accommodate future receipts from this reactor.

6.3.2.3 Potential Disposition Options for Spent Nuclear Fuel

In its EIS on SNF management at SRS, DOE identified seven technologies that could be used to prepare SNF for disposition (DOE 2000c). DOE consolidated these technologies into three groups: (1) new packaging technologies (*e.g.*, to prepare for direct disposal); (2) new processing technologies; and (3) conventional aqueous processing technologies. DOE chose the new, at that time, melt-and-dilute processing technology for about 60% of the mass of aluminum-based SNF at SRS and conventional processing for the remaining 40% of aluminum-based SNF (DOE 2000b).

Subsequently, DOE evaluated the option of treating all the aluminum-based SRS SNF through conventional processing as part of a proposed enriched uranium disposition project (Lanigan and Gillas 2009). In 2006, DOE approved the mission need statement for this project and estimated its lifecycle cost to be in the range of $4.3–$4.6 billion (Lanigan and Gillas 2009). The aluminum-clad SNF was to be processed between 2011 and 2019; however, DOE decided that it would not process aluminum-clad SNF until the recommendations of the President's Blue Ribbon Commission on America's Nuclear

Future were issued and evaluated by DOE (Triay 2011). After the recommendations were issued, DOE decided to manage approximately 3.3 MTHM at SRS using conventional processing at the site's H Canyon facility (DOE 2013i).

DOE studied the construction of a new dry storage facility for extended storage and subsequent disposal of all L Basin SNF (McConnell 2012; Adams et al. 2013; Maxted 2013b). A critical factor for operating that facility is ensuring that the SNF, especially aluminum-clad SNF, is adequately dried without significantly degrading the fuel's ability to be safely stored, transported, and placed in a geologic repository. DOE's study of this option considered a three-phase program (McConnell 2012) in which the first phase involves a dry storage demonstration that includes laboratory testing and field testing of three concrete overpacks. Each overpack contains 12 canisters of SRS SNF (Maxted 2013b). The canisters are 2 feet in diameter and 10 feet tall. The size of the canister is based on compatibility with the remote-handled shipping package (RH-72) and Waste Isolation Pilot Plant infrastructure (Adams et al. 2013) and does not include gadolinium-alloy baskets that would be required for disposal in a volcanic tuff repository. The second phase is a full-scale operation to transfer to dry storage as many as 960 SNF bundles contained in 110 canisters loaded in 22 concrete overpacks (Maxted 2013b). The third and final phase is removing the remaining aluminum-clad and non-aluminum-clad SNF in the L Basin, including the damaged fuel in isolation containers, and loading it in dry storage systems (Maxted 2013b). Remaining aluminum-clad SNF would be placed in 571 canisters that would then be loaded into 115 concrete overpacks. SRS planned to place the non-aluminum-clad SNF into 55 special canisters (each canister would be 14 inches in diameter and 13.5 feet tall) that would then be loaded into 11 tall concrete overpacks. The estimated cost for the program is $1.025–$1.3 billion (Maxted 2013b). DOE is not pursuing SRS SNF long-term dry storage. Instead, DOE "is modeling SRS whole systems cost for different disposition options" (Maxted 2013b). DOE's amended decision on SNF management at SRS (DOE 2013i) leaves all SNF in the L Basin, except for the 3.3 MTHM to be processed in H Canyon, for an indefinite period (DOE 2013i). DOE recognizes that a departmental decision is needed on the future direction of fuel storage or processing (Maxted 2014b).

6.3.2.4 Continued Storage of Spent Nuclear Fuel in the L Basin for an Indeterminate Time

Sindelar and Deible (2011) concluded that continued safe storage of the SNF in the L Basin for an additional 50 years is possible contingent on continuing existing fuel management activities and several augmented program activities. Responding to this study, DOE required the management and operating contractor for SRS to develop an augmented monitoring and condition assessment program (Maxted 2012; DOE 2013h). This augmented program would continue existing programs and implement three additional programs (Rose 2013). Existing programs include the following:

- A basin water chemistry control program (Sindelar and Deible 2011) to minimize fuel and storage fixture corrosion (Rose 2013).
- A corrosion surveillance program[190] to predict corrosion rates for SNF and fixture materials (Rose 2013).
- A microbial monitoring program (Rose 2013) that was implemented after discovering, in 2011, bacterial "cobwebs" on the tops of fuel bundles (Figure 6-3C and Figure 6-3E) (Maxted 2012; Maxted and Eisele 2013).
- A basin structural integrity program[191] that includes visually inspecting the basin floor and walls and accessible exterior walls every six years (Rose 2013; Sindelar and Deible 2011).

Additional monitoring and condition assessment programs include the following:

- Periodic remote underwater examination of bundled fuel, which includes aluminum-based fuels in standard storage configurations (Rose 2013).

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[190] According to Sindelar and Deible (2011), "Corrosion surveillance involves exposure of a set of test coupons to the L Basin water for a predetermined period, followed by removal and metallurgical evaluation to detect and characterize corrosion. Water quality parameters that are measured at periodic intervals are documented with the corrosion results. The effects of transients in water quality parameters on potential corrosion to the basin materials are captured in the corrosion surveillance program reports."

[191] Once the vinyl sealer was declared to be beyond its useful life during a structural integrity program baseline inspection (Sindelar and Deible 2011), further review of the sealer in the program was not needed.

- Assessing fuel in oversized isolation cans (Maxted and Eisele 2013).
- Assessing basin structural integrity using core samples from other concrete structures of similar age and with a similar operating history (*e.g.*, core samples from the C Basin at SRS; Maxted and Eisele 2013).

Each of the three additional programs consists of multiple separate activities (Rose 2013). For example, the program to assess SNF in oversized isolation cans includes *in situ* visual and ultrasonic examination of the cans. SRS has completed the first instance of this task (Rose 2013).

The program to assess fuel in isolation cans (Figure 6-3B) includes five activities to evaluate corrosion and degradation of isolation-can configurations (*i.e.,* an adverse change in the geometry of the inner can and SNF inside the isolation can). SRS completed three of these activities by October 2014 (Rose 2014a). According to Rose (2014a), one activity that has not been started is evaluating fuel isotopic characteristics and alteration products as they pertain to criticality. Because the isolation cans contain many fuel types, including uranium-based, plutonium-based, thorium-based, and blends, understanding the potential for criticality in each can is important and will depend on fuel alteration products and the fuel isotopic characteristics.

DOE's Office of Inspector General (DOE 2013h) noted that Sindelar and Deible's (2011) effort was a feasibility study and that DOE has determined that monitoring and assessment activities must be completed to validate the technical basis for continued use of the L Basin (DOE 2013h). For planning purposes, the management and operating contractor identified "a broad range of estimated costs, $4 million to $8 million, was projected to ensure completion of the monitoring and assessment activities" (DOE 2013h). By comparison, baseline operating costs for the L Basin are $40 million per year (Maxted 2013b). DOE has not fully implemented augmented monitoring and assessment activities because of funding constraints (DOE 2013h). For example, in fiscal year 2014, DOE planned only limited implementation of the augmented monitoring and condition assessment program (Hintze 2013). DOE has not specified when these activities must be completed (DOE 2013h).[192]

6.3.3 Existing Requirements That Would Affect Spent Nuclear Fuel Management

DOE's current direction for managing DOE SNF (Gelles 2012a) relies on the technical requirements in the "Waste Acceptance System Requirements Document" (DOE 2008a). Pertinent aspects of these waste acceptance technical requirements that affect the disposition path for DOE SNF at SRS include packaging SNF in a DOE standardized canister (with minor exceptions). The wide range of SNF types being stored at SRS means that meeting waste acceptance requirements (DOE 2008a) will be challenging. For example, DOE will need to determine that criticality limits have been met for each type of SNF. Gas generation in sealed DOE standardized canisters is another issue that could be problematic. Assumptions concerning fuel preparation and packaging at SRS, as described by Maxted (2013b), are not consistent with DOE (2008a) requirements (*e.g.*, using DOE standardized canister sizes).

U.S. Nuclear Regulatory Commission (NRC) regulations could also affect DOE's ability to continue to manage and dispose of SRS SNF off site. DOE will need to obtain NRC certification of its transportation system under Title 10, Code of Federal Regulations, Part 71, before the standardized DOE SNF canister can be transported off site. NRC (Rahimi 2007b) found that DOE's (Carlsen 2007) projection for the volume of hydrogen gas (10% by volume) that could be generated inside the canisters due to radiolysis of residual water is two times larger than the combustible gas limit that NRC uses

[192] In October 2014, the Board held a public meeting in Augusta, Georgia to hear from DOE on storage of SNF at SRS. Based on what it heard, the Board recommended " acceleration of the Augmented Monitoring and Condition Assessment Program to substantiate the condition of the fuel and facilitate future SNF handling, drying and packaging operations" and "that DOE consider further actions to validate the structural integrity of L Basin, including: obtaining and analyzing core samples of the L Basin structural concrete, including samples containing rebar; expanding the visual examination of the interior and exterior surfaces of the basin walls, including those areas of the exterior surface in contact with soils; obtaining and analyzing core samples of older (possibly on the order of 100 years old) representative concrete from other sources to gather data that can improve the understanding of the long-term performance of the concrete; and ensuring coordination with other efforts to study concrete aging, such as those being conducted by the DOE Light Water Reactor Sustainability Program, the Concrete Sustainability Hub at the Massachusetts Institute of Technology, and the DOE-EM Cementitious Barriers Partnership at Vanderbilt University" (Ewing 2015).

in its certification review of transportation packages. DOE recognizes that drying aluminum-based SNF for storage and transportation is difficult; according to Maxted (2013b), "determining how dry is dry is the crucial question."

6.4 Key Observations on the Management and Disposal of Savannah River Site Spent Nuclear Fuel

1. DOE's SNF management approach at SRS is constrained by four decisions DOE made as part of its National Environmental Policy Act (U.S. Congress 1969) activities. DOE plans to continue safe wet storage, process some of the aluminum-based SNF in H Canyon, indefinitely suspend its decision on the planned exchange of SNF with INL, and assess the potential for extended dry storage and subsequent transportation and disposal of SNF.

2. The L Basin wet storage facility stores 30 MTHM of SNF and is at or near its storage capacity for different types of SNF. DOE uses aqueous processing in H Canyon to treat aluminum-based SNF stored in the L Basin to ensure that adequate storage space is available to accommodate new additions of foreign and domestic SNF. Without a major change to H Canyon, DOE will be unable to process the 20 MTHM of non-aluminum-based SNF that are stored in L Basin.

3. About 29% of the DOE SNF multi-purpose canisters that could be sent to a repository will contain aluminum-based SNF (Table A1-2; Groups 14–17) that is stored at SRS (approximately 10 MTHM) and elsewhere. Protocols for drying SNF without incurring unacceptable degradation, especially aluminum-based SNF, during packaging remain to be specified. The drying protocols will need to be developed considering the potential addition of supplemental neutron absorber materials during packaging and the feasible duration and temperature of drying.

4. DOE completed an aging management assessment for the 60-year-old L Basin, and concluded that it may be safely used for another 50 years, provided that existing surveillance and maintenance programs (*e.g.*, a basin water chemistry control program to minimize aluminum-based SNF corrosion) continue and that augmented monitoring and condition assessment program activities (*e.g.*, evaluating fuel isotope characteristics and alteration products of non-aluminum-based SNF in oversized isolation cans) are completed. To date, these augmented activities have not been completed, and some activities must be repeated periodically. The Board has expressed the opinion that more data should be gathered to support the technical basis for continuing to operate the facility for an additional 50 years (Ewing 2015).

7. Spent Nuclear Fuel at Fort St. Vrain

The Fort St. Vrain (FSV) independent spent fuel storage installation[193] (Figure 7-1) is located in northern Colorado, about 4 miles northwest of Platteville and about 35 miles northeast of Denver (NRC 2011b). The Public Service Company of Colorado built this storage facility about 1,500 feet northeast of its 330-megawatt (electric) high-temperature, gas-cooled nuclear reactor, which ran commercially between 1979 and 1989. It created about 23.35 metric tons of heavy metal[194] (MTHM) of spent nuclear fuel (SNF), which is composed mainly of graphite moderator.

Figure 7-1. Fort St. Vrain independent spent fuel storage installation. The darker building in the background is the decommissioned nuclear power plant, which was converted to a natural gas–fired, electricity-generating station in 1996. (Source: CH2M-WG Idaho 2012).

The Public Service Company of Colorado had already sent about 37% of its SNF to Idaho National Laboratory (INL); however, in late 1989, the state of Idaho acted to block further shipments of SNF from FSV to INL. In June 1990, the Public Service Company of Colorado applied to the U.S. Nuclear Regulatory Commission (NRC) for a license to construct and operate a dry vault independent spent fuel storage installation (NRC 1991). In November 1991, NRC granted a 20-year license "to receive, possess, store, and transfer SNF from the reactor building to an independent spent fuel storage installation" (Figure 7-1; NRC 2011b), which has since been renewed until 2031. Between December 1991 and June 1992, the Public Service Company of Colorado transferred the remaining SNF from the nuclear power plant to this storage facility (NRC 2011b). The company subsequently decommis-

193 Upon first use in this chapter, underlined terms and phrases are explained in the Glossary (Chapter 11) and abbreviations are introduced.

194 Metric ton of heavy metal is a commonly used measure of the mass of "heavy metal" initially present in nuclear fuel. Heavy metal refers to elements with an atomic number greater than 89 (*e.g.,* thorium, uranium, and plutonium). The mass of other constituents of the fuel, such as the fuel matrix (graphite, in this case), alloy materials, and structural materials, are not included.

sioned the nuclear power plant and converted it to a natural gas–fired plant (Figure 7-1) that began generating electricity in 1996.

In the mid-1990s, the U.S. Department of Energy (DOE) decided "to procure the FSV independent spent fuel storage installation," take possession of the stored SNF, and transfer the license for the facility to itself (NRC 2011b). DOE immediately took title of the stored SNF, although the Public Service Company of Colorado continued to manage the SNF under its NRC license until June 4, 1999. NRC subsequently transferred the license to DOE (NRC 2011b).

7.1 Spent Nuclear Fuel Storage Facility and Stored Spent Nuclear Fuel

7.1.1 Storage Facility

The controlled land area that includes the FSV independent spent fuel storage installation is about 494,000 square feet. The storage installation uses a modular vault dry storage system housed in a heavily reinforced concrete storage building that is 143 feet long, 72 feet wide, and 80 feet tall (Figure 7-2; CH2M-WG Idaho 2012).

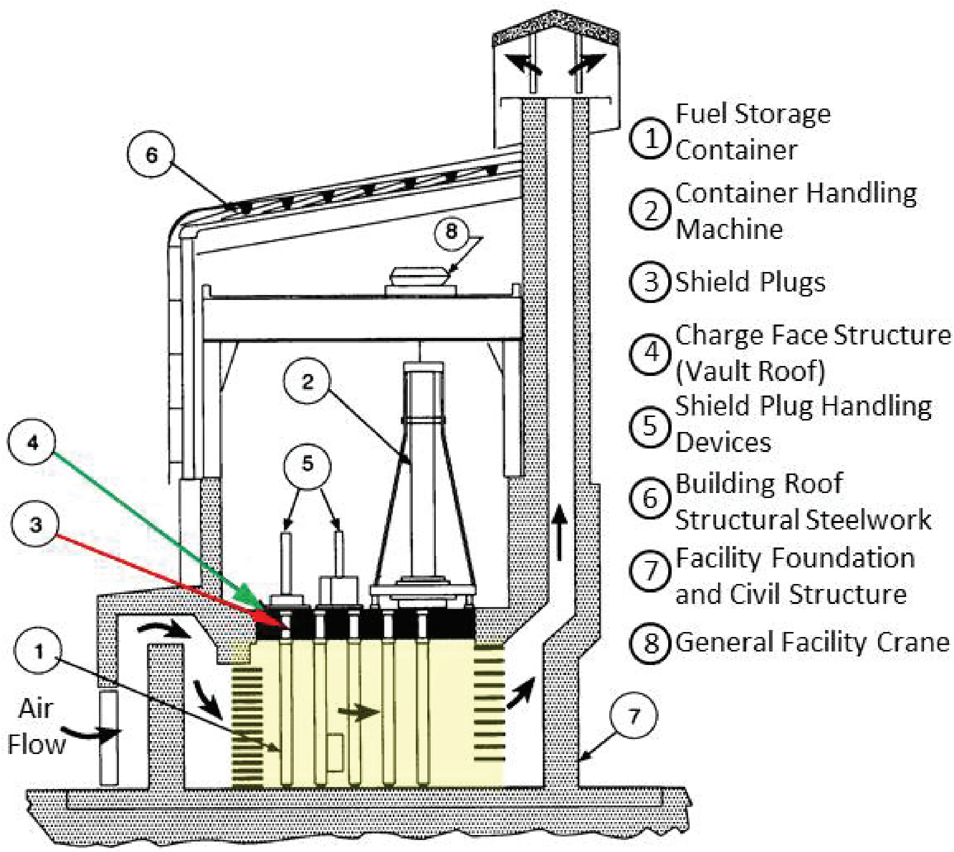

Figure 7-2. Major features of the modular vault dry storage system at Fort St. Vrain. Vertical cross section through the facility with a vault module highlighted in yellow. Red and green arrows are used for features 3 and 4 to clarify their locations. (Source: Raddatz and Waters 1996).

The facility includes a foundation structure that supports a matrix of six concrete vault modules[195] and six charge face structures. Each concrete vault contains a matrix of vertical storage positions that can each hold one fuel storage container (Figure 7-3). Each fuel storage container can hold up to six SNF elements. The facility has a design capacity of 1,482 SNF elements. Currently, 244 positions with fuel storage containers are loaded, giving a total inventory of 1,464 SNF elements (CH2M-WG Idaho 2012). The SNF is stored in an air environment within sealed storage containers that are in a

[195] A vault module is an open concrete box. The charge face structures are the roofs of the vault modules. The charge face structure is a concrete-filled carbon steel box that provides access and lateral support for the storage tubes.

dry environment cooled by the natural circulation of air (Figure 7-2). The dry storage system also has one neutron source storage well, two standby storage wells, and a transfer cask reception bay. The storage wells are separate from the vault modules. The design life of the facility is 40 years (NRC 2011c).

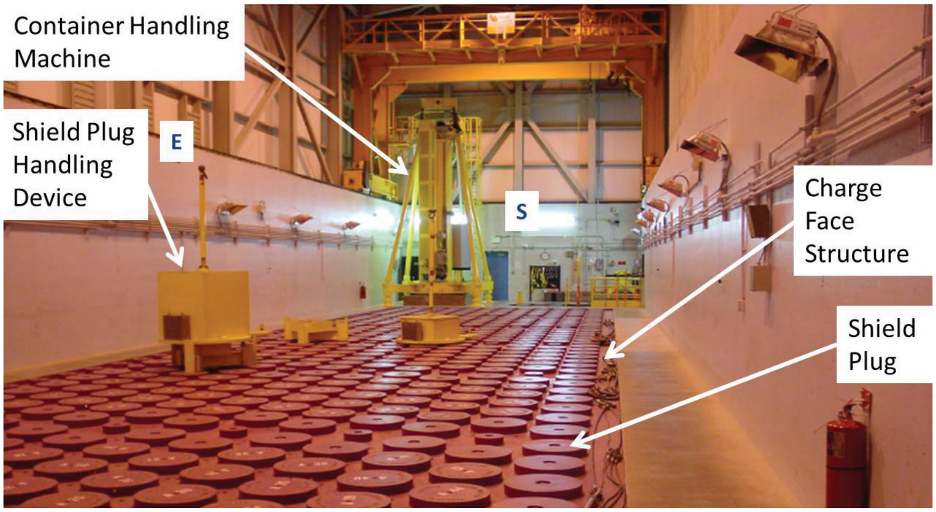

Figure 7-3. Inside the Fort St. Vrain storage facility.
The vertical storage positions are beneath shield plugs. The east (E) wall of the facility is at the left of the photo and the south (S) wall is in the middle of the photo. The neutron source storage well, two standby storage wells, and a transfer cask reception bay are near the container handling machine, beyond the red charge face structure, at the south end of the building. (Source: DOE 2009c).

The fuel storage containers used at FSV are cylindrical carbon steel canisters. Each canister is 16 feet long and 1.5 feet in diameter, and has a 0.5-inch-thick shell. Flame-sprayed aluminum covers the outer surfaces of the containers to prevent corrosion. The container lid, which is 1.5 inches thick, has a lifting feature. The lid is bolted to the body of the container with steel bolts and uses double metal O-ring seals. This forms a high-integrity sealing geometry that allows for checking leaks. The container is designed not to require maintenance during the 40-year design life and storage period. DOE confirms the seals of six containers every five years with a sealable, O-ring inter-space tapping.

DOE filed a license renewal application with NRC in November 2009 (NRC 2011b), and was granted a 20-year renewal, which now expires on November 30, 2031. DOE's application included a scoping evaluation that identified 10 items requiring an aging management review (DOE 2009c). DOE conducted aging management reviews for the fuel storage containers, the fuel in storage, and the structural concrete of the modular dry vault storage building, among others, and determined that neither the SNF nor the fuel storage containers were subject to aging effects that required management during the period of the proposed license renewal (DOE 2009c).

DOE's proposed aging management program also involved checking the outer surfaces of the independent spent fuel storage installation, which included a visual inspection of the accessible concrete and exposed steel. During a routine NRC storage facility inspection, Spitzberg (2011) noted that DOE had marked several suspected cracks on the outside concrete walls and was monitoring them. The proposed management program also required monitoring area radiation levels, as well as airborne and loose surface radioactive contamination in accessible areas. Furthermore, the proposed management program ensures that the cooling inlet and outlet screens do not become blocked. In its review of DOE's license renewal application, NRC determined that DOE needed to conduct additional activities as part of its aging management program. Specifically, the terms of the license renewal require DOE to establish and implement procedures for remote visual inspection to check for signs of degradation in several parts of the facility,[196] including the fuel storage containers and their supporting stools,[197] the underside of the charge face structure (vault ceiling), and the vault wall and floor surfaces (Waters 2011).

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[196] As part of its applied research and technology development program, DOE's Office of Environmental Management is developing remote visual inspection devices to determine *in situ* storage conditions.

[197] The fuel storage containers rest on carbon steel support stools coated with flame-sprayed aluminum that are fixed to the vault module floor with anchor studs and grout.

7.1.2 Stored Spent Nuclear Fuel

Table 7-1 provides summary information about the SNF stored in the FSV facility. Consistent with DOE's system for grouping fuels (DOE 2009a), the table indicates the type of fuel, the quantity in storage (in MTHM), the initial enrichment of the fuel (in percent uranium-235), the fuel burnup in megawatt-days per MTHM, and the type of system used to store the SNF.

The SNF stored at FSV consists of hexagonal graphite fuel elements (Figure 7-4). The "right hexagonal prisms" are about 31 inches long and 14 inches across the flat faces of the hexagon (Lotts *et al.* 1992). Within each element, are 210 axial fuel holes (diameter = 0.5 inches) that are drilled from the top face and extend to within about 0.3 inches of the bottom face. Each fuel element also contains 108 axial coolant channels. The fuel consists of microscopic spherical particles of thorium and uranium carbide, called "fuel kernels," that are coated with carbon and silicon carbide. The fuel kernels are compressed in a graphite matrix and then sintered to create rods called "compacts" that are about 2 inches long with a diameter of just under 0.5 inches. The "compacts" are stacked into the axial fuel holes and plugged at the top with graphite to retain the fuel in place during operations.

Table 7-1. Characteristics of stored spent nuclear fuel

SNF Source	Description (1)	Amount MTHM	Initial Enrichment, Percent U-235	Burnup, megawatt-days/ MTHM	Location and Storage System
FSV reactor	Th/U carbides in graphite matrix (1,464 fuel elements) DOE Fuel Group 19	~14.7	93	Maximum 52,000	Sealed carbon steel containers in modular vault dry storage system

Note
(1) Thorium (Th) and uranium (U) (Lotts *et al.* 1992; Taylor 2001; DOE 2009c).

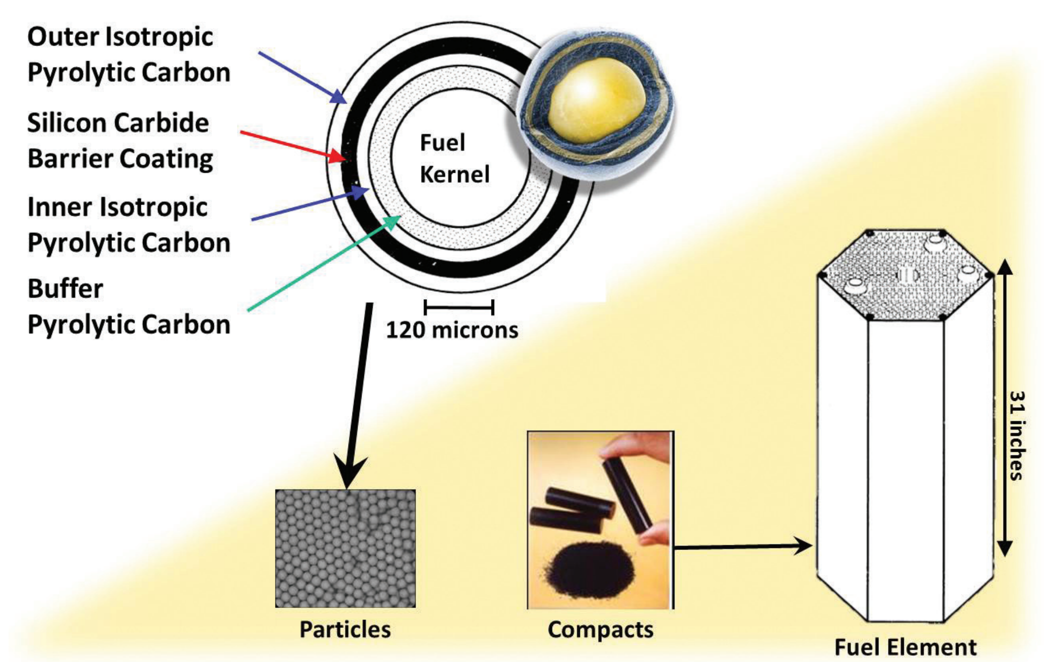

Figure 7-4. Details of a Fort St. Vrain fuel element.
The FSV fuel particles were about 0.5 millimeters (mm) in diameter, and the inset is a false-color image showing a larger (approximately 1 mm) diameter fuel particle. (Sources: Lotts *et al.* 1992; Hunn 2010; and Martin *et al.* 2012).

Each fuel element holds approximately 3,000 "compacts." The thorium-to-uranium ratio in fuel when it was fresh varied among fuel elements—in some fresh fuel blocks, the ratio was as low as 12 and, in others, it was as high as 33. The amounts of thorium and uranium in the first FSV core of fresh fuel totaled 15,905 kilograms and 774 kilograms, respectively (Lotts *et al.* 1992), and was enriched to a level of 93% uranium-235. The large-volume, graphitic SNF now stored at

FSV contains fission products, uranium-233 bred from thorium-232, other uranium isotopes, and small amounts of plutonium and higher actinides[198] (Lotts *et al*. 1992). Although DOE (2009a) states that the condition of the FSV SNF particle coating is good, elsewhere DOE acknowledges that "there is little qualified information concerning the condition of" the fuel (Bechtel SAIC Company 2004). If the fuel particles are damaged, exposing carbide layers (Figure 7-4) to an external environment, water interacting with degraded carbide fuel particles can create combustible gases (Sections 2.1 and 2.5.1). The maximum decay heat of this SNF in the year 2020 is estimated at about 100 watts per element (Taylor 2001, Appendix D). The maximum decay heat for a DOE standardized canister[199] containing FSV SNF in the year 2020 will be about 500 watts, which is in the low range for non-naval DOE SNF (Figure 2-5). FSV SNF that currently is stored at both FSV and INL represents about 14% of the estimated number (3,732) of canisters containing DOE SNF that could be sent to a repository (Table A1-2), but it represents only about 1% of the total mass of DOE SNF.

7.2 Legal Agreements and Decisions That Affect Spent Nuclear Fuel Management

7.2.1 The 1995 Settlement Agreement

The 1995 Settlement Agreement between the state of Idaho, DOE, and the Navy (Idaho *et al*. 1995) limits DOE's options for managing FSV SNF. Per the 1995 Settlement Agreement, DOE is not allowed to ship SNF from FSV to INL until a permanent repository or interim storage facility for SNF is opened outside Idaho and is accepting SNF from INL. Once this condition is met, the 1995 Settlement Agreement stipulates that SNF can be shipped from FSV to INL exclusively to treat[200] the SNF to make it suitable for disposal or storage. Shipments can remain at INL only long enough to treat the SNF (Idaho *et al*. 1995). The 1995 Settlement Agreement also limits the total number of FSV shipments to fewer than 244 and the total quantity shipped to 16 MTHM. Shipments of FSV SNF are in addition to the 55-MTHM limit on the total amount of DOE SNF (Idaho *et al*. 1995, Section D.2.d) that can be sent to INL under the 1995 Settlement Agreement.

7.2.2 The Colorado Agreement

Under an agreement signed by Roy Romer, then Governor of Colorado, and Thomas Grumbly, then Assistant Secretary for Environmental Management, DOE committed to removing all SNF from Colorado by January 1, 2035 (Colorado and DOE 1996; DOE 2009c). If DOE does not remove the SNF at FSV by this deadline, DOE must pay Colorado $15,000 for each day[201] that the SNF remains in Colorado after January 1, 2035.

7.2.3 Records of Decision

DOE's amended record of decision for SNF management (DOE 1996a) reflects the 1995 Settlement Agreement (Idaho *et al*. 1995). The amended decision stopped shipments of SNF from FSV to INL for storage.

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[198] Although the inventory of radionuclides in FSV SNF is different than the inventory in commercial SNF, which is a uranium-oxide-based fuel, these differences are not important from the point of disposal because the graphitic FSV SNF accounts for less than 1% (by mass) of DOE's total SNF. Examples of differences in the radionuclide inventory for FSV fuel compared with commercial fuel include (1) more than 100 times fewer curies (Ci) per MTHM for activation products (nickel-59, nickel-63, and niobium-93m), because the FSV fuel lacks metallic cladding; (2) more than 10 times more Ci/MTHM for thorium-232, its daughters, and isotopes produced from neutron absorption of thorium-232, because the FSV fuel has a high thorium content; and (3) more than 100 times fewer Ci/MTHM of uranium-238 and isotopes produced from the neutron absorption of uranium-238, because FSV fuel was highly enriched in uranium-235.

[199] DOE has not implemented the standardized canister. The U.S. Nuclear Waste Technical Review Board adopts DOE's nomenclature for this canister even though it is not standard by any conventional definition. The DOE standardized canister is a canister system that consists of four cylindrical stainless steel canisters with two different diameters (18 inches and 24 inches) and two different lengths (10 feet and 15 feet). The different sizes and eight internal basket designs of the multi-purpose canisters accommodate the wide dimensional variability of DOE spent nuclear fuel. DOE planned to package five FSV SNF elements in the 18-inch diameter, 15-feet long version.

[200] The 1995 Settlement Agreement defined the term "treat": "Treat shall be defined, as applied to a waste or spent fuel, as any method, technique, or process designed to change the physical or chemical character of the waste or fuel to render it less hazardous; safer to transport, store, dispose of; or reduce in volume."

[201] The $15,000/day payment is not automatic but is subject to the availability of the appropriations provided in advance for this purpose.

7.3 The Path Forward for Managing and Disposing of Spent Nuclear Fuel

7.3.1 Changes to the Spent Nuclear Fuel Inventory

The NRC license for the FSV independent spent fuel storage installation limits the amount of SNF that can be stored at this facility to that which is already stored there (Waters 2011). Thus, there will be no further additions to the current inventory. The FSV inventory will change only when DOE begins to ship SNF to INL, to another storage facility, or to a repository located outside Colorado (since the Colorado agreement requires removal of all DOE SNF from the state before 2035).

7.3.2 Proposed Actions That Would Affect Spent Nuclear Fuel Management

DOE proposed three steps for managing and disposing of FSV SNF. First, DOE will continue to store SNF in the independent spent fuel storage installation, consistent with the requirements of its renewed NRC license, which expires on November 30, 2031. Second, per the 1995 Settlement Agreement, DOE plans to ship FSV SNF to INL and repackage it for transport to a permanent repository or interim storage facility outside Idaho. The exact timing of shipments to INL remains to be determined and is a function of the timing of an operating interim storage facility or repository whose authorization includes this SNF (*i.e.*, commercial-origin DOE SNF that could not be disposed of in a defense repository; Figure 1-2). DeLeon (2011) indicated that transport to INL would require three years and would occur between 2028 and 2030 (Figure 5-10). Third, once the NRC storage license expires, DOE will dismantle, decontaminate, and decommission the independent spent fuel storage installation.

7.3.3 Existing Requirements That Would Affect Spent Nuclear Fuel Management

Because NRC regulates storage at the FSV facility and certifies the transportation cask for FSV SNF (Figure 7-5), DOE's SNF management activities are constrained by NRC regulatory requirements. NRC's current storage requirements under Title 10, Code of Federal Regulations, Part 72 stipulate that the initial license term for an independent spent fuel storage installation must not exceed 40 years, with each subsequent renewal period not to exceed 40 years. DOE can apply to NRC to renew its current SNF storage license for the FSV facility, using the same process DOE used in 2009 for its first renewal.

NRC's storage regulation also defines terms for the expiration and termination of the license. Once the license for an independent spent fuel storage installation expires, the actions the licensee can undertake at the facility are limited to only those related to decommissioning. NRC also imposes requirements for decommissioning the site.

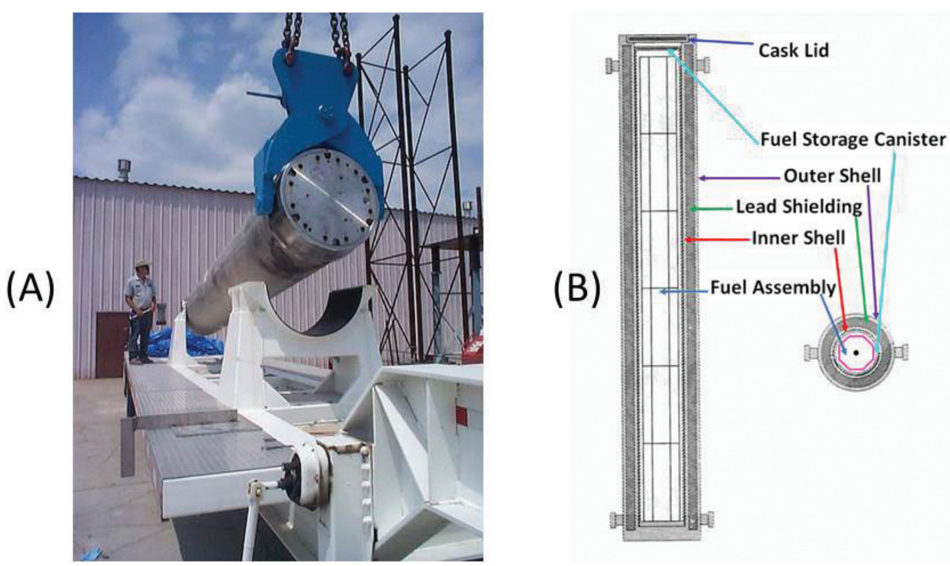

Figure 7-5. Model TN-FSV legal-weight truck transport cask.
A. An empty TN-FSV cask is unloaded from a truck. (Source: Greene *et al.* 2013). B. Schematic of a TN-FSV transport cask. (Source: Greene *et al.* 2013).

The transportation requirements in Title 10, Code of Federal Regulations, Part 71 stipulate that the license period for an NRC-certified cask design is five years. The certificate holder can apply to NRC to renew the certificate for subsequent five-year periods indefinitely. DOE's Model TN-FSV cask (Figure 7-5) is certified to transport FSV SNF and holds six FSV fuel elements (Benner 2009). The certification for the TN-FSV cask expires on June 30, 2019.

7.4 Key Observations on the Management and Disposal of Fort St. Vrain Spent Nuclear Fuel

1. Degradation of graphite matrix, carbide-based FSV SNF is more important to understand than its small mass (about 1% of total mass of DOE SNF) would suggest because repository processes are assessed on a per-package basis and FSV SNF would be in about 14% of the multi-purpose canisters that contain DOE SNF.

2. Because carbide-based FSV SNF has sufficiently different characteristics than oxide-based SNF, degradation processes associated with carbide-based SNF that were not important for geologic disposal in an unsaturated (air-filled) environment may need to be reevaluated as part of repository disposal studies for other disposal environments. For example, if the coatings of carbide-based SNF particles are not intact, reaction of the carbide with water will produce flammable gas (*e.g.*, acetylene) and could lead to repository pressurization.

3. Although the FSV storage facility was only about 20 years old when DOE assessed the activities needed to manage the effects of aging on the facility, the NRC review of DOE's aging management program identified additional activities, mainly related to structural integrity, that will be required to ensure safe storage and retrieval of the SNF at FSV for an additional 20 years.

4. Future DOE FSV activities depend on developing and operating a packaging facility at INL, and making an interim storage facility or geologic repository available that can receive SNF from INL. For example, DOE will need to either extend the duration of its NRC storage license that expires on November 30, 2031, or transport the SNF out of Colorado by that date.

8. Analysis

In 2010, when the Yucca Mountain program was placed in hiatus, it was not known when a repository or off-site storage[202] location for spent nuclear fuel (SNF) would become available. The U.S. Nuclear Waste Technical Review Board (Board) recognized at that time that the uncertainty could continue well into the future (Garrick 2010a), and recognized that the U.S. Department of Energy (DOE) should undertake studies "to identify and plan for actions that are needed for preventing problems from occurring during the transportation, repackaging, or disposal of SNF following extended periods of dry storage" (Garrick 2010a). Six years later, *the Board found that this need remains the case*[203] (Ewing 2016).

Since the Blue Ribbon Commission on America's Nuclear Future report (BRC 2012) was issued in 2012, DOE has been investigating and beginning to implement a new strategy to manage and dispose of its SNF and high-level radioactive waste (HLW; DOE 2013a). Given the diversity of DOE SNF and its characteristics (Chapter 2 and Appendix 1), and the legal and regulatory requirements (Chapter 3) that constrain DOE's actions, the Board's analysis of DOE's new strategy assumes that DOE's baseline strategy will use three multi-purpose (storage, transportation, and disposal) canisters [a multi-canister overpack (MCO), a naval canister, and a DOE standardized canister], without removing SNF from the canisters and repackaging in the future, to determine under what conditions the DOE strategy might work.

For any plan that culminates with disposal of DOE SNF, DOE needs to complete successfully the following SNF management activities. First, DOE needs to continue to store its SNF at existing facilities until it is retrieved for packaging into containers that can be transported off site. Second, once DOE begins packaging non-naval DOE SNF into DOE standardized canisters, DOE will need to dry the fuel that is stored in pools, as well as some fuel that is stored "dry" but has not experienced sufficient drying. In addition, DOE needs to continue to dry and package naval SNF[204] in naval SNF canisters. Third, once SNF is packaged in multi-purpose canisters, DOE needs to store the canisters until they are loaded into rail casks and transported off site. Subsequent management of the canisters could include either storing the canisters at a centralized interim location or receiving the canisters, packaging them into a waste package, emplacing and storing the waste packages underground at a deep geologic repository, and finally disposing of them by closing the repository. A snapshot in time of the status of DOE's SNF management activities is presented in Figure 8-1.

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[202] Upon first use in this chapter, underlined terms and phrases are explained in the Glossary (Chapter 11) and abbreviations are introduced.

[203] In this chapter, the Board findings are italicized.

[204] For naval SNF, the Board's analysis is limited as details on characteristics of naval SNF and its management are not publicly available. In its analysis, the Board does not differentiate between naval SNF and other DOE SNF unless there is citable evidence for the difference.

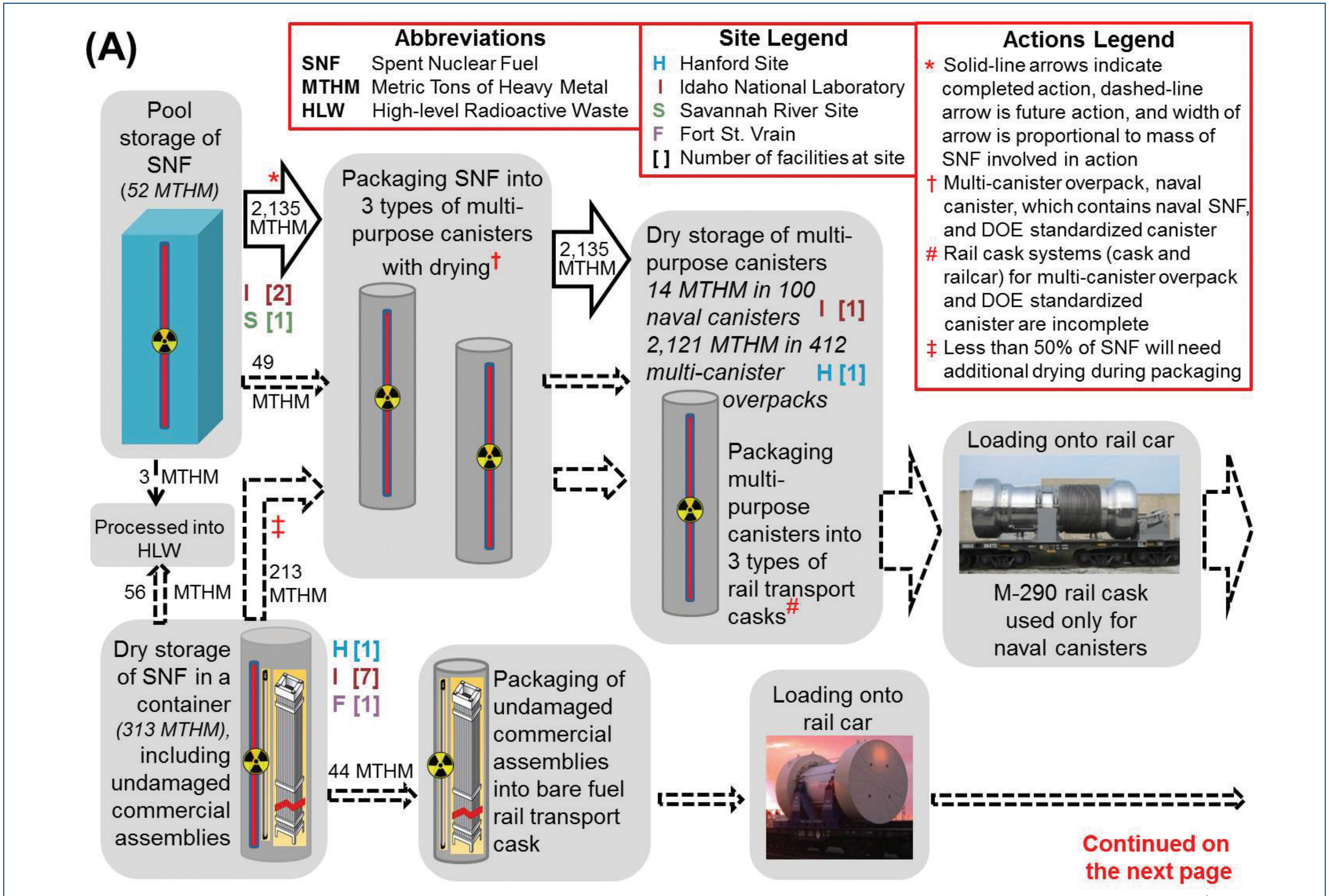

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Figure 8-1. Status of activities that lead to disposal of U.S. Department of Energy spent nuclear fuel.

A. Simplified depiction of DOE SNF management activities at the Hanford Site, Idaho National Laboratory (INL), Savannah River Site (SRS), and Fort St. Vrain independent spent fuel storage installation—from on-site storage of DOE SNF through loading SNF onto a rail car—that lead to disposal of SNF in a geologic repository. Mass of spent nuclear fuel in storage is depicted in *italics* (status as of August 2014). Some stored SNF will be processed into HLW—56 metric tons of heavy metal (MTHM) of sodium-bonded SNF at INL and 3 MTHM of aluminum-based SNF at SRS—and will not be disposed of as SNF.

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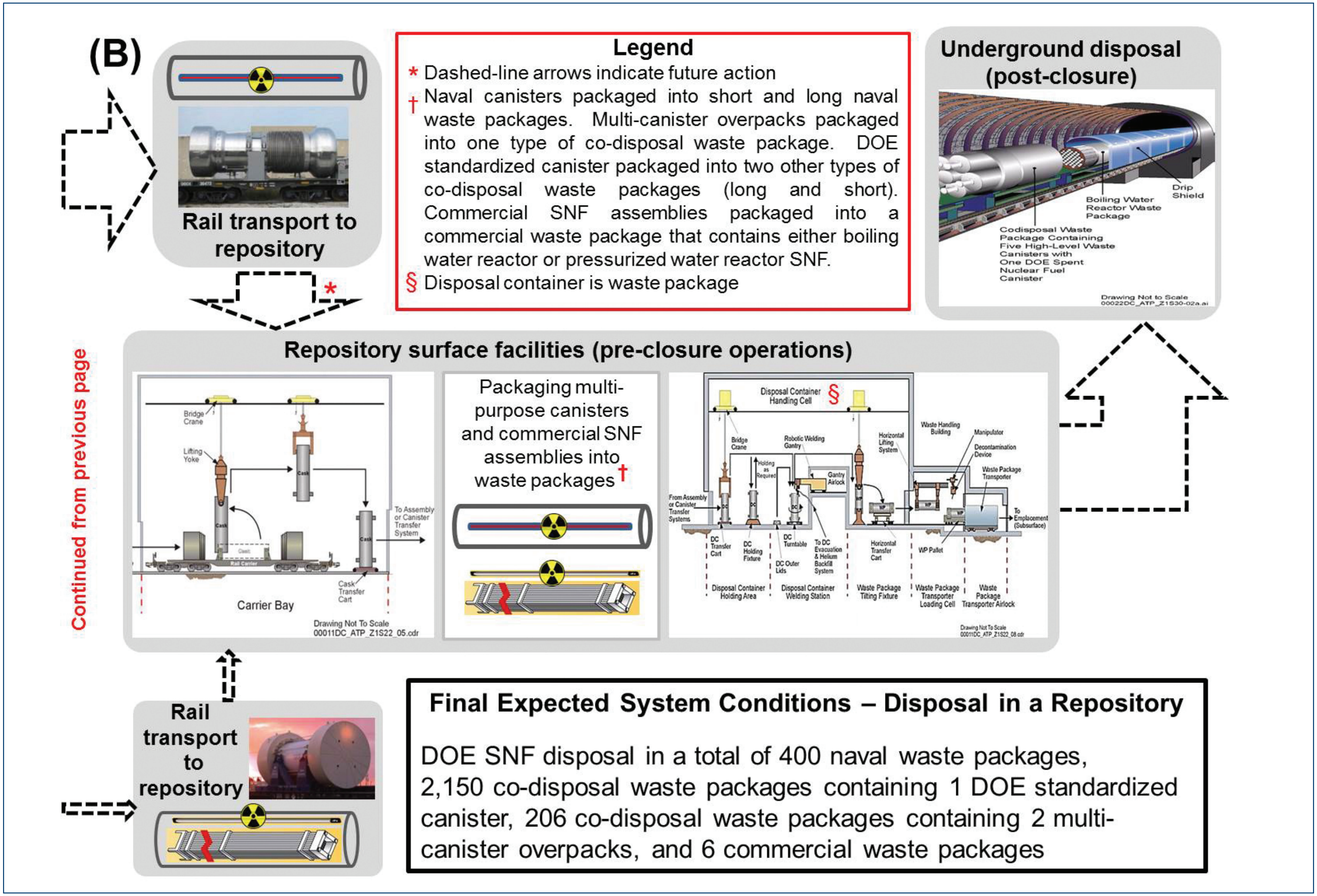

Figure 8-1 (cont.). Status of activities that lead to disposal of U.S. Department of Energy spent nuclear fuel (continued).
B. Simplified depiction of DOE SNF management activities from rail transport of DOE SNF—from the Hanford Site, INL, and SRS—through underground disposal in a volcanic tuff repository (status as of August 2014). SNF from Fort St. Vrain is packaged into DOE standardized canisters at INL and shipped from INL to a repository. The number of waste packages is based on the disposal of 2,333 MTHM of DOE SNF (DOE 2009a, Table 1.5.1-1) in the repository. A total of 2,919 waste packages containing one DOE standardized canister each are estimated to be required for disposal of 2,510 MTHM of DOE SNF (Table A1-3).

The snapshot does not reflect annual changes, which are small, and does not capture the small amount of DOE SNF (approximately 10 MTHM; Table A1-1) that is at sites other than those identified in the figure. The depiction of SNF management activities at the proposed Yucca Mountain repository (Figure 8-1B) is intended to be representative of the activities that could occur at any repository that DOE pursues (*e.g.*, packaging SNF into waste packages).

The technical challenges associated with DOE SNF management activities are driven by the diverse physical and chemical properties of DOE SNF and are, in general, increasing with time. The challenges DOE faces are also affected by legal and regulatory requirements. In the following analysis, the Board presents its major findings (listed in italics) and identifies actions required to address the challenges in retrieving stored DOE SNF, packaging it into multi-purpose canisters, and using the multi-purpose canisters in subsequent fuel cycle steps (Figure 8-1). If DOE continues to investigate disposal options other than volcanic tuff at Yucca Mountain for its SNF, the Board also identifies other actions that are needed.

8.1 Constraints on Management and Disposal of Spent Nuclear Fuel

8.1.1 Properties of Spent Nuclear Fuel That Affect Its Management and Disposal

The diversity in size, composition, concentration of fissile radionuclides, and extent of damage and degradation of DOE SNF (Chapter 2) affect its management and disposal. The diversity makes managing most of it more difficult than managing commercial SNF (Section 2.1) and requires that these differences be considered during storage (Section 2.2), packaging (Section 2.3), and transport (Section 2.4) to ensure safe operations. The characteristics of DOE SNF, and the canisters that contain it, also affect disposal of DOE SNF (Section 2.5).

The diversity of size, composition, concentration of fissile radionuclides, decay heat, and extent of DOE SNF degradation and knowledge thereof complicate DOE's efforts to store, dry and package, transport, and dispose of DOE SNF that is now stored at Hanford, INL, SRS, and Fort St. Vrain (FSV) in accordance with applicable regulations.

8.1.2 Legal Agreements, Decisions, and Regulatory Requirements

DOE has legal agreements (Section 3.1) with states that host its storage facilities. These agreements affect DOE SNF management activities at Hanford (Section 4.2.1), INL (Section 5.2.1), and FSV (Sections 7.2.1 and 7.2.2). As described in Sections 3.2, 4.2.2, 5.2.2, 6.2.2, and 7.2.3, decisions made under the National Environmental Policy Act of 1969 (U.S. Congress 1969) also constrain DOE SNF management activities at DOE SNF storage locations.

The U.S. Nuclear Regulatory Commission's (NRC's) storage and disposal regulations, like DOE's occupational radiation safety regulation, include a basic radiation protection principle known as ALARA—as low as (is) reasonably achievable (Section 3.3). Importantly, NRC regulations require DOE to apply the ALARA principle during repository operations and fuel cycle operations that precede it, but not during the post-closure disposal period. In its storage, transportation, and disposal regulations, NRC requires DOE to have a quality assurance program that, along with ALARA considerations, led DOE to adopt the DOE standardized canister (Section 2.3.2),[205] which could be more readily qualified under a quality assurance program, rather than relying on the SNF characteristics *per se* (Sections 2.3.2 and 3.5).

NRC's storage, packaging and transportation, and disposal regulations, and their associated guidance, vary in regulatory approach. The storage and transportation regulations have prescriptive requirements[206] (Section 3.3) that create challenges for both DOE's drying and packaging plans and its deployment of standardized canisters.

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[205] DOE decided "that relying on a sealed canister as an engineered barrier will provide confinement during credible preclosure events, thereby reducing the need for fuel-specific information and avoiding the costs and radiological exposures associated with fuel characterization activities" (DOE 2004b).

[206] "Worst-case" events or design-basis events and phenomena are used to assess the safety of dry storage system designs. Hypothetical accident conditions and numeric limits on the concentration of hydrogen are used to assess the safety of SNF transportation packaging.

Legal agreements between DOE and the states that host DOE SNF storage facilities, decisions DOE made under the National Environmental Policy Act of 1969 (U.S. Congress 1969), and regulatory requirements constrain DOE's SNF treatment, packaging, storage, transportation, and disposal activities.

8.2 Facilitating Retrieval, and Subsequent Management, of Stored Spent Nuclear Fuel and Continued Use of Multi-purpose Canisters

This section summarizes the issues that affect multi-decadal storage of DOE SNF and extended use of multi-purpose canisters. Specific drivers that will facilitate retrieval, and subsequent management, of stored SNF and continued use of multi-purpose canisters are presented in Sections 8.2.1–8.2.6.

DOE SNF that is still stored in pool and dry storage facilities is planned to be retrieved and packaged into multi-purpose canisters (Figure 8-1A). With time, the material properties of SNF, the containers used for SNF storage, and the components of a storage facility (*e.g.*, concrete in an SNF storage pool or cask) can change and degrade (Section 3.3.1 and Box 3-1). The longer DOE SNF is stored prior to being packaged into multi-purpose canisters, the more important it is to "manage its aging"[207] (Box 3-1). Once SNF is packaged into a sealed multi-purpose canister, aging management activities can increasingly focus on the canister, although the possibility that the contents (*e.g.*, the SNF itself, any remaining water, or materials added during packaging) can adversely affect canister performance will need to be considered as a part of aging management activities.

The purpose of an aging management program during storage is to prevent loss of intended function of the structures, systems, and components that are important to storing SNF safely (NRC 2016b), and to ensure that safety functions needed to ensure that criticality, shielding, confinement, heat transfer, structural integrity, and retrievability (NRC 2016b) requirements continue to operate. NRC's storage regulation requires that storage systems be designed to allow ready retrieval of SNF[208] for further processing or disposal for the duration of the storage facility's licensing period (Section 3.3.1; NRC 2016a).

The Board notes that NRC's approach to aging management during storage focuses only on storage, and does not address those activities required during storage to enable future transport[209] and subsequent disposal of SNF.[210]

The Board finds that DOE will need to consider how long multi-purpose canisters will be used in fuel cycle steps after on-site storage and determine what additional aging management activities may be needed to allow their continued use.

An integrated timeline of DOE SNF facilities (Figure 8-2) highlights the timeframes over which DOE will need to manage its aging SNF and SNF storage facilities, and the operational duration of DOE's existing storage facilities. The integrated timeline also depicts storage and repackaging facilities that either have been proposed (*e.g.*, a hot cell for repackaging at the Hanford Site) or have been licensed but not built (*i.e.*, Idaho Spent Fuel Facility), centralized storage and disposal facilities proposed in DOE's strategy for managing and disposing of SNF and HLW (DOE 2013a), and key

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207 Degradation is a change in material properties that adversely affects the behavior of the material. An aging management program anticipates and reduces the degradation effects to ensure continued safe operations for extended periods of time. Aging management activities may include prevention, mitigation, condition monitoring, and performance monitoring.

208 NRC (2016a) allows options that only include handling of canistered fuel to demonstrate ready retrieval of SNF; however, for SNF that is not already in multi-purpose canisters, DOE will need to remove individual or canned spent fuel assemblies from wet or dry storage and package the SNF into the multi-purpose canisters.

209 For example, a scoping study (Jung *et al*. 2013) that NRC relies on for ruling out potential degradation processes within dry storage casks (NRC 2016c) indicates that NRC's packaging and transportation acceptance criterion for flammability (the volume fraction of any flammable gas is to be less than 5%) could be exceeded under certain SNF drying and storage conditions.

210 At a repository, the multi-purpose canister is subject to NRC's disposal regulation and not NRC's storage regulation. Retrieval at a repository applies only in the context of waste that has been emplaced underground (Figure 8-1B), before which point the multi-purpose canister has been placed inside a waste package (Figure 8-1B). In addition, the Board notes that NRC's transportation and disposal regulations do not have specific requirements to manage the aging of structures, systems, and components important to safety.

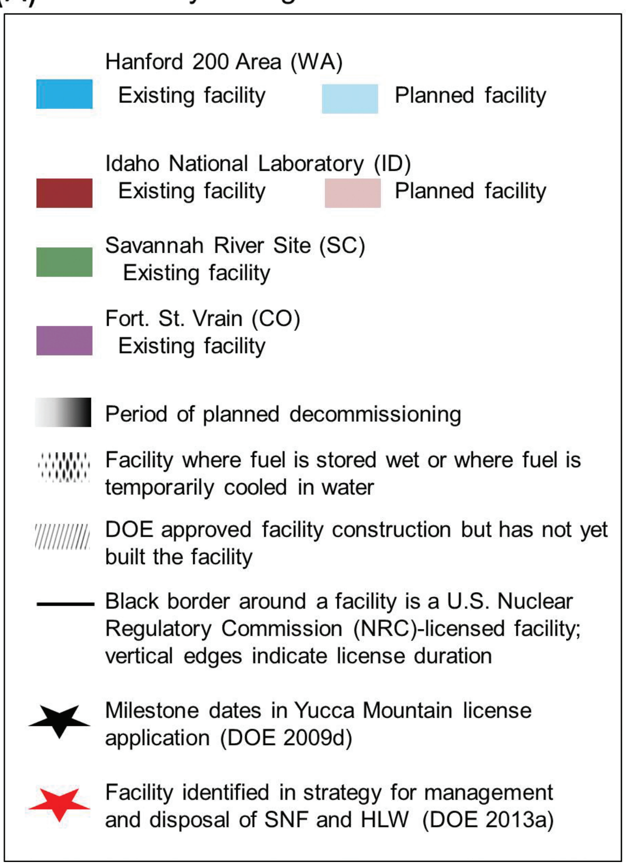
dates for the U.S. repository program based on current law. The program schedule (DOE 2009d) includes the time needed to initiate a repository program (*e.g.*, developing an application and constructing the facilities prior to accepting SNF).

DOE SNF storage facilities range in age from less than four years old to more than 60 years old (Figure 8-2B). Based on DOE's recent schedules (DOE 2013a), it could be another 30 or more years before DOE SNF is transported to a geologic repository. Given that the pre-closure operational period for a repository can last about 50 years (DOE 2009a), multi-purpose canisters that already store DOE SNF will need to contain the radionuclides for about 80 more years, or until DOE places an overpack (*e.g.*, an encapsulating waste package for disposal) around the multi-purpose canister, which can then serve as the radionuclide confinement barrier for DOE SNF.

Based on SNF management timelines, the Board finds that additional multiple decades of dry storage operations are likely, if not unavoidable, and will require DOE aging management efforts beyond the original estimated lifespans for SNF facilities, structures, systems, and components.

Both the U.S. Government Accountability Office (GAO 2011) and the Board (Garrick 2010b) previously recommended that DOE assess issues associated with aging management. GAO (2011) recommended that DOE "assess existing nuclear waste storage facilities and the resources and information needed to extend their useful lifetimes."

(A) Key for Figure 8-2B



Explanatory Text for Figure 8-2B

The locations of DOE SNF are identified in the left column (primary locations) and right column (other locations). The foreign research reactors in the Other Locations column represent locations from which spent highly-enriched-uranium fuel, and other SNF the United States has agreed to accept in accordance with its nuclear non-proliferation policy (DOE 2008a), is being returned.

The facilities at the Hanford site, and their dates of operations and decommissioning, are described in Chapter 4 and are based on Hanford's Lifecycle Report (DOE 2012b).

The Idaho National Laboratory facilities are described in Chapter 5. The end-of-operations date of 2035 for most of the facilities reflects the 1995 Settlement Agreement (Idaho *et al.* 1995) deadline for removal of all SNF from Idaho. Some amount of naval SNF is allowed to remain after 2035 (Idaho *et al.* 2008), and the new facility that is being built at the Naval Reactors Facility is expected to operate for at least the next 40 years (Section 5.2.2.5; DOE 2016a). The 1995 Settlement Agreement requires wet storage of SNF, which occurs at CPP-666, to end by 2023, with minor exceptions for naval SNF (Idaho *et al.* 2008).

The Savannah River Site storage facility is described in Chapter 6 and the 2055 end-of-operations date reflects an approximate end of safe operations date (Sindelar and Deible 2011).

The NRC-licensed Fort St. Vrain facility is described in Chapter 7. The initial and renewed license periods (NRC 2011b) are depicted.

continued on page 135

Figure 8-2. Figure key, explanatory text, and integrated timeline of existing and proposed U.S. Department of Energy facilities for managing and disposing of spent nuclear fuel.
A. Key and explanatory text for integrated timeline (depicted in Figure 8-2B). B. Graphic depiction of integrated timeline of existing and proposed DOE facilities for managing and disposing of SNF.

continued from page 134

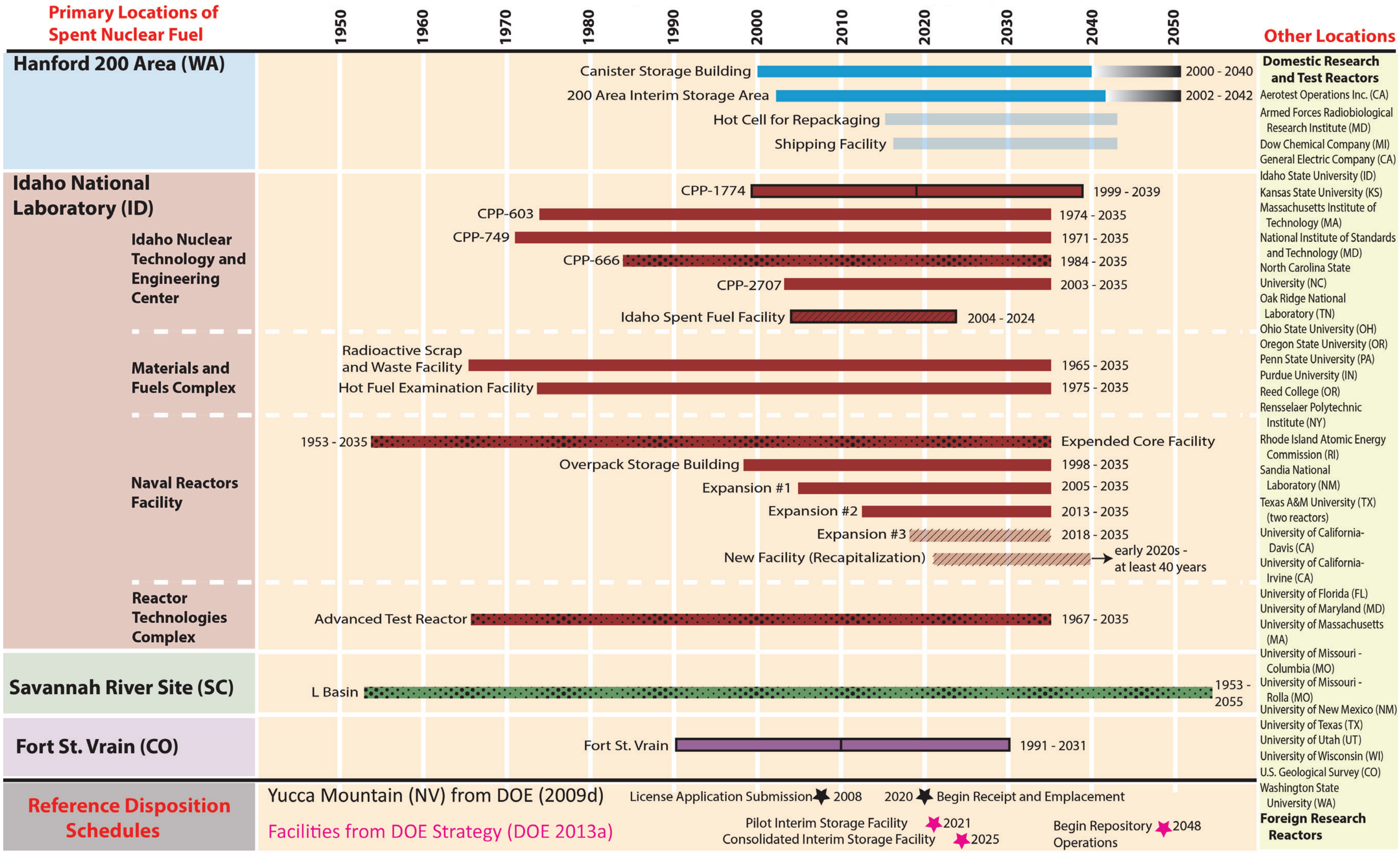


Figure 8-2 (cont.). Figure key, explanatory text, and integrated timeline of existing and proposed U.S. Department of Energy facilities for managing and disposing of spent nuclear fuel (continued).
A. Key and explanatory text for integrated timeline (depicted in Figure 8-2B). B. Graphic depiction of integrated timeline of existing and proposed DOE facilities for managing and disposing of SNF.

GAO (2011) also recommended that DOE "identify any gap between past and ongoing research into long-term nuclear waste storage and any additional actions needed to address DOE's … storage needs." In 2010, the Board recommended that the as-built lifetimes (as opposed to the design lifetimes[211]) of all SNF dry storage systems at INL be assessed because it was not known at that point when a repository or storage location outside Idaho would become available. Garrick (2010b) indicated that studies of the safety, cost, and technical issues associated with various alternatives for managing, packaging, and transporting SNF could also assist the DOE Office of Environmental Management (DOE-EM) in its long-term planning efforts. DOE has not yet completed an assessment that addresses GAO and the Board's (Garrick 2010b) recommendations.

The Board finds that, without aging management assessments that anticipate storing DOE SNF for multiple decades in DOE storage facilities, DOE cannot confidently determine whether the capability of existing storage facilities, including the ability to retrieve SNF for packaging and transportation, will be available when needed, and whether the retrieved SNF will be suitable for subsequent fuel cycle steps.

8.2.1 Programs to Manage Degradation of Spent Nuclear Fuel and Container Materials

At both the Idaho Nuclear Technology and Engineering Center (INTEC) CPP-1774 facility at INL (Sections 5.1.1.1 and 5.3.2.1.1) and the FSV storage facility (Section 7.1.1), DOE is managing age-related degradation according to NRC's aging management requirements. Also at INL, DOE and the Navy decided to recapitalize the Expended Core Facility infrastructure to overcome age-related degradation of its existing facility (Section 5.2.2.5). Finally, at the L Basin at SRS, DOE completed an aging management assessment comparable to that required by NRC (Section 6.1.1). For all other DOE SNF storage facilities, the Board could not find evidence that DOE has taken steps to manage age-related degradation of stored SNF or manage age-related degradation of packaged multi-purpose canisters.

The Board finds some DOE SNF storage facilities lack aging management programs to facilitate retrieval of stored DOE SNF either for packaging of fuel into multi-purpose (storage, transportation, and disposal) canisters or for continued use of already packaged multi-purpose canisters.

In October 2014, DOE described the SRS aging management assessment and SRS aging management activities at the Board's public meeting in Augusta, Georgia. The Board commends DOE for completing an assessment of the 60-year-old L Basin SNF storage facility (Sindelar and Deible 2011) to evaluate what aging management activities (*e.g.*, periodic inspection of the fuel and storage systems) are required to ensure that the facility can safely store and retrieve SNF from the pool for an additional 50 years. DOE's assessment also determined that an extensive set of aging management activities needed to be conducted (Sindelar and Deible 2011).

The Board finds that DOE's aging management assessment for the L Basin facility is a good example that DOE can use as a model for assessing aging management activities at its other SNF storage facilities.

Regarding aging management activities at SRS, the Board recommended accelerating the augmented monitoring and condition assessment program to substantiate the condition of the fuel and facilitate future SNF handling, drying, and packaging operations (Ewing 2015). DOE has not fully implemented[212] its augmented monitoring and condition assessment program. The Board also recommended that DOE consider additional actions to validate the structural integrity of L Basin (described in Section 6.3.2.4; Ewing 2015).

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[211] The design lifetime is the period during which the component is expected by its designers to work within its specified parameters. The design life of the facility or component is specified at the beginning of a project. Building and fabrication projects often undergo many changes during the construction phase as project teams respond to needed changes and unforeseen conditions. The as-built lifetime is the period during which the component is expected to work, based on the as-built conditions.

[212] Sautman and McCabe (2016) noted that DOE is looking for funds to pursue the following activities in future fiscal years: "completing the baseline evaluation of the designated aluminum (Al)-based fuels; evaluating options for non-intrusive examination of selected higher-risk non-Al fuels and fuels in isolation cans; conducting non-intrusive examinations of selected higher-risk non-Al fuels and fuels in isolation cans; periodically removing 'cobwebs' as needed; and completing galvanic isolation and installing covers for TSR [Technical Safety Requriements] fuel."

8.2.2 General Approach for Developing an Aging Management Program

DOE focuses on near-term safe SNF storage using a documented safety analysis for each SNF storage facility that is updated annually (DOE 2013h). This approach does not lend itself to analyzing slowly evolving conditions over the long term, such as aging components, nor does it provide an easy method to assess the future safety of a facility and its stored SNF for extended periods. The Board acknowledges that DOE addresses aging management of its facilities using an approach that includes monitoring, surveillance, and maintenance (Hain 2010a); however, this approach does not explicitly evaluate what would be required to retrieve the SNF after extended periods of storage and subsequently condition[213] (Section 5.3.2.2.2), package, transport, and dispose of it in the future.

The Board recognizes that not all DOE SNF storage facilities are subject to NRC regulation; however, the structured approach in NRC's guidance for renewing dry storage systems licenses (NRC 2016b, 2016c; Torres *et al*. 2015) provides a defensible technical approach to evaluate and manage aging effects associated with the extended periods of storage. NRC guidance documents identify and assess known aging degradation mechanisms (NRC 2016b), and provide example aging management programs (NRC 2016c),[214] including details on sampling techniques (NRC 2016b; Torres *et al*. 2015). Applying this type of approach would be of assistance to DOE in determining the research and development needs that would enable the anticipated extended periods of time SNF can be stored prior to packaging for off-site transport, and for subsequent aging management of SNF in multi-purpose canisters prior to their disposal.

8.2.3 Reflecting the Diversity of Spent Nuclear Fuel and Storage Conditions

NRC's dry SNF storage aging management guidance is based on aging management of light-water reactor SNF that is not significantly damaged (NRC 2016b, 2016c); however, DOE's SNF is more diverse, susceptible to degradation, and more damaged than commercial SNF (Appendix 2). This diversity both complicates and increases the importance of DOE's assessment and subsequent management of potential age-related degradation of SNF and canisters that contain it. Because of the diversity of DOE SNF, both in terms of composition and its physical state, addressing aging management will not be a simple undertaking for DOE.

The Board finds that the diversity of DOE SNF and cladding compositions, and the extent of DOE SNF and cladding degradation, requires DOE to focus on degradation of SNF while in storage to enable retrieval and subsequent SNF management activities.

The diversity of DOE storage containers and facilities at sites other than FSV may require developing new monitoring techniques and improving understanding of degradation mechanisms for materials beyond those already considered in aging management programs for stored commercial SNF. For example, DOE SNF storage facilities and the storage containers (*e.g.*, transportation casks and carbon steel pipes with shield plugs installed underground at INL) are more diverse, in terms of materials used and environments exposed, than NRC-licensed commercial SNF storage casks and storage facilities.

*Because different materials are subject to different degradation modes and rates (*e.g.*, carbon steel is much less resistant to uniform corrosion than stainless steel), and the modes and rates of degradation are a function of environmental conditions, DOE will need to assess age-related degradation for a wider variety of materials and storage environments than NRC has assessed.*

NRC developed generic aging lessons-learned guidance reports for a broad spectrum of materials and processes for commercial nuclear reactors, including pool storage of SNF (NRC 2010b, 2015b), for periods of up to 80 years. These docu-

213 Conditioning is defined as "any process which prepares or treats SNF or HLW for transportation or disposal in accordance with regulatory requirements and Office of Civilian Radioactive Waste Management acceptance criteria. This includes processing (*e.g.*, vitrification) of HLW and passivation of SNF" (DOE 2007a).

214 Electric Power Research Institute (2017) provides additional aging management guidance to address stress corrosion cracking of welded stainless steel canisters.

ments and others[215] are valuable for identifying the materials subject to aging, for describing methods for assessing the effects of aging on the different materials, and for defining potential aging management programs.

DOE addressed material interaction and degradation mechanisms (*i.e.*, aging) that could potentially affect the performance of a DOE standardized canister loaded with aluminum-based fuel during the interim storage period (50 years) between canister loading and transportation for final disposition (Hurt 2013). Material interactions that affect fuel,[216] baskets, or other canister internals were outside the scope of the report (Hurt 2013). The Board notes that DOE's evaluation (Hurt 2013) did not address the chemisorbed water that could remain in sealed multi-purpose canisters if supplemental neutron absorbers are used.

8.2.4 Knowledge Management

The Board finds that capturing past knowledge of DOE SNF management activities and leveraging the broader SNF community's knowledge of SNF and SNF storage facility aging are important for developing DOE's SNF aging management programs.

At its August 2014 public meeting in Idaho, the Board heard several examples that suggested that portions of DOE's experience base related to past SNF handling operations and other management activities have been lost in recent years. For example, in describing the difference in DOE SNF management programs now and in the recent past, McCormack (2014d) noted that, from a Hanford perspective, "… we have lost a lot of the people, not just at the national program, but even at the sites, that had familiarity with the programs to disposition the fuel. And that really shows up potentially in a lot of the decisions that are made or even the ability to resurrect work or understand what's important to the near-term decisions let alone the final decisions." The Board recommended (Ewing 2014a) that DOE take early action to capture this critical knowledge so that it can be used to support later DOE efforts related to handling of the wastes, certifying transportation and storage waste packages, interim storage, and final disposal.

At the same meeting, both Carlsen (2014b) and Beller (2014d) described to the Board the difficulty they faced in trying to retrieve information on past DOE operations including developing the DOE standardized canister and SNF drying efforts at INL. The Board recommended (Ewing 2014a) that DOE assess the level of record preservation and retrieval capability of DOE field office site organizations and ensure that all records related to the past management of SNF and HLW are easily accessible and retrievable to support future waste management activities.

The DOE Office of Nuclear Energy (DOE-NE) and, to a lesser extent, DOE-EM, participates in the Electric Power Research Institute Extended Storage Collaboration Program. The mission of this program is to provide the technical basis to ensure continued safe, long-term commercial SNF storage and future transportability (Kessler and Waldrop 2012). One goal of the program is to support development of industry aging management plans regarding inspection, mitigation, repair, and replacement. Previously, the Board stated that it regarded the program as an extremely valuable undertaking and strongly endorsed DOE's continued active participation in the collaboration (Garrick 2011). The Board continues to hold this opinion.[217]

In addition, DOE-EM has two other opportunities to leverage broader SNF storage aging management knowledge. DOE-EM has participated, to varying degrees over time, in the Transnuclear Inc. (now AREVA-TN) user group that is composed of the vendor and over 30 NRC licensees who use the NUHOMS® storage systems, like that used at INL at the INTEC CPP-1774 facility. Through the Institute of Nuclear Power Operators (INPO), the commercial SNF dry storage industry developed an aging management database known as the independent spent fuel storage installation AMID

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215 Electric Power Research Institute developed aging management guidelines for commercial nuclear reactors (*e.g.*, Electric Power Research Institute 2002). International experience on aging of a wide variety of SNF compositions and programs to manage aging fuel and storage facilities is compiled by the International Atomic Energy Agency (IAEA 2006).

216 A common assumption with use of multi-purpose canisters is that SNF, once packaged, is not retrieved from the canister.

217 The Board notes that during the Extended Storage Collaboration Program's meeting in November 2017, the topic of whether the scope of the program should be expanded to include aging management for research reactor and other non-commercial fuel types (*i.e.*, DOE SNF), as well as the associated containers and storage facilities, was discussed.

(Aging Management INPO Database). As described by the Nuclear Energy Institute (2016), the approach involves the collection and assessment of dry cask storage aging-related operating experience, research results, monitoring feedback, and inspection data, which "is being generated on a continual basis across the various dry storage technologies and at a wide variety of geographic locations nationwide." That information will be collected and made accessible to the appropriate parties via the independent spent fuel storage installation AMID (Nuclear Energy Institute 2016). As of June 2016, DOE was evaluating participating in the database via AREVA-TN (Banovac 2016) as part of its license renewal for the INTEC CPP-1774 facility [*i.e.*, the Three Mile Island Unit 2 (TMI-2) independent spent fuel storage installation].

8.2.5 Facilitating Aging Management in New Facilities and Designs

NRC's approach for aging management activities for commercial SNF storage facilities relies heavily on obtaining information from inspections and monitoring during storage (Csontos 2015a, 2015b). As more NRC-regulated facilities undergo formal aging management assessments and efforts are made to monitor existing cask systems, monitoring is made more difficult by configurations of existing storage casks that were not necessarily designed with ease of inspection, maintenance, and testing in mind (Csontos 2015a, 2015b). For example, it is difficult to determine whether corrosion is occurring from salt accumulations on canisters inside NUHOMS® concrete horizontal storage modules, like those used at the TMI-2 facility at INL. When DOE designed the Canister Storage Building and the MCO at Hanford, it included monitoring as a necessary function for both the package and storage facility. DOE monitors internal conditions in about 4% of the MCOs (Section 4.1.1) in storage at Hanford, at a decreasing frequency with time, by measuring pressure and temperature and by gas sampling.

Given the uncertainty in how long DOE SNF will be stored prior to disposal, the Board finds that having the ability to measure and monitor conditions of the SNF inside canisters, the external surfaces of canisters, and the storage facility itself during future storage is an important consideration in designing, developing, and deploying new DOE storage systems, such as a DOE standardized canister, and for new packaging and storage facilities.

8.2.6 Considering Post-storage Spent Fuel Management Activities

NRC's SNF aging management approach focuses solely on maintaining safety during storage, which is appropriate for the storage facilities, but may not be adequate to ensure that the contents are acceptable for subsequent fuel cycle operations involving the SNF storage containers and SNF—especially if the SNF needs to be retrieved or repackaged[218] after transportation.

For example, DOE described possible degradation mechanisms of DOE standardized canisters during long-term storage, which could generate 10% by volume of hydrogen gas inside the canisters due to radiolysis of residual water (Rahimi 2007b). NRC staff reminded DOE that the standard review plan for transportation packages of SNF (NRC 2000) states that "combustible gases should not exceed 5% of the free gas volume in any confined region of the package" (Rahimi 2007b). DOE projections of hydrogen that is generated during storage in the MCOs for a period of 40 years is greater than 10% by volume for 5 of the 15 monitored MCOs (Bader 2013, Appendix C). In those projections, hydrogen was assumed, conservatively, not to react with SNF and therefore to simply continue to build up (Bader 2010). However, the hydrogen does react with SNF and, as described in Section 4.1.1, measured values of hydrogen gas concentration in MCOs to date (<10 years of storage) ranged between <0.001% to almost 3% and seem to be decreasing with time, consistent with SNF reacting with hydrogen (Bader 2013). Whether the hydrogen gas concentration remains low during the decades of MCO storage will be determined by future monitoring results and associated data analysis.

The aging management program for multi-purpose canisters and their contents has not sufficiently considered both the requirements for storage per se, *in which the canister is the sole radionuclide confinement barrier, and NRC requirements for subsequent fuel cycle operations that are different and may be more restrictive.*

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[218] The surface facilities operations for the Yucca Mountain repository included capabilities and facilities for removing commercial SNF assemblies from dual-purpose canisters and repacking into transportation, aging, and disposal canisters (DOE 2009a, p. 1.2.1-6).

8.3 Developing Confidence That Drying Procedures Will Not Lead to Conditions That Require Future Repackaging

Adequately drying DOE SNF during packaging is important because residual water generates hydrogen in sealed multi-purpose canisters that could accumulate and prove to be a challenge for meeting NRC transportation criteria. Residual water also can lead to adverse material interactions that may affect canister integrity (Section 2.3.1). Residual water can include chemisorbed water associated with SNF and metal corrosion products as well as any supplemental neutron absorbers that are used for post-closure criticality control. Because DOE aluminum-based SNF will be in about 29% of all DOE standardized canisters (Section 6.4) and aluminum-based SNF can have a high surface area, a thick corrosion layer on the cladding, a hydrous chemical composition of the corrosion layer, and high potential water content, the Board focuses on drying procedures for aluminum-based SNF.

DOE recognizes the importance of residual water, both free and chemically bound, in its waste acceptance system requirements[219] (DOE 2008a). The DOE Office of Civilian Radioactive Waste Management (OCRWM) required information on this subject from DOE-EM[220] as part of its waste acceptance process (DOE 2007a) and required that drying results in similar residual water content to that required by NRC.

NRC states that, depending on the amount of water remaining after drying, adverse degradation processes within a sealed canister can be shown to be "not credible" or limited for a defined period of time[221] (NRC 2016c); however, the NRC guidance for managing aging processes in storage (NRC 2016c) has two important limitations relative to DOE SNF. First, the NRC report focuses on commercial SNF and relies on a scoping study of the adequacy of drying (Jung *et al*. 2013) that assumes 1 liter (0.26 gallon) of residual water per container, which is less than the range of chemisorbed water [1.7 to 3.2 liters (0.45 to 0.85 gallon)] for the amount of aluminum-clad DOE SNF to be stored in a standardized canister (Hurt 2013). Second, the NRC report (2016c) does not consider the implications of material interactions with the water, such as corrosion, that occur during storage and will continue beyond storage during subsequent transportation or potential repository handling operations. The water-related material interactions that occur within the DOE SNF multi-purpose canisters need to be evaluated to ensure that the containers can be safely stored for extended periods and subsequently transported, handled, and emplaced in a geologic repository.

DOE recognizes the importance of assessing the material interactions on canister integrity during storage and the limitations for the basis for its conclusion "that, if properly dried, sealed, and maintained under controlled storage conditions, the containment functions of the canister are highly unlikely to be jeopardized during the identified period [the 50-year storage duration of aluminum-clad SNF]" (Hurt 2013). In particular, Hurt (2013) recommends "additional scientific investigation to evaluate possible long term increases in free water or physisorbed water content via equilibration or dehydration/decomposition of chemisorbed water."

In August 2014, DOE described to the Board its experiences in drying SNF for storage at INL and at the Hanford Site (Beller 2014b; McCormack 2014b). At INL, from 1999 to 2001, DOE retrieved more than 300 canisters containing TMI-2 core debris from wet storage and dried them (Beller 2014b). Development of the INL drying process was based on extensive mock-up testing of the drying unit and most of the knowledge base for that drying campaign has since left INL (Beller 2014b).

As opposed to INL, Hanford relied more heavily on modeled results to determine the drying requirements for SNF stored in sealed MCOs (McCormack 2014b). Hanford did not focus on collecting data prior to drying the SNF. Instead, DOE

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[219] OCRWM "must ensure, through information and data provided by Federal Waste Custodians of SNF that the waste form (including residual free water) does not cause the repository or transportation system to fail to meet the applicable NRC performance-based requirements or any conditions of an operating license or certificate of compliance" (DOE 2008a).

[220] "This information will allow OCRWM the opportunity to consider the impact of the presence of free and chemically bound water and to develop an action plan, if necessary, jointly with the Federal Waste Custodian" (DOE 2008a).

[221] NRC (2016c) evaluates known aging degradation mechanisms "to determine if they could affect the ability of dry storage system components to fulfill their safety functions in the 20- to 60-year period of extended operation."

monitors some of Hanford's MCOs during storage (Section 4.1.1) to assess the sufficiency of its drying. Based on information communicated during the meeting, the Board recommended[222] that "DOE collect additional empirical data in order to develop an understanding of the important processes that can occur during drying and afterwards in a sealed container with SNF that may not have been adequately dried" (Ewing 2014a).

8.3.1 Obtaining Data to Develop a Better Understanding of Processes That Occur During Drying and Afterward in Sealed Multi-purpose Canisters

Unless storage basin water chemistry is carefully controlled, aluminum-based DOE SNF will corrode at unacceptable rates during wet storage (Figure 8-3A; Lundberg and Croson 1994). Corrosion damage and aluminum corrosion products of Advanced Test Reactor (ATR) SNF at INL are visible in underwater video surveillance (Lundberg and Croson 1994). It is difficult to estimate the amount of chemisorbed water present on aluminum-based DOE SNF prior to drying due to uncertainty in the types of aluminum hydroxides that may be present on the fuel surface. There is limited water vapor pressure data as a function of temperature for these partially hydrated oxides, which leads to uncertainty in projecting how much water could be released during heating. Water vapor concentrations also may change over time because of high temperature or slow decomposition (dehydration) of corrosion products on aluminum-based SNF.

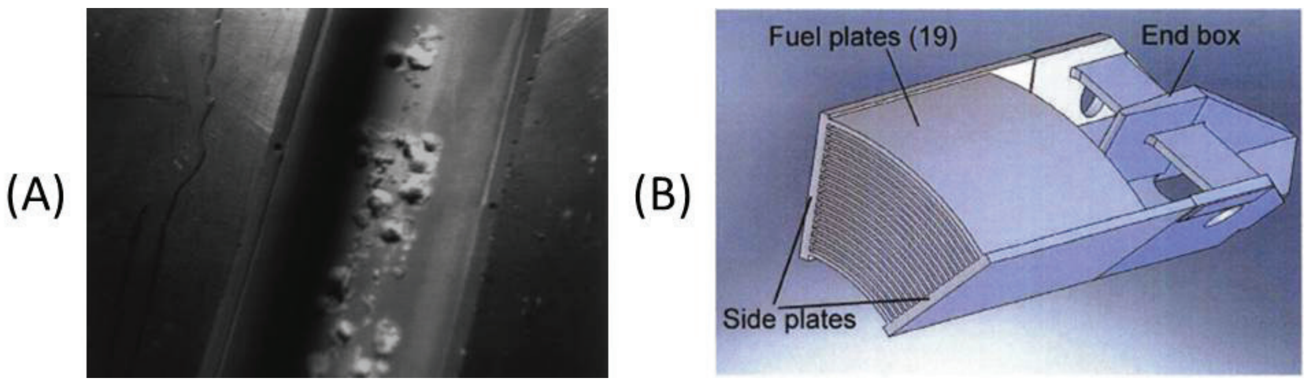

Figure 8-3. Aluminum-clad U.S. Department of Energy spent nuclear fuel.
A. Corrosion of Materials Testing Reactor–type assembly (aluminum-based) with pit corrosion damage on fuel plate cladding over fuel material region. (Source: Carlsen *et al.* 2005). B. Section view of the large surface area of an Advanced Test Reactor fuel element with 19 plates per element. (Source: AREVA Federal Services 2012).

A technical standard[223] exists that addresses drying of DOE SNF (ASTM 2008). The standard includes a drying process objective to minimize hydrogen generation or materials corrosion that could be a problem during transport or repository handling operations. ASTM (2008) identifies approaches to confirm dryness, involving estimating quantities of unbound water and chemisorbed water either by measurement or by process knowledge. Appropriate dryness measurement techniques include either a pressure rebound test or water vapor pressure measurements from devices mounted in-line on the cask exhaust during drying, pressure testing and monitoring during storage, and measuring the canister's internal hydrogen concentration. The process knowledge approach may be impractical for many DOE SNF types (ASTM 2008) because it requires good records of the history of the fuel irradiation, drying, and dry storage.

DOE will still need to determine accurately the amount of chemisorbed water remaining after drying because most of the chemisorbed water remains after the standard drying processes. To determine the amount of remaining chemisorbed water, DOE will have to estimate the location and amounts of chemisorbed water as a function of the type of SNF, the extent of fuel damage, the amount of corrosion products and sludge, and any other components that may be inside the

[222] DOE did not provide the MCO monitoring results (Bader 2013) to the Board prior to the Board's letter (Ewing 2014a).

[223] The National Technology Transfer and Advancement Act of 1995 mandates that all federal agencies use technical standards developed and adopted by voluntary consensus standards bodies, as opposed to using government-unique standards. ASTM (2008) "Standard Guide for Drying Behavior of Spent Nuclear Fuel" is one such technical standard.

multi-purpose canister (ASTM 2008). DOE used this approach for the Hanford drying process and identified five sources of chemisorbed water (*e.g.*, adhering particulates; Bader 2010, Table 2-1).

DOE used the same approach it used for the Hanford drying process to assess material interactions associated with aluminum-based SNF stored in sealed canisters (Hurt 2013); however, in developing its drying protocols for aluminum-based SNF (Hurt 2013), DOE did not account for the supplemental neutron absorbers that are locations for chemisorbed water, which may be added to approximately 200 DOE standardized canisters (Table 2-2). For a DOE standardized canister containing gadolinium phosphate—a type of neutron absorber—Carlsen *et al*. (2005) estimated there could be as much as 900 grams of chemisorbed water. The actual amount of gadolinium-phosphate-associated water that could be in a canister will depend on the final specifications for the absorber (DOE 2009e) and how much supplemental absorber is added to a canister to control post-closure criticality.

As described in ASTM (2008), DOE will need to estimate the rates of corrosion and radiolytic decomposition of water for the materials and the quantity of chemisorbed water in the DOE standardized canister. Although DOE has already assessed corrosion rates, it has only partially assessed radiolytic decomposition. Hurt (2013) used available *G* values (the number of hydrogen molecules produced per 100 electronvolts of energy absorbed by a substance) for surface water films on Al_2O_3 (*G* value of 0.2) and pure minerals free of fission products (Icenhour *et al*. 2002) to assess radiolytic hydrogen generation; however, *G* values are material-specific. Drying aluminum-clad SNF at 200–250°C to 3 torr is expected to decompose the hydrated aluminum oxides and uranium oxides to boehmite and $UO_3 \bullet 0.5H_2O$ and release water (Hurt 2013); however, uncertainty in how much water will be released from trihydrates during drying (Hurt 2013) results in uncertain effective *G* values for alumina corrosion products.

ASTM (2008) identifies that estimating equilibrium water vapor pressure over the fuel as a function of temperature must be considered in determining the effects of chemisorbed water. ASTM (2008) states that estimating the rates for reaction/recombination of radiolyzed species by other materials within the container (*e.g.*, formation of uranium hydride on uranium metal from reaction with hydrogen) can be part of determining the effects of chemisorbed water. DOE conservatively neglected this process for estimating hydrogen generation of N Reactor SNF stored in MCOs at the Hanford Site (Bader 2010). MCO gas monitoring results indicate that hydrogen is clearly reacting with uranium and that this process helps avoid a flammable gaseous mixture inside an MCO (Bader 2013).

Based on its review, the Board finds that obtaining the following data will provide DOE a better understanding of processes that occur during drying and afterward in sealed multi-purpose canisters that will contain the remaining DOE SNF that needs to be packaged: data on chemisorbed water that remains under proposed vacuum drying protocols (Hurt 2013), including waters of hydration for the fuel; water associated with uranium, aluminum, and iron oxides and hydroxides; and water associated with gadolinium phosphate neutron absorber material.

Because of the uncertainty in masses and types of aluminum corrosion products that could be on aluminum-clad SNF that is packaged, characterizing aluminum minerals (mass and mineral identification) that are present after drying will constrain estimates of remaining chemisorbed water. Information on the *G* value of supplemental neutron absorbers and the iron or aluminum shot that incorporate the absorber (DOE 2009e) could inform DOE's selection of the final design requirements for the supplemental absorber and shot. Similarly, determining radiolytic hydrogen generation rates of actual aluminum minerals that remain after drying would enhance confidence. Furthermore, data that confirm the validity of the limited water vapor pressure data as a function of temperature for partially hydrated oxides would reduce uncertainty. Refining estimates of the amount of time it takes to reach a specified level of dryness (*e.g.*, how many drying steps are needed before the pressure rebound test is passed) could inform the design of the packaging facility at INL (Section 5.3.2.2.2) and its potential throughput.

DOE-NE is funding a project to experimentally simulate and model commercial SNF that is dried by vacuum for dry cask storage (Knight 2016). The experiment uses heater rods to simulate the decay heat of SNF to be dried. This experiment does not use SNF: instead, it uses non-radioactive analog materials (*e.g.*, cerium oxide to simulate uranium oxide in a failed fuel rod). Key parameters that will be measured or evaluated indirectly include temperature, chamber pressure, gas composition, gas flow rate, water removed as a function of time, and indication of ice formation[224] (Knight 2016).

The Board finds that this experimental setup, the data generated during the ongoing experiments, and the associated computational modeling may be useful to address some of the data gaps associated with the DOE SNF drying process.

8.3.2 Predicting and Monitoring Gas Composition and Pressure of Sealed Multi-purpose Canisters

Hurt (2013) assessed processes that could occur in DOE standardized canisters and concluded that "there are no credible degradation mechanisms that would significantly degrade canister performance during a 50-year period of interim storage and subsequent transportation and related operations, provided proper heated drying is conducted before sealing and that temperatures of sealed canisters remain below the drying temperature" (Hurt 2013). Both Hurt (2013) and Jung *et al.* (2013) point to radiolytic hydrogen generation, leading to hydrogen accumulation, as the key uncertainty and potential problem, especially for longer periods of storage. However, Hurt (2013) assessed whether pressurization of the canister by hydrogen generation could reach the canister's pressure limit and not whether hydrogen concentrations could be larger than NRC's acceptance limit for transportation.

Hurt (2013) argues that estimates for hydrogen production in DOE standardized canisters[225] significantly overestimate the potential hydrogen concentration increase. More sophisticated models of hydrogen accumulation are available (Bader 2010; Jung *et al*. 2013), but there are often insufficient data to support a regulatory decision adopting a less conservative approach. Nonetheless, Hurt (2013) concludes that "any pressurization by residual water or hydrogen gas, sufficient to jeopardize the performance of the canister, is highly unlikely over the 50-year period, contingent upon implementation of confirmatory monitoring of the pressure within a representative sample of sealed canisters over 10 years or more."

Up to this point, monitoring the MCOs confirms that DOE model projections of hydrogen accumulation, which did not credit hydrogen reactions with metallic uranium SNF, were conservative. Continued monitoring of pressure and gas constituents could provide DOE the data needed to support its analyses concluding that the MCOs can be transported and used for decades into the future.

The Board finds that, based on both the results of the Hanford Site's monitoring approach and the uncertainty in how to dry SNF sufficiently so that it does not need to be repackaged, DOE could adopt an approach, similar to that used for the MCOs, of predicting and monitoring gas composition and pressure of sealed DOE standardized canisters. Doing so will add confidence that the standardized canisters could be used for decades into the future and will allow DOE to move away from conservative estimates, which could indicate that repackaging or other compensatory action is required.

DOE incorporated a design option for a threaded plug in the top and bottom heads of the DOE standardized canister that could be used for monitoring (Section 2.3.2); however, the plug is not part of the baseline design of the standardized canister.

The Board finds that the lack of a threaded plug in the baseline design for DOE's standardized canister will preclude monitoring of gas constituents and pressure in the standardized canisters.

8.4 Implementing Use of Multi-purpose Canisters

A multi-purpose canister, such as the MCO, along with its transportation infrastructure, must be designed, developed, reviewed, and approved prior to its use in storage, transportation, and disposal. Each of DOE's multi-purpose canisters is at a different stage in this process (Figure 8-1 and Table 8-1). Many of the actions that need to be completed are routine activities in waste management operations (*e.g.*, actions D–I in Table 8-1) and are independent of whether a multi-purpose canister is stored off site prior to its transportation to a repository. Section 8.4.1 addresses the activities that need to

[224] One reason why DOE is using elevated temperatures to dry some of its SNF is to reduce the potential for ice formation (Hurt 2013).

[225] DOE's projections for hydrogen (volume percent) in MCOs range between 2% and 26% after 40 years of storage, assuming hydrogen does not react with the uranium metal fuel (Bader 2013).

be completed to use the MCOs in a waste management system. Section 8.4.2 addresses both the routine activities and the more complex activities that need to be completed to use the DOE standardized canister (*i.e.*, actions A–C in Table 8-1) in a waste management system. Section 8.4.3 addresses considerations if multi-purpose canisters are transported to, and stored at, an interim storage facility prior to their transport to a repository.

Table 8-1. Gaps to address before multi-purpose canisters can be used in a waste management system

Gap or Action to Complete	Multi-Canister Overpack	DOE Standardized Canister	Naval Canister
A. Complete research and development to support the canister design	✓ (1; see Notes)	TBC (1)	✓ (1)
B. Obtain canister moderator exclusion approval from NRC (2)	TBC	TBC	✓
C. Complete multi-purpose canister design (3)	✓	TBC	✓ (1)
D. Analyze criticality (4)	TBC	TBC	✓
E. Analyze off-site transportability (5)	TBC	✓	✓
F. Determine whether an existing NRC-certified rail cask can be used (6)	TBC	TBC	✓
G. Complete canister packaging design within rail transport cask (7)	TBC	TBC	✓
H. Obtain NRC approval for rail transport cask with multi-purpose canister (8)	TBC	TBC	TBC
I. Evaluate safety during repository operations (9)	TBC	TBC	TBC

Notes

(1) A ✓indicates the action is complete and TBC indicates an information gap or action that needs to be completed. For the DOE standardized canister, DOE needs to complete development of remote welding and real-time non-destructive weld testing. Also, DOE needs to complete efforts for structural inserts using an advanced neutron absorber (a nickel-chromium-molybdenum-gadolinium alloy) and for iron- or aluminum-based shot with a gadolinium neutron absorber, such as gadolinium phosphate. NRC approved the naval canister for storage (Section 5.1.3.2) and the canister is in use.

(2) DOE's proposed approach for the DOE standardized canister is described in Section 2.4. For the naval M-290 cask, the requirement was met because water exclusion was not necessary to meet criticality requirements (Sampson 2014). Although DOE will need to obtain approval for the MCOs during rail cask certification, this should not be difficult because of the low-enriched uranium within the MCOs (Loscoe 2000).

(3) The indicated gap is based on results of research and development efforts, results from NRC's review of DOE's moderator exclusion approach, and DOE's pending decision whether to include a shield plug for monitoring the DOE standardized canister during storage as part of the baseline design.

(4) For MCOs, this gap applies only to MCOs loaded with scrap baskets. After developing supplemental neutron absorbers and additional NRC requirements that could be placed on the DOE standardized canister are determined as part of NRC's moderator exclusion review, DOE will need to complete criticality analyses to determine criticality loading limits for each canister with each criticality group (Section 2.5.1.2; DOE 2009a). "Final loading configurations (*i.e.*, fuel quantity, basket, and poison form) for each DOE SNF will be specified prior to packaging for repository acceptance" (DOE 2009e).

(5) For the MCO, this includes structural analyses for transporting the canister, steady state thermal analyses for a hypothetical MCO transportation cask, and criticality analysis for N Reactor fuels in a rail transportation cask. DOE completed these types of analyses as part of its DOE standardized canister topical report on moderator exclusion effort (Carlsen 2007, 2008).

(6) DOE's MCO scoping analyses used the NRC-certified HI-STAR 100® rail cask as a hypothetical cask. This cask, or another cask, will need to be confirmed once canister packaging design inside the rail cask effort is completed. For the DOE standardized canister, DOE is awaiting results of NRC's approval of DOE's moderator exclusion approach.

(7) For both the MCO and DOE standardized canister, the number of packages needs to be determined along with the design of a packaging insert. For the MCO, an internal to the cask supplemental impact limiter may need to be completed.

(8) For the MCO and DOE standardized canister, DOE will need to arrange for NRC recertification of rail casks for each canister. For the M-290 cask, the Navy needs to obtain NRC approval for transport of the long and short naval canister and has already planned for that action. "Due to the uncertainty in the opening of a repository, those safety analysis reports for packaging (SARP) are not included in this schedule. The earliest date that a SARP for shipments to a repository would be submitted to the NRC is in 2018" (Trautman 2014).

(9) The types of evaluations that need to be completed include providing sufficient design information and reliability analyses necessary to determine nuclear safety design bases for the MCO canisters (NRC 2015a). DOE also needs to complete structural and thermal finite element analyses of the three waste package configurations (5-DHLW/DOE long co-disposal, 2-MCO/2-DHLW co-disposal, Naval short), including performance under normal and event sequence load combinations (NRC 2015b). The types of analyses DOE needs to complete include (1) assessing the thermal responses of waste packages to a hypothetical fire accident and (2) structural analyses of vertical impacts of the waste package onto the emplacement pallet and rockfall impacts onto the waste packages (NRC 2015a).

8.4.1 Facilitating Use of Multi-canister Overpacks

When DOE closed OCRWM in 2010 (DOE 2010b), it assigned responsibility to DOE-NE for designing, securing NRC certification for, and fabricating the transportation cask systems to be used with the MCO and DOE standardized canister. However, since 2010, DOE-NE has focused its storage and transportation efforts on commercial SNF rather than on DOE SNF. Aside from developing system analysis tools (Jarrell 2016) that could be used for evaluating a waste management system that includes DOE SNF, DOE-NE is not currently conducting activities to support using the MCO (Kotek 2016a). DOE indicated it will include consolidated interim storage and transport to a repository or a consolidated interim storage facility for DOE SNF into out-year planning activities (Kotek 2016b).

During its August 2014 meeting in Idaho (Ewing 2014a), the Board learned that remaining developmental work for the MCOs is focused on survivability from off-angle drops during handling operations at a repository (*i.e.*, pre-closure safety) and off-site transportability (McCormack 2014a; Carlsen 2014c). The National Spent Nuclear Fuel Program identified key findings and recommended actions for dealing with off-angle drops during the pre-closure period (*e.g.*, an MCO-specific fragility curve should be developed); however, the program was put on hold prior to taking any actions on its recommendations (Carlsen 2014c). The National Spent Nuclear Fuel Program also completed scoping analyses for transporting the MCOs off site, which included structural analyses for transporting the MCO and steady state thermal analyses for a hypothetical MCO transportation cask. Other scoping analyses included transportability of a partially loaded MCO and criticality analyses for low-enriched uranium N Reactor fuels in a rail transportation cask (McCormack 2014a). DOE also noted the need to complete criticality analyses for MCOs loaded with scrap baskets (McCormack 2014d).

In addition, a DOE contractor shared[226] that DOE needs to (1) ensure the availability of a compatible commercial, NRC-certified transportation cask to transport the MCOs; (2) finalize the design for the loaded transportation cask, including determining the number of MCOs and the need for impact limiters within the cask; and (3) amend the certification of the commercial transportation cask to transport the MCOs. Based on what was communicated during the August 2014 meeting, the Board recommended that DOE resume efforts on the MCOs and DOE standardized canisters and that DOE explicitly assign responsibility for all transportation activities for SNF and HLW (Ewing 2014a).

The Board finds that DOE has not yet completed the MCO analyses and design for, or obtained NRC approval to use, the MCO in a SNF management system. The Board believes that, from a technical standpoint, completing the MCO tasks is not as urgent as DOE's efforts for the DOE standardized canister because the MCOs are monitored and stored in one of DOE's youngest storage facility and contain low-enriched SNF.

8.4.2 Facilitating Use of the U.S. Department of Energy Standardized Canister

DOE completed substantial work on developing the standardized canister (Section 2.3.2) prior to suspending efforts (Carlsen 2014a) in 2008, but it still has not completed standardized canister research and development, finalized its design, developed the necessary transportation capability, and obtained required approvals to use the DOE standardized canister in a waste management system (Table 8-1). Hanford, SRS, and INL all planned to use DOE standardized canisters for packaging DOE SNF now stored in a variety of aging facilities and packages. Completing the remaining work on the DOE standardized canister is a necessary step for each of the sites to manage its SNF.

Carlsen (2014b) noted that an early version of the DOE standardized canister was approved by NRC for storage at the unbuilt Idaho Spent Fuel Facility, but that version did not include the plug to enable monitoring of internal gas pressure and composition while in storage (Rodgers 2001). The Board recommended that DOE resume efforts on the DOE standardized canisters (Ewing 2014a), and more specifically it recommended that DOE resolve criticality issues related to transporting and disposing of the DOE standardized canister: "These efforts should include the submission of a topical report to NRC in order to confirm that the standard canister would be acceptable to the NRC staff as part of a transportation package based on the canister's ability to prevent intrusion of water under hypothetical transportation accident

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226 Telephone conversation between Bret Leslie, NWTRB staff, and Roger McCormack, CH2MHill Plateau Remediation Company, on September 29, 2014.

conditions" (Ewing 2014a). As Carlsen (2014a) pointed out, storage, transport, and repository handling operations[227] are independent of specific repository location or geology; thus, completing analyses that are not site-specific will facilitate using the DOE standardized canister in any waste management system.

The Board finds that DOE has not completed the actions and closed the gaps identified in Table 8-1 for the DOE standardized canister to be used in a waste system, especially items A–C that are complex undertakings requiring considerable time to complete.

8.4.3 Considerations for Off-site Storage

Long-term, interim, off-site storage of multi-purpose canisters was not part of DOE's original waste management system (Figure 8-1B). The waste acceptance system requirements (DOE 2008a) that DOE-EM is using do not consider interim off-site storage, nor do they include NRC's SNF storage regulation (Section 3.3.1) requirements, which DOE will need to use should this option be pursued. DOE developed the MCO and the Canister Storage Building at Hanford to achieve NRC nuclear safety equivalence[228] (Garvin 2002a, 2002b). In addition, DOE received an NRC storage license for an early version of the DOE standardized canister and vault storage in the Spent Fuel Facility at INL that DOE has not yet built (Section 5.3.2.2.2). Both these actions suggest that the MCO and DOE standardized canister could meet NRC's storage regulation and be stored at an NRC-licensed consolidated interim storage facility; however, several factors complicate potential off-site interim storage of DOE SNF in multi-purpose canisters.

First, NRC requires that the conditions at other sites be assessed if the same package is proposed to be transported to a new site and used there[229] to ensure that it can be safely handled and stored at the new site. Second, when NRC-certified SNF storage canisters are transported from their initial storage facility to another storage facility, they are subjected to conditions that are beyond approved storage design bases (*i.e.*, canisters and enclosed SNF may be exposed to forces during transportation that are not considered for a stationary canister). NRC expects applicants for a new storage facility to demonstrate, prior to storage at a new facility, that the canisters continue to meet the license conditions under which they were loaded (Lombard 2016). Third, DOE has not sought or obtained NRC approval for off-site transport of either the MCO or the DOE standardized canister.

If DOE continues to contemplate consolidated interim storage of DOE SNF at NRC-licensed facilities, it will be important for DOE to explore storage-transportation-storage issues to provide the basis for seeking NRC approval for off-site transport of the MCO and DOE standardized canisters.

Storage systems used for commercial SNF (Williams 2013) are canister-based or cask-based and are stored outdoors. By contrast, DOE uses for the MCOs and FSV SNF, and had planned to use for the DOE standardized canister (Section A2.3), indoor modular-vault-based systems, which rely on features of the building for cooling the SNF. Initial DOE consolidated storage facility (DOE 2013a) design concepts have focused on outdoor non-vault storage designs (AREVA Federal Services 2013; Shaw Environmental & Infrastructure 2013; EnergySolutions 2013) typically used for commercial SNF. If MCOs and/or the DOE standardized canisters are to be stored at a DOE consolidated storage facility, the impact of changing from an indoor modular-vault-based system to an outdoor non-vault storage design will need to be addressed.

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[227] Carlsen's statement is supportable for surface facility handling operations; however, vertical shaft emplacement versus transport down a ramp into a repository has different implications from an accident perspective to the waste packages that will contain the canisters.

[228] DOE defined nuclear safety equivalence to mean that DOE's design and construction had to be comparable to that of facilities licensed by NRC. DOE completed an assessment of compliance to demonstrate that the MCO met NRC equivalency criteria (Garvin 2002b, Appendix A1).

[229] For example, NRC (2015a) required, through a proposed condition of construction authorization for the proposed Yucca Mountain repository, that "DOE shall not, without prior NRC review and approval, accept dual-purpose (storage and transportation) canisters [that had been licensed for storage elsewhere] at the repository." NRC determined that additional analyses are needed to determine whether the dual-purpose canisters, which contain commercial SNF, meet site-specific nuclear safety design bases and criteria at the proposed repository (NRC 2015a, p. 7-114).

8.5 Designing, Building, and Operating a Packaging Facility

As described in Chapters 4, 5, and 6, Hanford, INL,[230] and SRS will need to design, build, and operate facilities to package DOE SNF into standardized canisters. To date, INL has the most well-defined packaging plans. As described in Section 5.3.2.2.2, DOE anticipated it would develop and evaluate alternative fuel disposition recommendations for a packaging and storage facility at INL starting in 2017. Also, DOE intended to approve project construction in 2023 and begin retrieving SNF for packaging in 2025 (Beller 2014d). The schedule described by Beller (2014a, 2014d) likely will be delayed because DOE did not receive funding in 2017 to develop and evaluate alternative fuel disposition options for a packaging and storage facility.

8.5.1 Completing Activities That Define the Scope of Required Operations Prior to Substantial Design Development of the Packaging Facility

At the Board's August 2014 meeting in Idaho, DOE described its plans for a packaging facility (Beller 2014a) and SNF management plans that affect the packaging facility (Lacroix 2014a, 2014b; Boyle 2014). DOE noted that, because requirements and schedules for a consolidated interim storage facility or geologic repository for SNF are not known, it cannot finalize plans and designs for the packaging and storage facility. Based on what it heard, the Board recommended "that DOE review and update the scope of the proposed packaging facility, taking into account the possibility that some SNF could be stored at the site beyond 2035, and examine how this extended period of storage could impact the capabilities needed and the timing for packaging the SNF" (Ewing 2014a).

Although DOE may not be able to finalize its plans and design, DOE can complete some activities that will help define the scope of required operations at the facility. For example, DOE could determine whether the packaging facility will be regulated by NRC and, if so, under which NRC regulation (Section 5.3.2.3.2). Knowing which regulatory requirements will apply is crucial for the facility design. If DOE obtains early NRC approval of the DOE standardized canister for storage and transport (*e.g.*, completing items B and F–H in Table 8-1), then DOE can refine design requirements for the standardized canister and its associated packaging and storage facility accordingly. In addition, completing development of supplemental neutron absorber materials and remote welding technology for a standardized canister in the near term will reduce the design uncertainty for the proposed packaging and storage facility. Finally, conducting the required research and development activities for drying DOE SNF[231] described in Section 8.3.1 and any necessary SNF treatment processes (*e.g.*, epoxied fuel and Fermi blanket fuel; see Figure 5-10 and discussion in Section 5.2.2.4) for unique DOE SNFs will also inform design development.

The Board heard from Lacroix (2014b) that DOE plans to continue to operate the ATR at INL beyond 2023,[232] which will continue to generate SNF at the site. The Board recommended that DOE assess the implications of the future generation and storage of SNF from the ATR beyond 2023 on DOE's proposed packaging facility (Ewing 2014b).

DOE is considering whether the INTEC CPP-603 facility, described in Section 5.1.1.2, could be reused as the drying and packaging facility. Alternatively, INL (Bohachek *et al.* 2013) has evaluated the INTEC CPP-603 facility for possible use in the high-burnup SNF cask demonstration program (Electric Power Research Institute 2014). Based on what it heard at its August 2014 meeting, the Board recommended that, as DOE reviews and updates the scope of the proposed packaging facility, it "consider the infrastructure that may be needed to support DOE's research and development efforts related to high-burnup SNF and to the periodic examination of the commercial SNF that is currently in dry storage at INL" (Ewing 2014b).

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[230] FSV fuel is transported to INL for packaging into DOE standardized canisters (Section 7.3.2).

[231] DOE (2007b) noted that "the throughput capability of the facility is dependent on … the drying time required for the wide range of fuel types and the repository opening date."

[232] "The Board recognizes the national importance of the Advanced Test Reactor to nuclear research and to the production of cobalt-60 for medical applications and understands DOE's plans to continue operations beyond 2023" (Ewing 2014b). As described in Section 5.3.2.1.2, DOE is assessing options for disposition of ATR SNF.

The Board finds that DOE will need to consider required packaging facility capabilities in light of ongoing and anticipated missions and the potentially long duration of storage prior to disposal.

8.6 Disposal in a Geologic Repository

After DOE stopped work on the proposed Yucca Mountain repository, it began to investigate other geologic disposal options. In 2014, DOE qualitatively evaluated disposal options for HLW and SNF (Sandia National Laboratories 2014). DOE assigned different types of SNF and HLW into waste groups and evaluated disposal options for each group (Sandia National Laboratories 2014). DOE concluded (Sandia National Laboratories 2014) that all the waste groups, except for sodium-bonded SNF, potentially could be disposed of in any of the three host-rock types [salt, crystalline (*e.g.*, granitic) rock, and clay/shale] being considered[233] for a mined, geologic repository. The DOE study generically assessed the long-term performance of the repository to determine whether the disposal option is likely to comply with long-term protections standards. The long-term performance of the repository was one of the six evaluation metrics that DOE used. The Board questioned the outcomes of this exercise,[234] which were depicted qualitatively but seem to indicate that the three host-rock types considered for a mined geologic repository (salt, crystalline rock, and clay/shale) show similar performance (Ewing, 2014c).

In 2015, the Board stated that DOE's implementation of a separate repository program for both defense HLW and SNF, as well as SNF from DOE's research and development activities, needed to be better informed by considering the performance of the waste form in the different potential host-rock types *after* degradation of the waste package (Nuclear Waste Technical Review Board 2015a). The Board also recommended that DOE "develop a better understanding of the degradation rates of DOE SNF in potential repository geologic environments, particularly the DOE SNF types that could contribute most to radionuclide release and calculated dose, to improve the basis for the separate repository safety assessment" (Nuclear Waste Technical Review Board 2015a).

The Board expands its previous evaluation here to assess technical factors that could affect the validity of Sandia National Laboratories' (2014) conclusion as it relates to DOE SNF. The Board recognizes that the contribution of DOE SNF to repository risk[235] is likely to be negligible if the DOE SNF is commingled with commercial SNF; however, understanding how a repository isolates radioactivity from the public involves more than just looking at the inventory of disposed radionuclides. Here the Board briefly assess technical factors that could affect Sandia National Laboratories' (2014) conclusions by looking at the characteristics of DOE SNF and its packaging, and identify degradation processes and rates that are dependent on factors (*i.e.*, features, events, and processes) that can vary between different disposal environments (*e.g.*, host-rock types or saturated versus unsaturated conditions) and disposal options (*e.g.*, a commingled repository containing commercial SNF and DOE SNF or a separate repository containing some DOE HLW and DOE SNF).

8.6.1 Radionuclide Inventory

For the SNF being contemplated for disposal in a volcanic tuff repository,[236] the total radioactivity for 63,000 MTHM of commercial SNF exceeds that for 2,268 MTHM of non-naval DOE SNF (Table A2-1) by a factor of about 200. The total

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233 The study did not address disposal in volcanic tuff, such as that found at Yucca Mountain, Nevada. At Yucca Mountain, the proposed disposal zone is in the unsaturated zone above the groundwater table.

234 The Board stated "At this point, the waste form/disposal options evaluation is based on qualitative metrics and appears to not address a number of issues: (1) temperature dependence of corrosion rate and mechanism for different waste forms, (2) matching waste forms to geochemical conditions in order to improve waste form performance, and (3) matching waste form performance to the half-life and radiotoxicity of different waste streams. Perhaps a useful and objective approach to improving this evaluation would be to analyze in more detail the results available in other countries: (1) Sweden for granite, (2) France and Switzerland for clay, and (3) Germany for salt" (Ewing 2014c).

235 Risk from a repository is commonly measured in terms of a peak dose to a member of the public. The dose derives from the radionuclides that are released from the repository. The radionuclides travel from the disposal site to where a member of the public can access them via a transporting media, such as water. Each radionuclide has a specific dose conversion factor, which is the amount of dose per unit concentration of the radionuclide in the transporting media. The amount of radioactivity from DOE SNF is small compared with commercial SNF (Figure A2-6).

236 The amount of naval SNF is 65 MTHM. There is no public information on the total radioactivity or radionuclide concentration of naval SNF.

radioactivity per MTHM of commercial SNF is seven times greater than the total radioactivity per MTHM of non-naval DOE SNF. The larger mass of commercial SNF and its larger radioactivity per unit mass suggests that non-naval DOE SNF may not be an important contributor to post-closure safety considerations for disposal in repositories where both commercial and DOE SNF are emplaced. However, for individual repositories for different types of waste, different specific radionuclides may be the most important contributors to risk in terms of peak dose to a member of the public during the post-closure repository performance period (Croff and Krahn 2015; Sections 2.5.1 and 2.5.1.3).[237]

The total radioactivity of chlorine-36, actinium-227, and radium-226[238] in non-naval DOE SNF are each 20% or greater than the total radioactivity of the same radionuclides in commercial SNF (Table A2-1). These radionuclides are important contributors to risk in terms of peak dose[239] to a member of the public during the post-closure repository performance period for different disposal environments. For clay/shale repositories in France (ANDRA 2005) and in Switzerland (NAGRA 2002) and a salt repository (German concept; Forschungszentrum Jülich GmbH 2007), which have reducing environments and where diffusive transport of radionuclides is expected, chlorine-36 is the second most important dose contributor. For a granite repository in Sweden (SKB 2006, 2011), which has a reducing environment and where advective transport of radionuclides is expected, radium-226 and actinium-227 are important dose contributors.

Thus, in general, different geochemical conditions, as well as transport mechanisms, in different disposal environments will control the release of radionuclides from the waste package through the engineered barrier system and natural barriers and into the accessible environment where radioactive exposure can occur.

The Board finds that accounting for the concentration of individual radionuclides in DOE SNF, and its differences from that of commercial SNF, will be important to understand better the impacts of disposal of DOE SNF in different repository environments if DOE proceeds with disposal options that differ from current law.

8.6.2 Waste Form Degradation Processes That Affect Repository Performance

Degradation processes associated with DOE SNF are important to consider in different disposal environments.

8.6.2.1 Gas Generation

Creation of combustible gases and gas pressurization of the repository are two processes that were screened out from the proposed Yucca Mountain repository performance assessment even though there is evidence from the CPP-749 facility at INL that some carbide-based DOE SNF can create combustible gases when contacted by water. For the Yucca Mountain repository, creating combustible gases was screened out because DOE asserted that the relatively small mass of carbide SNF relative to the large mass of commercial SNF, together with the unsaturated nature of the repository[240] and high permeability of the rock to gas, would not allow significant accumulation of combustible gas (Sandia National Laboratories

[237] There are several reasons why radionuclides important to safety can differ for different disposal environments. Different elements have different geochemical behavior in terms of solubility—the amount of a substance that can dissolve in a given amount of another substance—which, for an individual element with multiple oxidation states, can vary over orders of magnitude depending on whether the water is oxidizing or reducing. Sorption—a physical and chemical process by which one substance becomes attached to another—onto engineered materials and geologic media also varies as a function of the disposal environment. In this case, atoms of a radionuclide dissolved in water become attached to surfaces of minerals in engineered materials or the host rock. If radionuclide transport in the geologic environment is dominated by advection through fractures rather than through a porous matrix, or by diffusion, then retardation of radionuclides during transport by sorption is reduced.

[238] This radionuclide is a radioactive daughter of thorium-230 and its radioactivity is provided in Table A2-1. After about 8,000 years, the radioactivity of radium-226 will be equal to thorium-230. The total radioactivity of thorium-230 in DOE SNF is 20% of that in commercial SNF (Table A2-1).

[239] The type of dose (*e.g.*, peak mean annual dose and hypothetical dose) and the period over which the dose is calculated varies by country and for different assessments. The performance assessments that are used to project dose to members of the public are controlled by many assumptions that are not necessarily the same between performance assessments, even for the same disposal environment, and the assumptions can be unrealistic and conservative.

[240] In an environment with no oxygen, such as a saturated and reducing environment, the gas produced would not be combustible, but would lead to potential gas pressurization of the repository.

2008). Similarly, DOE screened out gas pressurization of a volcanic tuff repository because of the unsaturated nature of the repository and high permeability of the rock to gas (Sandia National Laboratories 2008).

Understanding gas generation and reactions that consume the produced gases is, however, an important part of the knowledge needed for repositories located in other disposal environments (*e.g.*, salt) or for other disposal concepts (*e.g.*, granite or shale/clay) that rely on an engineered bentonite buffer as a barrier to radionuclide release and transport (Nuclear Energy Agency 2001; Shaw 2015). Gas generation is of concern because it can affect pressurization of waste containers as well as perturb groundwater flux, host-rock mass-transport properties, repository backfill and seals, the engineered disturbed zone and self-sealing properties, heat dissipation, release of active gases, and/or displacement of contaminated groundwater (Shaw 2015).

About 85% of the mass of DOE SNF is uranium metal. Under anoxic conditions, uranium metal degrades fast and generates hydrogen (Shelton-Davis 2003), which is then available for reaction or accumulation.

Understanding gas generation from degradation of DOE SNF and subsequent reactions may be an important consideration in different repository environments if DOE proceeds with disposal options that differ from current law.

8.6.2.2 Features and Processes Related to Radionuclide Release

Processes occurring to DOE SNF and waste package internal components can affect the rate of release and movement of radionuclides from the waste package if it fails. These processes include waste form degradation, precipitation and dissolution that are controlled by solubility limits, colloid generation and stability, and sorption to and desorption from waste package internal components. These processes are, in turn, affected by the chemistry of the aqueous solution inside the failed waste packages as well as the water flow rate within the packages. Both the chemistry of the aqueous solution and water flow rate vary depending on geologic disposal concept (ANDRA 2005; NAGRA 2002; SKB 2011).

In probabilistic calculations of repository performance, both the number of breached waste packages and the content of radionuclides contained in each specific package[241] are important parameters for estimating radionuclide releases and dose to members of the public (Section 2.5.2.3) because the radionuclide content differs between packages and the materials within packages differ. About 40% of the multi-purpose canisters with DOE SNF will include aluminum-based SNF (Tables 2-3 and A1-2). Aluminum corrosion products and aluminum oxide colloids—similarly to iron oxide colloids—can sorb a variety of radionuclides; however, DOE has not included aluminum corrosion products or aluminum oxide colloids in its non-tuff repository assessments (Sevougian *et al.* 2016) for waste packages containing DOE SNF.

The Board finds that for disposal options where the DOE SNF radionuclide inventory is a substantial fraction of the total, processes that could affect the release of radionuclides from DOE SNF to the engineered barrier system, and beyond, could be an important consideration.

The waste package degradation processes (*e.g.*, stress corrosion cracking, localized corrosion, and general corrosion) and the rates at which these processes lead to waste package failure are critical issues for determining radionuclide release (Section 2.5.2.3). For most DOE SNF fuel types, there are no known direct experimental test data for the degradation and dissolution of the waste form in repository groundwaters (Section 2.5.1.3). DOE's SNF release experiments were limited to uranium metal, aluminum-based, and mixed oxide SNF and primarily used a water composition and oxidizing conditions that could be expected in a volcanic tuff repository.

Based on the above observations, the Board finds that features, events, and process that are specific to DOE SNF will be an important area to reconsider for non-tuff disposal options if the DOE SNF inventory is a significant fraction of the total.

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[241] Uniformly distributing the mass and radioactivity into all non-naval DOE SNF canisters greatly increases the mass of SNF in most canisters because about 85% of the mass is in about 12% of the canisters (*i.e.*, the MCOs that contain N Reactor SNF).

8.6.3 Assessing Disposal of All U.S. Department of Energy Spent Nuclear Fuel

Disposal of commercial-origin DOE SNF together with commercial SNF will be required if DOE proceeds with a defense-waste-only repository (Figure 1-2). If DOE pursues the option of a defense-waste-only repository, there will still be about 270 MTHM of commercial-origin DOE SNF, and potentially 65 MTHM of naval SNF, which may need to be disposed of in a non-defense repository because of the high heat loads and large waste package sizes (Sections 2.5.1.1 and 2.5.2.1).

Since DOE-NE began generically investigating other potential alternative disposal options, DOE has not addressed disposal of commercial-origin DOE SNF, including the carbide-containing FSV SNF. The reference case waste inventory for generic repository system analyses includes only commercial SNF and not commercial-origin DOE SNF (Mariner *et al*. 2015). DOE-NE did begin a preliminary assessment of features, events, and processes for disposing of non-commercial-origin DOE SNF (Sevougian 2016; Sevougian *et al*. 2016) and reviewed disposal concepts for a crystalline rock (*i.e*., granite) repository for the same materials (Hardin and Matteo 2016; Matteo *et al*. 2016).

The Board finds that, if DOE pursues one or more new repository concepts, it will be important to consider the wastes that are projected to be the dominant contributors to repository risk or cause additional processes to occur (e.g., *gas generation), and the potential for differing waste degradation processes to be associated with these wastes in different disposal environments.*

8.6.4 Identifying and Prioritizing Research

Previously, DOE-NE applied a systems engineering approach and assessed research and development needs for both borehole disposal and its generic repository program, which are documented in research and development roadmaps (Arnold *et al*. 2012; DOE 2011d). DOE-NE's roadmapping approach focuses on identifying knowledge gaps and opportunities where research and development have the greatest potential to contribute to advancing the understanding of technical issues regarding the deep geologic disposal of nuclear waste (DOE 2011d). The generic repository roadmap approach focused on commercial SNF, acknowledged the need to find out more about advanced reactors fuels, and did not assess specific research and development needs relative to DOE SNF (DOE 2011d).

DOE-NE is conducting research and development activities on potential disposal of commercial SNF in different host-rock types as part of its generic repository studies and has begun assessing alternative disposal options for some DOE SNF.[242] As noted in Sections 8.6.1 and 8.6.2, there are several factors that DOE will need to assess, with greater attention, regarding the implications of disposal of DOE SNF in other geologic disposal environments.

The Board finds that DOE has not completed an assessment of the key uncertainties or gaps for disposal of all DOE SNF, whether in a repository with a host rock other than volcanic tuff or in more than one repository in different disposal environments.

[242] DOE only began technical studies on disposal of non-commercial DOE SNF in a defense HLW repository in 2016 (Sevougian and McMahon 2016). The initial efforts focus on inventory and waste characterization (Sassani 2016; Walkow 2016; Wilson 2016), preliminary design concepts (Hardin and Matteo 2016; Matteo *et al*. 2016), organizational and procedural framework (Swift 2016), and safety analysis and site evaluation (Sevougian 2016; Stein *et al*. 2016).

9. Observations, Findings, and Recommendations

Managing and disposing of U.S. Department of Energy (DOE) spent nuclear fuel (SNF) is a daunting task. DOE stores almost all its SNF at four sites across the United States: the Hanford Site [2,130 metric tons of heavy metal (MTHM)] in Washington, Idaho National Laboratory (INL; 325 MTHM) in Idaho, the Savannah River Site (SRS; 30 MTHM) in South Carolina, and the Fort St. Vrain storage facility (15 MTHM) in Colorado. The wide variety of DOE SNF—in terms of chemical composition, fissile isotope enrichments, and physical dimensions, combined with the more degraded condition of DOE SNF relative to commercial SNF—complicates how it is stored, packaged, transported, and disposed of. Furthermore, DOE SNF management actions are constrained by legal agreements with the states where DOE SNF is stored and by requirements that differ between storage, transportation, and disposal regulations.

To manage these challenges and constraints, DOE adopted a versatile multi-purpose canister approach that employs the same canister to store, transport, and dispose of SNF. Three different multi-purpose canisters were designed to accommodate the many different types of SNF under DOE's purview. The naval canister system (two sizes) is used for naval SNF that is stored at INL. As of August 2014, 100 naval canisters have been filled, and DOE plans to continue filling the naval canisters until the entire expected inventory (65 MTHM) is packaged (a total of 400 canisters). At Hanford, DOE filled 412 multi-canister overpacks (MCOs) with about 2,120 MTHM of SNF that is primarily metallic uranium fuel from the Hanford N Reactor that degraded during storage in water basins. At Hanford, INL, and SRS, DOE intends to use a standardized canister system (four sizes, totaling several thousands of canisters) to package the remaining DOE SNF stored at the four sites. Given the varied and specific storage requirements for different types of fuel, and that many of the storage facilities are being used beyond their original design lifespan, DOE needs to ensure that the current storage facilities and systems are able to continue storing SNF—potentially for many decades—before it can be retrieved for packaging into standardized canisters and for any subsequent fuel cycle operations (*e.g.*, transport and disposal). To date, DOE has not completed developing the DOE standardized canister, a type of multi-purpose canister that DOE planned to use at the proposed Yucca Mountain repository. If DOE is to use each of the three types of multi-purpose canister systems (naval, MCO, and standardized) to store, transport, and dispose of SNF without repackaging, it will need to demonstrate that, over a time scale of multiple decades into the future, degradation of the SNF within the canister and of the canister itself will not lead to conditions that exceed design requirements.

9.1 Findings and Recommendations

Based on the information developed in this report, the Board presents six principal findings and recommendations on managing and disposing of DOE SNF.

9.1.1 Aging Management

1. **Finding: DOE's aging management programs are not fully implemented.** Some DOE SNF storage facilities lack aging management programs to facilitate retrieving stored SNF and packaging it into multi-purpose canisters needed to transport it to either a centralized interim storage facility or a permanent repository. Aging management programs also provide assurance that the SNF can continue to be safely stored and transported when required, and retrieved if necessary. For most of its SNF storage facilities, DOE has not completed an aging management assessment identifying the actions it should take now and in the future to facilitate retrieving stored SNF many decades from now. DOE does have an aging management assessment for the Savannah River Site pool facility, but it has yet to implement all the activities identified in the assessment. Furthermore, DOE has not completed aging management assessments that could facilitate continued use of the multi-purpose canisters at its existing storage facilities beyond 40 years and during subsequent transportation and geologic repository operations.

   Recommendation: *The Board recommends that DOE develop and fully implement programs to manage degradation of SNF, the materials that contain SNF, and SNF facilities for additional multiple decades of storage operations at all storage facilities. Managing degradation includes assessing its potential of occurring, and—when it is predicted to occur at unacceptable rates—monitoring storage conditions of the SNF and the materials in which it is stored to prevent degradation, or to mitigate degradation effects. These programs should take into account the following important considerations:*

   a. *the diversity of degraded DOE SNF, storage facility construction materials, and storage systems that differ from those used commercially;*
   b. *the potential for additional multiple decades of storage operations;*
   c. *the requirements that may have to be met to manage degradation of multi-purpose canisters—and any other canisters that may be used—after multiple decades of storage until final disposal occurs;*
   d. *the impact of potential future missions in existing storage facilities when assessing what aging management activities may be needed at each facility; and*
   e. *lessons learned from similar programs developed for commercial nuclear reactors and commercial SNF dry storage facilities.*

9.1.2 Measuring and Monitoring Conditions During Storage

2. **Finding: Measuring and monitoring conditions of the SNF during dry storage is important.** The ability to measure and monitor conditions of the SNF in the storage facility during future dry storage (*e.g.*, monitoring gas composition in a multi-purpose canister like that being done for the MCOs) is important to the design, development, and deployment of new DOE storage systems. Although DOE has considered including monitoring capability for new storage systems, it has not done so in its baseline design for the DOE standardized canister.

   Recommendation: *The Board recommends that DOE include the capability for measuring and monitoring the conditions of the SNF in new DOE storage systems, such as the DOE standardized canister, and in new packaging and storage facilities to aid in establishing the condition of the SNF during subsequent operations and its acceptability for those operations.*

9.1.3 Drying Procedures

3. **Finding: An improved technical basis is needed for proposed drying procedures for DOE SNF before packaging it in multi-purpose canisters.** A better understanding of how much water remains in sealed multi-purpose canisters and the cumulative conditions inside the canisters adds confidence that proposed drying procedures for DOE SNF will be satisfactory. DOE assessed physical and chemical processes that could occur inside sealed DOE standardized canisters over a 50-year storage period. DOE proposed drying procedures for aluminum-based SNF, but it did not consider all the sources of water that could be in the canisters. It also did not account for how long the sealed multi-purpose canisters may serve as a radionuclide containment barrier. Using the expected amount of residual water, including chemisorbed water associated with supplemental neutron absorbers and hydrated SNF corrosion products, can improve DOE's understanding and technical basis for drying SNF. An understanding of gas composition and pressure in multi-purpose canisters can inform the technical and regulatory considerations for following storage, transport, and disposal operations. Predicting—and monitoring—gas composition and pressure of sealed multi-purpose canisters (see Recommendation #2) can confirm DOE's understanding of and the basis for its conclusion that proposed SNF drying procedures are adequate.

   Recommendation: *The Board recommends that DOE conduct research and development activities to confirm that reactions between DOE SNF and any water remaining in any multi-purpose canister do not cause cumulative conditions inside the canister (*e.g.*, combustibility, pressurization, or corrosion) to exceed either the design specifications or applicable regulatory operational requirements. The period of interest extends over the duration of canister use, including the time spent in storage, in transportation, and at a repository, until DOE closes the repository. These research and development efforts should include the following activities:*

   a. collecting and analyzing data applicable to drying DOE SNF—particularly aluminum-based fuels—that focus on the quantity of chemisorbed water;

   b. determining whether the results and associated models from a DOE Office of Nuclear Energy (DOE-NE) study of a vacuum drying chamber can be used to inform efforts to understand and implement DOE SNF drying;

   c. collecting data on potential hydrogen generated from SNF corrosion products that is focused on characterizing the mass and chemical composition of water-bearing aluminum minerals present after drying;

   d. collecting data on the rates of hydrogen produced from dissociation of water molecules by materials composing and within storage canisters (e.g., supplemental neutron absorbers or fuel corrosion products) by ionizing radiation;

   e. using validated models for physical and chemical processes that could occur inside sealed canisters to predict internal gas composition and pressure over the expected length of time the canisters will be in use and comparing model predictions to monitoring data collected during storage; and

   f. re-evaluating the adequacy of proposed drying protocols that reflect all the sources of water to assess the extent of potential corrosion damage and gas pressurization of the canister during its use.

9.1.4 Packaging Facilities

4. **Finding: Technical and regulatory uncertainties complicate planning for packaging facilities.** A key step in DOE's SNF management plans is developing packaging facilities at Idaho National Laboratory, Hanford, and Savannah River Site for DOE SNF that still needs to be placed into about 3,500 DOE standardized canisters. DOE has not completed all the research and development activities for the standardized canister that will define the full capabilities required for a packaging facility. DOE does not know whether the packaging facility would be licensed by NRC, or which NRC licensing regulation(s) would apply if NRC regulated the facility. NRC will also need to approve

the canister for transport years hence, and any conditions associated with NRC's approval could affect the design for the canister and packaging facility. These technical and regulatory uncertainties complicate planning for these packaging facilities, the first of which is planned for Idaho National Laboratory.

Recommendation: *To minimize complications in developing and operating a packaging facility for DOE SNF at Idaho National Laboratory, the Board recommends that DOE complete research, development, and licensing-related activities for the DOE standardized canister—and any other canisters that may be used—prior to completing the facility's preliminary design. In particular, DOE should complete the following tasks related to the DOE standardized canister:*

a. conduct remote welding and real-time, non-destructive, weld-testing research and development activities;

b. research and develop materials that will be packaged with the SNF (e.g., structural inserts using an advanced neutron absorber);

c. decide on and develop SNF treatment processes needed for specific SNF types (e.g., epoxied fuel may need organic components removed, and Fermi blanket fuel may be electrochemically processed or may have sodium removed and be placed in high integrity cans that are made with advanced corrosion-resistant metals such as Alloy 22);

d. confirm, through research and development, that reactions between SNF and any water remaining in a canister do not cause conditions inside the canister to exceed either the design specifications or any applicable regulatory requirements during dry storage, transportation, and repository pre-closure operations;

e. obtain NRC approval that the DOE standardized canister meets the transportation moderator exclusion requirements or receive an exemption to these requirements;

f. analyze an existing NRC-certified rail transport cask or develop a new one, and obtain NRC approval to transport DOE standardized canisters to ensure that any canister packaging design features needed inside the rail cask (e.g., a supplemental impact limiter) to meet regulatory requirements are considered in the design of the packaging facility; and

g. define the technical requirements for the packaging facility, including the regulatory standards (e.g., NRC regulations) that it will need to meet.

9.1.5 Waste Acceptance System Requirements

5. **Finding: Waste acceptance system requirements affect the disposition of DOE SNF and DOE-NE is not subject to the requirements.** Both the DOE Office of Environmental Management (DOE-EM) and the naval nuclear propulsion program are waste custodians and have signed agreements with the DOE Office of Civilian Radioactive Waste Management (OCRWM) to accept their SNF for disposal. These agreements require waste custodians to use waste acceptance system requirements, which apply to all SNF and high-level radioactive waste (HLW) that will be disposed of in a repository, in order for the DOE organization responsible for waste disposal (at that time the agreements were signed it was OCRWM) to accept the waste for disposal. Both DOE-EM and the naval nuclear propulsion program continue to manage their waste according to the waste acceptance system requirements ("Civilian Radioactive Waste Management System Waste Acceptance System Requirements Document," Revision 5, ICN 01, DOE/RW-0351). DOE-NE manages some SNF and is treating sodium-bonded SNF to yield two HLW forms, both of which will need to be shown to be acceptable for geologic disposal. Previously, DOE-NE transferred some of its SNF from the Advanced Test Reactor to DOE-EM. DOE-NE is not a "waste custodian" and does not have a waste acceptance agreement with OCRWM.

Recommendation: *The Board recommends that DOE-NE implement the existing OCRWM waste acceptance system requirements to increase the likelihood that SNF managed by DOE-NE and that waste forms resulting from electrochemical processing of sodium-bonded SNF will be acceptable for geologic disposal in a repository.*

9.1.6 Disposal Research Efforts

6. **Finding: The diversity of DOE SNF combined with differences in physical and chemical characteristics of potential repository environments complicates the potential disposal of DOE SNF.** Since 2010, DOE has focused on alternative geologic disposal options, including generic environments other than tuff and deep borehole disposal of some types of wastes. The diversity of DOE SNF in terms of chemical composition and radionuclide content, combined with the diverse physical and chemical environments that can occur in repositories located in generic environments such as granite, clay/shale, and salt, complicates potential disposal of DOE SNF. Understanding processes that may adversely affect the isolation properties of the repository, such as gas generation, is a key issue in the assessment of repository performance. Evaluations of repository post-closure performance depend on the mass and radionuclides content of SNF in a specific package and the number of packages. The diversity of chemical and physical characteristics of DOE SNF leads to widely variable masses of SNF and radionuclides in each package, depending of the specific fuel type and the design of engineered barrier systems. DOE identified and prioritized its research on these different disposal environments based on disposing of commercial SNF without thoroughly considering the need to dispose of DOE SNF that has a wide variety of compositions and conditions.

   Recommendation: *If DOE continues to conduct generic investigations of a range of potential repository environments, the Board recommends that DOE identify and prioritize its research efforts concerning DOE SNF degradation related to disposing of DOE SNF in each of the potential host-rock environments. As part of this effort DOE should complete the following tasks:*

   a. *Improve its current understanding of post-closure DOE SNF degradation processes for DOE SNF types that constitute a large portion of the mass or radionuclide content or that could be in a large fraction of the disposal packages in a repository.*

      i. *For each disposal environment, identify the processes that will occur, their rates, and their impact on repository performance, including assessing the potential generation of corrosion products that could affect the release of radionuclides from a waste package and the potential generation of hydrogen and other gases.*

   b. *Prioritize its research based on analyzing the features, events, and processes associated with those aspects of DOE SNF that differ significantly from commercial SNF and on types of DOE SNF that could constitute a significant fraction of the estimated post-closure risk to the public.*

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Glossary

This glossary is provided for information and is not exhaustive. The glossary provides explanations for underlined terms.

advection The process in which dissolved substances, particles, or molecules are transported by the motion of flowing fluid.

ALARA An acronym for "as low as (is) reasonably achievable," which means making every reasonable effort to maintain exposures to ionizing radiation as far below the dose limits as practical, consistent with the purpose for which the licensed activity is undertaken, taking into account the state of technology, the economics of improvements in relation to state of technology, the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations, and in relation to utilization of nuclear energy and licensed materials in the public interest.

Blue Ribbon Commission on America's Nuclear Future (BRC) In 2010 President Barack Obama requested the Secretary of Energy to establish a commission to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense used nuclear fuel, high-level waste, and materials derived from nuclear activities. The Blue Ribbon Commission issued its final report in January 2012.

boiling water reactor A common nuclear power reactor design in which water flows upward through the core, where it is heated by fission and allowed to boil in the reactor vessel. The resulting steam then drives turbines, which activate generators to produce electrical power. About one-third of the operating nuclear power plants in the United States are boiling water reactors.

breeder reactor A nuclear reactor that produces more nuclear fuel than it consumes.

burnup The energy extracted per unit mass of nuclear fuel. Typical units for burnup are megawatt-days per metric ton of heavy metal originally contained in the fuel (MWd/MTHM) or gigawatt-days per metric ton of uranium (GWd/MTU).

canister A metal cylinder that is sealed at both ends and that may be used to provide for the confinement of spent nuclear fuel in a dry cask storage system. Typically, the canister has a relatively thin wall and a separate overpack or horizontal storage module performs the function of providing radiological shielding and physical protection.

cask A passive stand-alone component that performs the functions of confinement, radiological shielding, decay heat removal, and physical protection of spent nuclear fuel. A cask is a heavily shielded container that is used for the dry storage or shipment (or both) of radioactive materials such as spent nuclear fuel or other high-level radioactive waste. Casks are often made from lead, concrete, or steel.

cladding An external layer of material applied directly to another material to provide protection in a chemically reactive environment. In commercial nuclear fuel, cladding is typically the tube of material that houses the nuclear fuel pellets and that serves to contain the radioactive species produced during fission.

colloid As applied to radionuclide migration, colloids are large molecules or very small particles, having at least one dimension with the size range of 10^{-6} to 10^{-3} millimeters [10^{-8} to 10^{-5} inches], that are suspended in a solvent. Colloids in groundwater arise from clay minerals, organic materials, or (in the context of a proposed geologic repository) from corrosion of engineered materials.

confinement The ability to limit or prevent the release of radioactive substances into the environment from a dry cask storage system for spent nuclear fuel.

containment system The assembly of packaging components that is intended to retain radioactive material during transport.

criticality The normal operating condition of a reactor, in which nuclear fuel sustains a fission chain reaction. A reactor achieves criticality (and is said to be critical) when each fission event releases a sufficient number of neutrons to sustain an ongoing series of reactions. In nuclear waste management, criticality refers to the probability and circumstances in which a quantity of waste could achieve criticality.

damaged fuel As used in this report and as applied by the U.S. Department of Energy, spent nuclear fuel that has lost its functional design capabilities with regard to handling and confinement. Damage is a result of experimental activities and destructive examinations; incidents during reactor operations, packaging, handling, and transportation; or degradation that has occurred during storage. Examples of damage include failed cladding, failed fuel, sectioned test specimens, dismantled assemblies, and assemblies with lifting fixtures removed.

declad fuel Spent nuclear fuel from which the outer metal cladding has been removed.

DOE spent nuclear fuel or **DOE SNF** Spent nuclear fuel that is managed by the U.S. Department of Energy. Both naval spent nuclear fuel and some commercial spent nuclear fuel is managed by the U.S. Department of Energy. Where the characteristics of naval spent fuel and its management differ from all other U.S. Department of Energy spent nuclear fuel, the term "DOE spent nuclear fuel" is used to refer to all non-naval spent nuclear fuel.

DOE standardized canister The U.S. Department of Energy's term for a canister system that consists of four cylindrical stainless steel canisters with two different diameters (18 inches and 24 inches) and two different lengths (10 feet and 15 feet). The different sizes and eight internal basket designs of the multi-purpose canisters accommodate the wide dimensional variability of DOE spent nuclear fuel.

dry cask storage system Any system that uses a cask or canister as a component for storing spent nuclear fuel without using water to remove decay heat. A dry cask storage system provides confinement, radiological shielding, physical protection, and inherently passive cooling of the spent nuclear fuel it contains.

dry storage The placement of spent nuclear fuel or solidified heat-generating waste in a facility that allows for the removal of decay heat through the natural or forced convection of air. This method allows spent nuclear fuel to be sealed in a container with an inert gas atmosphere. U.S. Nuclear Regulatory Commission guidance for dry storage recommends that spent nuclear fuel be stored in an inert atmosphere. Not all DOE spent nuclear fuel in dry storage is stored under an inert atmosphere.

electrometallurgical treatment A type of spent nuclear fuel processing that has been chosen by the U.S. Department of Energy to treat sodium-bonded spent nuclear fuel. The treatment employs an electrorefiner, which uses a molten salt electrolyte at high temperature to dissolve the spent nuclear fuel and separate the sodium and fission products from the heavy metals.

events In a performance assessment of a repository, occurrences of phenomena that have a specific starting time and, usually, a duration shorter than the time being simulated in a model.

features Physical, chemical, thermal, or temporal characteristics of a site or potential repository system. For the purposes of addressing features, events, and processes in a performance assessment of a repository, a feature is defined as an object, structure, or condition that has the potential to affect disposal system performance.

fissile material A nuclide that is capable of undergoing fission after absorbing a low-energy (slow) neutron. Although sometimes used as a synonym for fissionable material, this term has acquired a more restrictive interpretation with the limitation that the nuclide must be fissionable by slow neutrons. With that interpretation, the primary fissile materials are uranium-233, uranium-235, plutonium-239, and plutonium-241.

fission The splitting of an atom, which releases a considerable amount of energy. Fission may be spontaneous, but it is usually caused by the nucleus of an atom becoming unstable after absorbing a neutron. During fission, the heavy nucleus usually splits into two parts, producing the nuclei of at least two lighter elements called fission products. In addition to energy, this reaction usually releases gamma radiation and two or more daughter neutrons.

fuel rod The nuclear fuel, its cladding, and any associated components necessary to form a structural entity for use in a reactor. A commercial fuel rod consists of a tube, typically made of Zircaloy™, into which fuel material—usually in the form of pellets of uranium oxide—is placed with the tube sealed on both ends via welded end plugs. The tube that houses the nuclear fuel is called cladding. Fuel rods may be mechanically linked to form a fuel assembly or fuel bundle.

geologic repository A facility for the disposal of radioactive waste that is located underground (usually several hundred meters or more below the surface) in a geological formation intended to provide long-term isolation of radionuclides from the biosphere.

half-life For a radionuclide, the time required for the population of a radionuclide nuclei and associated radioactivity to decrease, by a radioactive decay process, by half.

heavy metal Actinide elements (elements with an atomic number greater than 89; *e.g.*, uranium, plutonium, americium).

high-enriched uranium Uranium that has been enriched through isotopic separation to 20% or greater uranium-235. Percentage is in terms of abundance of isotopes and not mass.

high-level radioactive waste The highly radioactive material that results from the reprocessing or processing of spent nuclear fuel, including liquid waste produced and any solid material derived from such liquid waste that contains fission products in sufficient concentrations.

horizontal storage module A reinforced, heavy-walled concrete structure designed to store dry spent nuclear fuel canisters in a horizontal position. The horizontal storage module provides physical and radiological protection for the canisters, while allowing passive cooling by natural convection.

independent spent fuel storage installation A complex designed and constructed for the interim storage of spent nuclear fuel; solid, reactor-related, greater than Class C waste; and other associated radioactive materials that is licensed by the U.S. Nuclear Regulatory Commission under Part 72 of Title 10 of the Code of Federal Regulations. A spent fuel storage facility may be considered independent, even if it is located on the site of another U.S. Nuclear Regulatory Commission -licensed facility.

low-enriched uranium Uranium that has been enriched through isotopic separation to greater than 0.7% uranium-235 (natural concentration) but less than 20% uranium-235.

metric ton Equal to 1,000 kilograms (1 kilogram = 2.205 pounds).

moderator exclusion An approach by the U.S. Nuclear Regulatory Commission under Part 71 of Title 10 of the Code of Federal Regulations that requires a package used for the shipment of fissile material be designed and constructed and its contents limited so that under tests of hypothetical accident conditions the package would be subcritical. A moderator is a material such as ordinary water or graphite that is used in a reactor to slow down high-velocity neutrons, thus increasing the likelihood of fission. Under the hypothetical accident conditions, the transportation cask is assumed to be fully flooded with water.

monitored retrievable storage facility A Federal storage facility described in section 141(b)(1) of the Nuclear Waste Policy Act. The facility design is required to accommodate spent nuclear fuel and high-level radioactive waste resulting from civilian nuclear activities.

multi-canister overpack A stainless steel container used at the Hanford Site for interim storage of spent nuclear fuel. The multi-canister overpack (MCO) is a cylindrical tube with a plate welded at the bottom and a shield plug at the top; five or six baskets loaded with intact fuel rods or fuel pieces may be stacked inside the MCO.

multi-purpose canister A container used for the storage, transportation, and disposal of spent nuclear fuel without the intent for retrieval.

Nuclear Waste Policy Act The federal statute enacted in 1982 that establishes both the Federal Government's responsibility to provide a place for the permanent disposal of high-level radioactive waste and spent nuclear fuel, and the nuclear power generators' responsibility to bear the costs of permanently disposing of commercial spent nuclear fuel. Amendments to the Act in 1987 limited the Federal Government's site characterization activities to a possible geologic repository at Yucca Mountain, Nevada. The Act provides for extensive state, tribal, and public participation in the planning and development of permanent repositories.

overpack A secondary (or additional) outer container for one or more waste or spent nuclear fuel packages that may be used for handling, transport, storage, or disposal.

pressurized water reactor A common nuclear power reactor design in which pure water is heated to high temperature by fission, kept under high pressure (to prevent it from boiling, as in a boiling water reactor), and sent to a steam generator where it transfers its heat energy to a secondary water stream. The resulting steam is used to drive turbine generators to produce electrical power. About two-thirds of the operating nuclear reactor power plants in the United States are pressurized water reactors.

processes In a performance assessment of a repository, phenomena and activities that have gradual, continuous interactions with the system being modeled.

processing As used in this report, a process or operation to treat spent nuclear fuel to create high-level radioactive waste forms that can be transported and disposed of without separating the fissile material for weapons use.

radioactivity The spontaneous transformation of one radioisotope into one or more different isotopes (known as "decay products" or "daughter products"), accompanied by a decrease in radioactivity (compared with the parent material). This transformation takes place as a result of electron capture, fission, or the emission of alpha particles, beta particles, or photons (gamma radiation or x-rays) from the nucleus of an unstable nucleus. Each isotope in the sequence (known as a "decay chain") decays to the next until it forms a stable end product.

radiolysis The process of molecular decomposition of a substance by ionizing radiation.

reprocessing A process or operation to extract radioactive isotopes from spent nuclear fuel for further use or to separate out various waste streams.

retrieval A process to safely remove spent nuclear fuel from its current storage arrangement for further processing or disposal.

risk-informed and performance-based A risk-informed, performance-based regulation is an approach in which risk insights, engineering analysis and judgment (including the principle of defense-in-depth and the incorporation of safety margins), and performance history are used to (1) focus attention on the most important activities, (2) establish objective criteria for evaluating performance, (3) develop measurable or calculable parameters for monitoring system and licensee performance, (4) provide flexibility to determine how to meet the established performance criteria in a way that will encourage and reward improved outcomes, and (5) focus on the results as the primary basis for regulatory decision making.

spent nuclear fuel Fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing (also called "used nuclear fuel").

storage The holding of spent nuclear fuel and/or high-level waste in a facility that provides for its containment, with the intention of retrieval. Storage, by definition, is an interim measure.

systems engineering approach An interdisciplinary approach to managing a system from the definition of functions and requirements, through design, fabrication, and operation, to the end of the system lifecycle.

target Material that cannot sustain a chain reaction and that is placed inside a nuclear reactor to produce particular radioisotopes through reactions induced by neutrons from the nuclear fuel as they sustain a chain reaction and by radioactive decay.

target material The residual materials left after the desired radioisotopes have been removed from the target.

vitrification The process of incorporating materials into a glass or glass-like form. Vitrification is commonly used to solidify liquid high-level radioactive waste from the reprocessing of spent nuclear fuel.

waste form Radioactive waste materials and any encapsulating or stabilizing matrix.

waste package The container, shielding, packing, and other absorbent materials that immediately surround an individual waste container used to dispose of waste forms.

Zircaloy™ The trademark name for a family of zirconium alloys that contain small amounts of tin, iron, chromium, and nickel.

APPENDICES

Appendix 1. Inventory of U.S. Department of Energy Spent Nuclear Fuel

This appendix provides an inventory of U.S. Department of Energy (DOE) spent nuclear fuel (SNF) at the Hanford Site, the Idaho National Laboratory (INL), the Savannah River Site (SRS), the Fort St. Vrain (FSV) independent spent fuel storage installation, and all other locations (other). This appendix also provides information on the number and type of packages that could be used for off-site transportation of DOE SNF. There are several hundred types of DOE SNF. Table A1-1 provides a breakdown of the DOE inventory using the 34 groups that DOE designated for its *Yucca Mountain Repository License Application Safety Analysis Report* (DOE 2009a). The groups are based on fuel characteristics, including compound and matrix, cladding, cladding condition, and enrichment. These parameters have a major impact on the release of radionuclides from DOE SNF and are important in assessing nuclear criticality scenarios.

The descriptions for the 34 groups in Table A1-1 have been edited for clarity from descriptions presented in Section 1.5.1.3.1.1.1 of the *Yucca Mountain Repository License Application Safety Analysis Report* (DOE 2009a). The group name (*e.g.*, "Uranium Oxide, Zirc Clad, Intact, High-Enriched Uranium" for Group 5) identifies the fuel compound and any other characteristics needed to describe the group, such as matrix, type of cladding, cladding condition, and enrichment, respectively. The fuel compounds used to define groups include uranium metal, uranium-zirconium, uranium-molybdenum, uranium oxide, uranium-aluminum, uranium silicide, thorium-uranium carbide, plutonium-uranium carbide, mixed oxide, thorium-uranium oxide, and uranium-zirconium hydride. The matrices used to define groups include tristructural isotropic (TRISO)- or buffered isotropic (BISO)-coated particles in graphite, and monopyrolytic carbon-coated particles in graphite. The types of cladding used to define groups include zirc (which includes zirconium and Zircaloy™), non-zirc (*e.g.*, lead covered by aluminum covered by aluminum-silicon), stainless steel, Hastelloy™, aluminum, and Incoloy™. For purposes of defining groups, cladding may be identified as intact, nonintact, and declad (*i.e.*, fuel that has had cladding removed). Terms used to describe the condition of the cladding include good (*i.e.*, no known or suspected through-cladding defects), fair (*i.e.*, known or suspected defects are limited to hairline cracks or pinhole leaks), poor (*i.e.*, known or suspected defects are greater than hairline cracks and pinhole leaks), and none (*i.e.*, declad or unclad SNF). The terms used to describe fuel enrichment include high-enriched, medium-enriched, and low-enriched; they correspond to levels of enrichment greater than or equal to 20%, greater than or equal to 5% but less than 20%, and less than 5%, respectively. Fuel burnup (*i.e.*, the energy that has been extracted per unit mass of the fuel) is given in gigawatt-days per metric ton of uranium (GWd/MTU). Additional information on these fuel groups may be found in Tables 1.5.1-23 and 1.5.1-24 of the *Yucca Mountain Repository License Application Safety Analysis Report* (DOE 2009a).

The total inventory of DOE SNF in each fuel group is given in metric tons of heavy metal (MTHM) in the right-hand column of the table. With the exception of Groups 31 and 32, the figures shown are based on the Spent Fuel Database (INL 2007), Version 6.2.3, which was released on March 24, 2011.[243] The quantity given for Group 31 is based on Simpson (2010); the quantity given for Group 32 is a rough estimate based on Carter *et al*. (2012). DOE plans to process some sodium-bonded SNF and aluminum-clad SNF at the INL Materials and Fuels Complex and SRS H Canyon, respectively. The amounts of these materials are not included in the inventory column. The U.S. Nuclear Waste Technical Review Board (Board) notes that although the information presented here for Groups 1–30 and Group 34 and the corresponding information published by Sandia National Laboratories (2014) are both derived from the Spent Fuel Database, Version 6.2.3, there are several unexplained differences in the listed quantities of MTHM. Furthermore, Sassani (2013) and Wagner *et al*. (2012) document different values as well. For example, Wagner *et al*. (2012) lists 90 MTHM in SNF Group 7 while Sassani (2013) and Sandia National Laboratories (2014) list 64 MTHM for this group. Table A1-1 lists 82.2 MTHM in Group 7, which is the value provided to the Board. [244]

Data shown in Figure 2-2 are derived from Table A1-1. Major categories of DOE SNF depicted in the figure are composed of DOE SNF groups. The groups included in each category were based on descriptions of the dominant type of SNF in each group. For example, the N Reactor category is Group 1. The commercial-origin category includes Groups 4, 5, 7, 10, 19, 20, 25, and 26. The commercial-origin category also includes the non-Three Mile Island Unit 2 (TMI-2) portion of 13 and the TMI-2 category depicted in Figure 2-2 is the remaining mass in Group 13. The sodium-bonded category is Group 31. The naval category is Group 32. The domestic and foreign research reactors category includes Groups 15, 16, 17, 18, 27, 28, and 29. The "other" category includes Groups 2, 3, 6, 8, 9, 11, 12, 14, 21, 22, 23, 24, 30, 33, and 34.

It is important to note that the MTHM values given in the table reflect a "snapshot" of the inventory at a particular point in time (January 2013). Quantities for several of the SNF groups change on a relatively frequent basis. SRS routinely receives shipments of foreign and domestic research reactor fuel and stores that fuel in the L Basin facility (these shipments generally add to SNF Groups 14, 16, 17, and 18). For example, fuel discharged from the High Flux Isotope Reactor at Oak Ridge National Laboratory that is transported to SRS adds to the total of Group 14 at the site. Additions to the naval SNF inventory at INL occur routinely as the U.S. Navy decommissions or refuels its nuclear-powered ships (SNF Group 32). Fuel discharged from the Advanced Test Reactor at INL adds to the total of Group 16 at the site. DOE continues to process certain SNF types at the H Canyon facility at SRS, removing some non-clad and aluminum-clad SNF from the inventory (SNF Groups 12, 14, 15, 16, 17, and 18). Finally, the Fuel Conditioning Facility at INL continues to process sodium-bonded fuel, reducing the inventory of that fuel (SNF Group 31).

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[243] *Source:* Sandra Birk, Idaho National Laboratory, e-mail message, with attachments, to Gene Rowe, former NWTRB staff, January 21, 2013.

[244] Ibid.

Table A1-1. Inventory of U.S. Department of Energy spent nuclear fuel

Group	Description	Site	MTHM
1	**Uranium Metal, Zirc-Clad, Low-Enriched Uranium** – This group contains a low-enriched uranium metal SNF with zirconium cladding (this group accounts for approximately 86% of the DOE SNF inventory by mass). Greater than 99% of the MTHM of SNF in this group is N Reactor SNF. The N Reactor was used for both material and power production. N Reactor fuel consists of two concentric tubes about 2.4 inches in diameter and typically 2 feet long. N Reactor SNF has a nominal enrichment of about 1% and a typical burnup of about 2.4 GWd/MTU. The cladding condition of N Reactor SNF is fair to poor.	Hanford	2,100
		SRS	0.43
2	**Uranium Metal, Non-Zirc-Clad, Low-Enriched Uranium** – This group contains a low-enriched uranium metal SNF with non-zirc cladding. The largest single source of SNF in this group (over 40% by mass) is from the Hanford Single Pass Reactors, which were used for plutonium production. The Single Pass Reactor SNF consists of circular tubes roughly 1.5 inches in diameter and 0.66 feet long. The Single Pass Reactor SNF has a nominal enrichment of about 1% and an average burnup of about 3 GWd/MTU. The cladding condition of the aluminum cladding on the Single Pass Reactor SNF is generally poor.	Hanford	4.9
		INL	4.2
		SRS	0.09
		Other	0.03
3	**Uranium-Zirconium** – This group contains uranium-zirconium SNF. Greater than 99% of the MTHM of fuel in this group is from the SRS Heavy Water Components Test Reactor. Heavy Water Components Test Reactor semi-production run SNF is the dominant SNF in this group (67% by mass). Heavy Water Components Test Reactor semi-production run SNF consists of circular tubes about 2.1 inches in diameter and 11 feet long. The Heavy Water Components Test Reactor semi-production run SNF is about 0.6% enriched. The condition of the Heavy Water Components Test Reactor semi-production run SNF cladding is fair.	INL	0.002
		SRS	6.7
		Other	0.001
4	**Uranium-Molybdenum** – This group contains a uranium-molybdenum alloy compound SNF. More than 99% of the inventory in this group (by mass) is from the Enrico Fermi Atomic Power Plant, and the majority (over 90% by mass) of the SNF in this group consists of Fermi standard fuel subassemblies. Fermi driver fuel consists of rods roughly 0.16 inches in diameter and 2.7 feet long. The Fermi standard fuel subassembly SNF has an enrichment of about 26% and an average burnup of about 1.6 GWD/MTU. The condition of the cladding for SNF in this group ranges from good to none.	INL	3.9
		SRS	0.008
5	**Uranium Oxide, Zirc-Clad, Intact, High-Enriched Uranium** – This group consists of a high-enriched uranium oxide SNF with intact zirc cladding. Greater than 90% of the SNF in this group (by mass) consists of Shippingport pressurized water reactor Core 2 seed SNF, which is a uranium oxide compound dispersed in a zirconium-oxide (Seed 1) or zirconium-oxide calcium-oxide (Seed 2) matrix. Shippingport pressurized water reactor fuel assemblies consist of 19 flat plates; the assemblies are 7.4 inches square and about 8.7 feet long. The Shippingport pressurized water reactor Core 2 seed SNF has an enrichment of about 69% to 81% and a burnup of roughly 38% of the initial fissile mass. The Shippingport pressurized water reactor Core 2 seed fuel cladding is in good condition.	INL	0.54
		SRS	0.03
		Other	0.005
6	**Uranium Oxide, Zirc-Clad, Intact, Medium-Enriched Uranium** – This group contains medium-enriched uranium oxide SNF with intact zirc cladding. SNF from the Experimental Boiling Water Reactor accounts for more than 80% of the SNF inventory in this group (by mass). Experimental Boiling Water Reactor SNF consists of plate-type assemblies, roughly 3.75 inches square and 5.2 feet long. This SNF has an enrichment of 6% and a maximum burnup of 1.6 GWd/MTU. The cladding is in fair condition.	INL	0.29
		SRS	1.6
7	**Uranium Oxide, Zirc-Clad, Intact, Low-Enriched Uranium** – This group contains low-enriched uranium oxide with intact zirc cladding. Most of the SNF in this group (75% by mass) was generated by typical commercial power reactors, such as the Robert E. Ginna, Calvert Cliffs, Big Rock Point, Surry, and Turkey Point reactors. The commercial power reactor SNF configuration includes intact rod arrays, with enrichment levels ranging from 0.6% to 2.9%. The average burnup of the commercial power reactor SNF in this group ranges from about 1.6 GWd/MTU for some Big Rock Point SNF to about 43 GWd/MTU for the SNF from Calvert Cliffs 1. The condition of the cladding in this group is good.	Hanford	18.0
		INL	61.8
		SRS	2.0
		Other	0.35

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Table A1-1. Inventory of U.S. Department of Energy spent nuclear fuel (continued from page 187)

Group	Description	Site	MTHM
8	**Uranium Oxide, Stainless Steel/Hastelloy™**–Clad, Intact, High-Enriched Uranium – This group contains high-enriched uranium oxide with intact stainless steel or Hastelloy™ cladding. About 40% of the SNF in this group (by mass) was generated by the Pathfinder Atomic Power Plant and the Boiling Reactor Experiment V. The Pathfinder SNF consists of rods 0.9 inches in diameter and 6.5 feet long. The Boiling Reactor Experiment V SNF consists of flat plate assemblies 3.7 inches wide and 2.1 feet long. The SNF in this group has an enrichment of roughly 93%. The Pathfinder and Boiling Reactor Experiment V SNF has a burnup of less than 6% of the initial fissile mass, and the cladding condition is good to fair.	INL	0.074
		SRS	0.12
9	**Uranium Oxide, Stainless Steel–Clad, Intact, Medium-Enriched Uranium** – This group contains medium-enriched uranium oxide SNF with intact stainless steel cladding. Driver fuel for the Power Burst facility accounts for more than 80% of the mass of SNF in this group. Power Burst Facility SNF consists of rods measuring 0.75 inches in diameter and 4 feet in length. Power Burst Facility SNF has an enrichment of about 18% and an average burnup of about 0.5 GWd/MTU. The cladding is in good condition.	INL	0.56
		SRS	0.01
		Other	0.12
10	**Uranium Oxide, Stainless Steel–Clad, Intact, Low-Enriched Uranium** – This group contains low-enriched uranium oxide SNF with intact stainless steel cladding. The Connecticut Yankee reactor accounts for more than 40% (by mass) of the relatively small amount of SNF in this group. The Connecticut Yankee SNF has an enrichment of 1.9% and a burnup of about 32 GWd/MTU. The cladding is in good condition.	Hanford	0.35
		INL	0.38
		SRS	0.16
11	**Uranium Oxide, Non-Aluminum-Clad, Nonintact or Declad, High-Enriched Uranium** – This group contains high-enriched uranium oxide SNF with non-aluminum cladding that is not intact or that has been removed. About 60% of the SNF in this group (by mass) is from medical isotope production targets from research reactors in Canada. The Canadian research reactor targets have an enrichment of about 50% and have no cladding, hence its fuel cladding is categorized as none.	INL	0.32
		SRS	0.006
		Other	0.50
12	**Uranium Oxide, Non-Aluminum-Clad, Nonintact or Declad, Medium-Enriched Uranium** – This group contains medium-enriched uranium oxide SNF with failed non-aluminum cladding or no cladding. Virtually all of this SNF was generated as a result of severe-condition fuel experiments. These experiments generally involved segments of previously irradiated fuel rods that were sectioned and placed into capsules for further irradiation under extremely high temperatures. Enrichment levels for SNF in this group range from 5% to nearly 20%. The condition of the cladding in this group is either poor or none (the cladding has been removed).	Hanford	0.003
		INL	0.34
		SRS	0.01
		Other	0.08
13	**Uranium Oxide, Non-Aluminum-Clad, Nonintact or Declad, Low-Enriched Uranium** – This group contains low-enriched uranium oxide SNF with failed non-aluminum cladding or no cladding. Nearly all (99% by mass) of the failed-clad SNF in this group is core debris from the TMI-2 reactor accident. This fuel has an enrichment of about 2.4% and a burnup of about 3.2 GWd/MTU. The condition of the cladding is poor.	Hanford	0.13
		INL	108
		SRS	0.0005
		Other	0.057
14	**Uranium Oxide, Aluminum-Clad, High-Enriched Uranium** – This group contains high-enriched uranium oxide SNF with aluminum cladding. More than 80% of the SNF in this group (by mass) is High Flux Isotope Reactor SNF. This SNF takes the form of two concentric assemblies consisting of curved involute plates that are separated for disposal. The outer assemblies are about 17 inches in diameter and 2.6 feet long; the inner assemblies are about 12 inches in diameter and 2.5 feet long. High Flux Isotope Reactor SNF has an enrichment of about 87% and an average burnup of about 230 GWd/MTU. The condition of the cladding is good.	INL	0.067
		SRS	1.3
		Other	2.4
15	**Uranium Oxide, Aluminum-Clad, Medium-Enriched Uranium, Low-Enriched Uranium** – This group contains medium-enriched and low-enriched uranium oxide SNF with aluminum cladding. Nearly all of the SNF in this group was generated from a number of foreign research reactors. The largest single source (56% of the inventory by mass) comes from the G.A. Siwabessy RSG-GAS-30 reactor in Indonesia. This Indonesian research reactor SNF consists of square assembly plate-type fuel with a typical width of 3 inches and a length of about 2.9 feet. It has an enrichment of about 10% and a burnup of about 50% of the initial fissile mass. The condition of the cladding for most of the Indonesian research reactor SNF in this group is good.	SRS	0.30
		Other	0.035

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Table A1-1. Inventory of U.S. Department of Energy spent nuclear fuel (continued from page 188)

Group	Description	Site	MTHM
16	**Uranium-Aluminum, Aluminum-Clad, High-Enriched Uranium** – This group contains high-enriched uranium aluminide SNF. The SNF in this group is generated from domestic and foreign test, research, and education reactors. The Advanced Test Reactor is the largest single source of SNF in this group, accounting for 67% of the total inventory by mass. The Advanced Test Reactor SNF consists of curved plate assemblies about 4.2 inches wide, 2.6 inches high, and 5.5 feet long. The assemblies have been cropped to a length of about 4.1 feet for storage. The Advanced Test Reactor SNF has a typical enrichment of about 80% with an average burnup of about 250 GWd/MTU. The Advanced Test Reactor SNF cladding is in good condition.	INL	4.84
		SRS	1.66
		Other	0.91
17	**Uranium-Aluminum, Aluminum-Clad, Medium-Enriched Uranium** – This group contains medium-enriched uranium aluminide SNF. The SNF in this group is generated from numerous domestic and foreign test, research, and education reactors. The largest single source of SNF in this group (30% of the inventory by mass) is the R-2 reactor in Sweden. The R-2 SNF is in the form of a square assembly of plate-type fuel about 3 inches wide and about 2.9 feet long. The R-2 SNF has an enrichment of about 9% and a burnup of 60% of the initial fissile mass. The condition of the SNF cladding in this group is generally good.	SRS	1.68
		Other	0.40
18	**Uranium Silicide** – This group contains uranium silicide (U_3Si_2) SNF. The SNF in this group is generated from numerous domestic and foreign test, research, and education reactors. About 45% of the inventory (by mass) in this group consists of foreign research reactor multi-pin clusters that were generated by the National Research Universal reactor in Canada. National Research Universal SNF has a typical enrichment of about 5.6% and a burnup of about 76% of the initial fissile mass. The cladding is in good condition.	SRS	1.88
		Other	5.09
19	**Thorium-Uranium Carbide, TRISO- or BISO-Coated Particles in Graphite** – This group contains thorium-carbide and uranium-carbide SNF with tristructural isotropic- or buffered isotropic-coated particles embedded in a graphite matrix. About 95% of the inventory in this group (by mass) was generated by the FSV reactor. The FSV SNF consists of hexagonal graphite blocks about 14 inches wide by 31 inches long, containing tristructural isotropic-coated particles (*i.e.*, with inner coatings of pyrocarbon and silicon carbide, and an outer coating of pyrocarbon). The FSV SNF has an enrichment of about 80% and a burnup of about 45% of the initial fissile mass. The condition of the FSV SNF particle coating is good.	INL	9.94
		FSV	14.7
20	**Thorium-Uranium Carbide, Monopyrolytic Carbon-Coated Particles in Graphite** – This group contains thorium-carbide and uranium-carbide SNF with monopyrolytic carbon-coated particles in a graphite matrix. The coated particles are embedded in a graphite matrix. Nearly all (greater than 99%) of the SNF in this group is Peach Bottom Unit 1 Reactor Core 1 fuel. The Peach Bottom Unit 1 Core 1 SNF is about 3.5 inches wide and 12 feet long. The Peach Bottom Unit 1 Core 1 SNF has a typical enrichment of about 86% and a burnup of about 30% of the initial fissile mass. The condition of the Peach Bottom Unit 1 Core 1 SNF particle coating is poor.	INL	1.65
21	**Plutonium-Uranium Carbide, Non-Graphite-Clad, Not Sodium-Bonded** – This group contains a small quantity of plutonium-uranium carbide SNF with non-graphite cladding and no sodium bonding. This SNF was generated primarily by the Fast Flux Test Facility and has stainless steel cladding. About 56% of the inventory in this group (by mass) consists of the Fast Flux Test Facility test fuel assembly TFA-FC-1. A cross section of this assembly forms a hexagon about 4.6 inches across the flats and 5.2 inches across the points; the assembly is 12 feet long. The Fast Flux Test Facility TFA-FC-1 SNF is about 21% enriched and has a burnup of about 60 GWd/MTU. The condition of the cladding is good.	Hanford	0.054
		INL	0.018
		Other	0.004
22	**Mixed Oxide, Zirc-Clad** – This group contains a small quantity of mixed (plutonium-uranium) oxide, uranium-oxide, and plutonium-oxide SNF with zirc cladding. SNF from the Experimental Boiling Water Reactor accounts for about 60% of the inventory in this group (by mass). This SNF has an enrichment of 1.6% and a burnup of 3% of the initial fissile mass. The condition of the Experimental Boiling Water Reactor SNF cladding is fair.	Hanford	0.045
		INL	0.89
		SRS	1.17

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Table A1-1. Inventory of U.S. Department of Energy spent nuclear fuel (continued from page 189)

Group	Description	Site	MTHM
23	**Mixed Oxide, Stainless Steel–Clad** – This group contains mixed (plutonium-uranium) oxide, uranium-oxide, and plutonium-oxide SNF with stainless steel cladding. About 80% of the inventory in this group (by mass) consists of Fast Flux Test Facility reactor driver fuel assemblies and test driver fuel assemblies. A cross section of these assemblies forms a hexagon about 4.6 inches across the flats and 5.2 inches across the points; each assembly is 12 feet long. The Fast Flux Test Facility driver fuel assembly and test driver fuel assembly SNF have enrichments of about 24% and an average burnup of about 70 GWd/MTU. The condition of the SNF cladding in this group is poor to good.	Hanford	10.3
		INL	0.18
		SRS	0.11
		Other	0.019
24	**Mixed Oxide, Non-Stainless Steel–Clad or Non-Zirc-Clad** – This group contains a small quantity of mixed oxide (uranium-oxide and plutonium-oxide, mixed plutonium-uranium oxide) SNF that does not have stainless steel or zirc cladding. The SNF in this group is mostly the residue from hot cells and small experiments and does not have intact cladding. The majority of the SNF in this group (97% by mass) consists of mixed-oxide scrap with an enrichment of about 15%. The condition of the SNF cladding in this group is either poor or none.	INL	0.11
		Other	0.003
25	**Thorium-Uranium Oxide, Zirc-Clad** – This group contains thorium-oxide and uranium-oxide SNF with zirc cladding. The SNF in this group was generated by the Shippingport Atomic Power Station with the Light Water Breeder Reactor core. About 27% of the inventory in this group (by mass) is Shippingport Light Water Breeder Reactor Type IV reflector SNF. Shippingport Light Water Breeder Reactor Type IV reflector assemblies take the form of rods arranged in a rectangular array about 17.1 inches by 13.8 inches and 11.8 feet long. The Shippingport Light Water Breeder Reactor Type IV reflector SNF has an average burnup of about 2 GWd/MTU. The condition of the cladding is generally good.	INL	42.6
		Other	0.00004
26	**Thorium-Uranium Oxide, Stainless Steel–Clad** – This group contains thorium-oxide and uranium-oxide SNF with stainless steel cladding. About 66% of the SNF in this group (by mass) was generated from the Elk River Reactor. Elk River Reactor assemblies consist of rods in square arrays that are about 3.5 inches wide by 5.3 feet long. Elk River Reactor SNF has an enrichment of 96% and a typical burnup of about 5.4 GWd/MTU. The condition of the cladding is generally fair.	INL	0.009
		SRS	7.58
27	**Uranium-Zirconium Hydride, Stainless Steel/Incoloy™–Clad, High-Enriched Uranium** – This group contains high-enriched, uranium-zirconium hydride SNF with stainless steel or Incoloy™ cladding. Most of the SNF in this group was generated from more than 10 domestic and foreign Training, Research, Isotope, General Atomics (TRIGA®) research reactors. No single generator dominates the inventory but generally the SNF was part of a fuel life improvement program design. TRIGA® fuel life improvement program rods are typically 1.5 inches in diameter and 2.4 feet long. The enrichment of the TRIGA® fuel life improvement program SNF in this group ranges from about 60% to 70%, and the burnup ranges from about 9 GWd/MTU to over 300 GWd/MTU. The cladding condition of the TRIGA® fuel life improvement program SNF is generally good.	Hanford	0.0003
		INL	0.14
		Other	0.01
28	**Uranium-Zirconium Hydride, Stainless Steel/Incoloy™–Clad, Medium-Enriched Uranium** – This group contains medium-enriched uranium-zirconium hydride SNF with stainless steel or Incoloy™ cladding. The SNF in this group was generated from more than 20 domestic and foreign TRIGA® research reactors; no single generator dominates the inventory. TRIGA® rods in this group are typically 1.5 inches in diameter and 2.4 to 3.8 feet long. Enrichment of the TRIGA® SNF in this group ranges from about 12% to 20%, and the burnup ranges from slight irradiation to nearly 95 GWd/MTU. The condition of the SNF cladding in this group is generally good.	Hanford	0.023
		INL	0.34
		Other	1.14
29	**Uranium-Zirconium Hydride, Aluminum-Clad, Medium-Enriched Uranium** – This group contains medium-enriched uranium-zirconium hydride SNF with aluminum cladding. The SNF in this group was generated from numerous domestic and foreign TRIGA® research reactors, with no dominant single generator. The TRIGA® rods in this group are typically 1.5 inches in diameter and 2.4 feet long. Enrichment levels range from about 17% to 20%. The SNF in this group has highly variable burnup, ranging from slight irradiation to about 37 GWd/MTU. The condition of the SNF cladding in this group is generally good.	Hanford	0.012
		INL	0.21
		Other	0.13

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Table A1-1. Inventory of U.S. Department of Energy spent nuclear fuel (continued from page 190)

Group	Description	Site	MTHM
30	**Uranium-Zirconium Hydride, Declad** – This group contains uranium-zirconium hydride SNF that has been declad. The SNF in this group was generated from the System for Nuclear Auxiliary Power program. The System for Nuclear Auxiliary Power rods are about 1.2 inches in diameter and 1.2 feet long. The enrichment level is about 90%. Cladding has been removed, so the cladding condition is none.	INL	0.030
31	**Sodium-Bonded** – This group includes a wide variety of SNF that has the common attribute of containing sodium bonding between the fuel matrix and the cladding. This group was not included in the SNF to be disposed of at the proposed Yucca Mountain repository.	INL	55.7
		SRS	0.078
		Other	0.0008
32	**Naval** – Naval SNF consists of solid metal and metallic components that are nonflammable, highly corrosion-resistant, and neither pyrophoric, explosive, combustible, chemically reactive, nor subject to gas generation by chemical reaction or off-gassing. Naval SNF to be emplaced in a geologic disposal repository is from pressurized water reactors, with the exception of one design operated in sodium-cooled reactors. A small amount of the naval SNF from the sodium-cooled reactors remains. Residual sodium has been cleaned from this naval SNF.	INL	28
33	This SNF group is being processed in the SRS H Canyon facility. High-level waste that results from this processing will be vitrified at SRS and disposed of in a repository.	SRS	
		Other	
34	This group contains SNF that does not fit into other groups. The SNF in this group was generated from numerous reactors of different types. The dominant contributor to the inventory is Keuring van Electrotechnische Materialen SNF from the Aqueous Homogeneous Suspension Reactor, an experimental power reactor that was located in the Netherlands. Keuring van Electrotechnische Materialen SNF consists of canisters of thorium-oxide and uranium-oxide scrap. This SNF has an enrichment of about 90% and does not have cladding.	Hanford	0.21
		INL	0.37
		SRS	0.08
		Other	0.0008

Inventory information that was provided to the Board from the Spent Fuel Database, Version 6.2.3 (Version 6.2.3 was released on March 24, 2011; the database itself is described in INL 2007) also included data on the projected number and type of canisters that could be used to transport the SNF off site.[245] Table A1-2 indicates the number of DOE standardized canisters or multi-canister overpacks (MCOs) that DOE projected would be used at each site for the transport of each SNF group (assuming no plugs in the bottom or head of the container). The DOE standardized canister system consisted of four cylindrical, stainless steel canister designs with two different diameters (18 inches and 24 inches) and two different lengths (10 feet and 15 feet). As described in Chapter 4, DOE used MCOs to store most of the mass of SNF at Hanford. DOE also planned to use U.S. Nuclear Regulatory Commission-certified "bare fuel" (un-canistered) transportation casks for off-site transport of undamaged commercial SNF assemblies stored at its sites. Information on the number of bare fuel assemblies from either pressurized water reactors or boiling water reactors that would need to be transported is also provided in Table A1-2. In some cases, a site will be listed multiple times for a single SNF group (*e.g.*, Group 7) because individual fuel types in the group were to be transported differently due to their different characteristics. As described in Section 5.2.2.4, sodium-bonded SNF (Group 31) will be processed into two different solid forms of high-level waste (HLW) and will not be transported as SNF. Similarly, Group 33 SNF is being processed to form HLW. Group 32 (naval) SNF will be transported to a repository in naval SNF canisters. DOE (2009a) projects that a total of 400 naval canisters will be needed to dispose of the projected 65 MTHM inventory of naval SNF. In Table A1-2, groups that contain SNF that is predominantly of commercial origin are in bold font. Table A1-3 summarizes the number of multi-purpose (storage, transportation, and disposal) canisters that DOE projected could be used to package SNF for disposal.

245 *Source:* Sandra Birk, e-mail message, with attachments, to Gene Rowe, former NWTRB staff, January 21, 2013.

Table A1-2. Number and type of packages for off-site transportation of U.S. Department of Energy spent nuclear fuel

Group	Sites	Number of Canisters by Type					Bare Fuel	
		18 in x 10 ft	18 in x 15 ft	24 in x 10 ft	24 in x 15 ft	MCO	PWR (1) (assembly)	BWR (1) (assembly)
1. Uranium Metal, Zirc-Clad, Low-Enriched Uranium	Hanford	-	-	-	-	388	-	-
	SRS	-	2	-	-	-	-	-
2. Uranium Metal, Non-Zirc-Clad, Low-Enriched Uranium	Hanford	-	-	-	-	7	-	-
	INL	3	-	-	-	-	-	-
	SRS	2	-	-	-	-	-	-
	Other	-	-	-	-	-	-	-
3. Uranium-Zirconium	INL	-	1	-	-	-	-	-
	SRS	11	7	-	-	-	-	-
	Other	-	-	-	-	-	-	-
4. Uranium-Molybdenum (2)	INL	9	-	-	-	-	-	-
	SRS	1	-	-	-	-	-	-
5. Uranium Oxide, Zirc-Clad, Intact, High-Enriched Uranium (2)	INL	-	54	-	-	-	-	-
	SRS	3	-	-	-	-	-	-
	Other	-	1	-	-	-	-	-
6. Uranium Oxide, Zirc-Clad, Intact, Medium-Enriched Uranium	INL	2	-	-	-	-	-	-
	SRS	6	-	-	-	-	-	-
7. Uranium Oxide, Zirc-Clad, Intact, Low-Enriched Uranium (2)	Hanford	-	3	-	-	18	-	-
	INL	12	27	-	-	-	39	2
	SRS	18	1	-	-	-	-	-
	Other	3	-	-	-	-	-	-
8. Uranium Oxide, Stainless Steel/Hastelloy™–Clad, Intact, High-Enriched Uranium	INL	6	-	-	-	-	-	-
	SRS	7	-	-	-	-	-	-
9. Uranium Oxide, Stainless Steel–Clad, Intact, Medium-Enriched Uranium	INL	-	9	-	-	-	-	-
	SRS	1	-	-	-	-	-	-
	Other	3	-	-	-	-	-	-
10. Uranium Oxide, Stainless Steel–Clad, Intact, Low-Enriched Uranium (2)	Hanford	-	2	-	-	-	-	-
	INL	-	-	-	-	-	1	-
	SRS	1	1	-	-	-	-	-
11. Uranium Oxide, Non-Aluminum-Clad, Nonintact or Declad, High-Enriched Uranium	INL	21	6	-	-	-	-	-
	SRS	1	-	-	-	-	-	-
	Other	168	-	-	-	-	-	-
12. Uranium Oxide, Non-Aluminum-Clad, Nonintact or Declad, Medium-Enriched Uranium	Hanford	-	-	-	-	-	-	-
	INL	3	-	-	-	-	-	-
	SRS	-	-	-	-	-	-	-
	Other	-	1	-	-	-	-	-

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Table A1-2. Number and type of packages for off-site transportation of U.S. Department of Energy spent nuclear fuel (continued from page 192)

Group	Sites	Number of Canisters by Type					Bare Fuel	
		18 in x 10 ft	18 in x 15 ft	24 in x 10 ft	24 in x 15 ft	MCO	PWR (1) (assembly)	BWR (1) (assembly)
13. Uranium Oxide, Non-Aluminum-Clad, Nonintact or Declad, Low-Enriched Uranium (2)	Hanford	-	-	-	-	-	-	-
	INL	3	344	-	-	-	40	76
	SRS	1	-	-	-	-	-	-
	Other	1	-	-	-	-	-	-
14. Uranium Oxide, Aluminum-Clad, High-Enriched Uranium	INL	8	-	-	-	-	-	-
	SRS	88	-	37	-	-	-	-
	Other	114	-	97	-	-	-	-
15. Uranium Oxide, Aluminum-Clad, Medium-Enriched Uranium, Low-Enriched Uranium	SRS	8	-	-	-	-	-	-
	Other	2	-	-	-	-	-	-
16. Uranium-Aluminum, Aluminum-Clad, High-Enriched Uranium	INL	290	-	-	-	-	-	-
	SRS	213	-	-	-	-	-	-
	Other	46	92	-	-	-	-	-
17. Uranium-Aluminum, Aluminum-Clad, Medium-Enriched Uranium	SRS	60	-	-	-	-	-	-
	Other	14	-	-	-	-	-	-
18. Uranium Silicide	SRS	52	-	-	-	-	-	-
	Other	41	145	-	-	-	-	-
19. Thorium-Uranium Carbide, TRISO- or BISO-Coated Particles in Graphite (2)	INL	-	212	-	-	-	-	-
	FSV	-	293	-	-	-	-	-
20. Thorium-Uranium Carbide, Monopyrolytic Carbon-Coated Particles in Graphite (2)	INL	-	63	-	-	-	-	-
21. Plutonium-Uranium Carbide, Non-Graphite-Clad, Not Sodium-Bonded	Hanford	-	3	-	-	-	-	-
	INL	2	-	-	-	-	-	-
	Other	-	-	-	-	-	-	-
22. Mixed Oxide, Zirc-Clad	Hanford	-	-	-	-	-	-	-
	INL	-	-	-	-	-	-	5
	SRS	4	-	-	-	-	-	-
23. Mixed Oxide, Stainless Steel–Clad	Hanford	-	125	-	-	-	-	-
	INL	10	-	-	-	-	-	-
	SRS	1	1	-	-	-	-	-
	Other	-	3	-	-	-	-	-
24. Mixed Oxide, Non-Stainless Steel–Clad or Non-Zirc–Clad	INL	1	-	-	-	-	-	-
	Other	-	1	-	-	-	-	-
25. Thorium-Uranium Oxide, Zirc-Clad (2)	INL	-	12	-	27	-	-	-
	Other	-	-	-	-	-	-	-
26. Thorium-Uranium Oxide, Stainless Steel–Clad (2)	INL	1	-	-	-	-	-	-
	SRS	11	1	-	-	-	-	-

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Table A1-2. Number and type of packages for off-site transportation of U.S. Department of Energy spent nuclear fuel *(continued from page 193)*

Group	Sites	Number of Canisters by Type					Bare Fuel	
		18 in x 10 ft	18 in x 15 ft	24 in x 10 ft	24 in x 15 ft	MCO	PWR (1) (assembly)	BWR (1) (assembly)
27. Uranium-Zirconium Hydride, Stainless Steel/Incoloy™–Clad, High-Enriched Uranium	Hanford	1	-	-	-	-	-	-
	INL	18	-	-	-	-	-	-
	Other	1	-	-	-	-	-	-
28. Uranium-Zirconium Hydride, Stainless Steel/Incoloy™–Clad, Medium-Enriched Uranium	Hanford	2	-	-	-	-	-	-
	INL	15	-	-	-	-	-	-
	Other	34	-	-	-	-	-	-
29. Uranium-Zirconium Hydride, Aluminum-Clad, Medium-Enriched Uranium	Hanford	1	-	-	-	-	-	-
	INL	11	-	-	-	-	-	-
	Other	7	-	-	-	-	-	-
30. Uranium-Zirconium Hydride, Declad	INL	-	-	-	-	-	-	-
31. Sodium-Bonded (3)		-	-	-	-	-	-	-
32. Naval	INL							
33. This SNF group is being processed in the SRS H Canyon facility.								
34. Miscellaneous (Not Previously Listed)	Hanford	-	1	-	-	-	-	-
	INL	3	-	-	-	-	-	-
	SRS	-	1	-	-	-	-	-
	Other	1	-	-	-	-	-	-

Notes
(1) Pressurized water reactor (PWR) and boiling water reactor (BWR). DOE plans to package fuel assemblies into bare fuel transportation casks. The only U.S. Nuclear Regulatory Commission (NRC)-certified bare fuel cask for pressurized water reactor assemblies can hold 40 assemblies. The only NRC-certified bare fuel cask for boiling water reactor assemblies can hold 68 assemblies.
(2) Groups that contain SNF that is predominantly of commercial origin are in bold font.
(3) Sodium-bonded SNF will be treated and not transported off site as SNF.

Table A1-3. Number of multi-purpose canisters that could be used to package spent nuclear fuel stored at different sites

Sites and Total	Number of Canisters						
	DOE Standardized Canister				MCO	Naval	Total
	18 in x 10 ft	18 in x 15 ft	24 in x 10 ft	24 in x 15 ft			
Hanford	4	134	-	-	413	-	551
INL	418	728	-	27	-	400	1,573
SRS	489	14	37	-	-	-	540
FSV	-	293	-	-	-	-	293
Other	435	243	97	-	-	-	775
Total	1,346	1,412	134	27	413	400	3,732

DOE calculated the inventory of radionuclides (in curies) for each type of non-naval SNF (DOE 2004a, Volumes 1–3). DOE calculated both a nominal and bounding inventory for the years 2010 and 2030. This information is contained in DOE's Spent Fuel Database (DOE 2007c). The nominal inventory in 2030 for a subset of the radionuclides is provided in Table A1-4. The listed radionuclides are a dominant contributor to the total radioactivity of a SNF degradation group (Table 2-3), or are important radionuclides to understanding barrier performance of a geologic repository containing light water reactor SNF (in the U.S. this is commercial SNF), or are dominant contributors to the dose to a member of the public from the post-closure repository performance for different geologic disposal environments.

In its review of the radionuclide inventory, the Board identified that DOE's calculated radioactivity for uranium-235 for degradation group 6 (DG6; Table A1-4) is about 100 times smaller than for actinium-227 and protactinium-231, which are radioactive daughters of uranium-235. The calculated curies for degradation group 6 of actinium-227 and protactinium-231 are larger than the calculated curies of all other DOE SNF and commercial SNF combined.

DOE uses the Shippingport Light Water Breeder Reactor as the typical SNF in degradation group 6 (Table 2-3). The Shippingport breeder SNF is about 85%, by mass, of the total SNF in degradation group 6. The Shippingport Light Water Breeder Reactor was a pressurized, light water moderated and cooled thermal reactor with zirconium-clad ThO_2-UO_2 fuel rods (DOE 2004a). The beginning-of-life UO_2 was fully enriched in uranium-233 (>98%), not uranium-235. In addition to the ThO_2-UO_2 fuel rods, the entire fueled active core region was reflected radially or circumferentially around the core, and both above and below with ThO_2 fuel rods. The ThO_2 rods in the outer reflector regions and the very large ThO_2 loading in the active core were designed to reduce neutron leakage and breed uranium-233. ThO_2 is composed of thorium-232. Addition of a neutron to thorium-232 and release of two neutrons in the reactor creates thorium-231 that rapidly decays to protactinium-231. The unique composition of the fuel and the associated nuclear processes during reactor operation explains the large inventory of actinium-227 and protactinium-231.

Table A1-4. Nominal non-naval U.S. Department of Energy spent nuclear fuel inventory, in curies, in 2030

Radionuclide	Total (1)	DG2 (2)	DG3	DG4	DG5	DG6 (3)	DG7	DG8	DG9	DG10	DG11
actinium-227	5.8E+01	1.7E-02	5.0E-08	2.3E-01	3.7E+00	5.4E+01	1.1E-02	3.2E-02	5.9E-03	1.3E-02	5.5E-04
americium-241	2.2E+06	1.5E+04	1.1E+03	9.3E+05	2.9E+03	7.8E+03	7.5E+05	4.9E+05	3.2E+04	2.8E+03	7.4E+02
carbon-14	1.8E+04	7.1E+02	2.2E-01	1.1E+04	2.1E+01	1.6E+02	3.1E+03	3.0E+03	1.5E+00	3.9E+01	1.5E+01
cesium-137	2.8E+07	5.4E+05	1.2E+04	2.8E+06	1.1E+06	7.9E+05	6.5E+06	4.8E+06	1.1E+07	1.3E+05	2.2E+05
chlorine-36	3.0E+02	6.0E-03	2.9E-06	2.1E+02	9.8E-01	3.1E+00	3.7E+01	4.4E+01	1.5E-03	7.0E-01	3.2E-01
cobalt-60	8.0E+05	8.1E+02	2.8E+01	6.5E+05	2.9E+02	2.6E+04	1.0E+04	5.6E+04	2.3E+02	4.7E+02	5.1E+04
curium-244	1.4E+05	2.1E+00	1.3E+01	1.1E+04	5.1E+03	1.6E+02	3.7E+03	1.1E+05	3.2E+03	1.9E+01	8.1E+01
iodine-129	2.0E+01	5.7E-01	1.1E-02	2.3E+00	9.3E-01	8.8E-01	6.7E+00	3.9E+00	4.0E+00	1.1E-01	9.2E-02
krypton-85	9.5E+05	4.8E+03	2.3E+02	5.2E+04	2.9E+04	3.2E+04	7.8E+04	7.9E+04	6.6E+05	3.7E+03	1.4E+04
neptunium-237	2.1E+02	4.0E+00	3.2E-02	1.9E+01	1.2E+01	2.1E-01	7.0E+01	4.1E+01	6.4E+01	3.8E-01	5.5E-01
nickel-59 (4)	4.6E+04										
plutonium-238	8.5E+05	3.2E+03	1.2E+02	1.5E+05	1.4E+05	2.9E+03	1.4E+05	2.2E+05	1.9E+05	6.8E+02	1.7E+03
plutonium-239	4.8E+05	1.4E+04	1.0E+03	1.7E+05	1.3E+02	3.9E+02	2.2E+05	5.1E+04	1.0E+04	2.1E+03	5.5E+02
plutonium-240	3.6E+05	5.3E+03	8.4E+02	1.3E+05	2.5E+02	2.7E+02	1.7E+05	5.3E+04	5.4E+03	1.9E+02	2.3E+02
plutonium-241	9.4E+06	2.2E+04	1.9E+04	4.6E+06	1.5E+04	4.5E+04	2.2E+06	2.0E+06	5.0E+05	5.8E+03	1.2E+04
plutonium-242	5.1E+02	1.3E+00	2.7E-01	1.8E+02	3.6E+00	2.2E+00	1.1E+02	2.0E+02	6.0E+00	7.2E-01	2.0E-01
promethium-147	3.6E+06	2.1E+00	1.3E+02	1.5E+04	9.3E+01	1.4E+02	1.2E+04	9.8E+03	3.5E+06	1.2E+02	7.5E+04
protactinium-231	7.1E+01	2.8E-02	1.1E-07	2.7E-01	4.4E+00	6.6E+01	2.0E-02	5.1E-02	1.4E-02	2.2E-02	1.0E-03
radium-226	8.0E-02	1.9E-02	6.9E-08	9.5E-03	3.0E-03	1.2E-02	1.6E-02	1.8E-02	2.1E-03	5.1E-05	5.2E-07
selenium-79	2.9E+02	9.4E+00	8.5E-02	2.8E+01	1.9E+01	2.0E+01	8.7E+01	5.5E+01	7.0E+01	1.6E+00	1.6E+00
strontium-90	2.3E+07	4.7E+05	4.1E+03	1.8E+06	1.1E+06	8.0E+05	4.7E+06	3.4E+06	1.0E+07	1.2E+05	2.1E+05
technetium-99	8.9E+03	3.2E+02	3.3E+00	1.0E+03	3.1E+02	1.8E+02	2.9E+03	1.8E+03	2.3E+03	4.5E+01	5.4E+01
thorium-230	4.9E+00	1.1E+00	8.9E-06	6.8E-01	1.9E-01	6.4E-01	1.0E+00	1.0E+00	2.3E-01	3.0E-03	5.5E-05
tin-126	2.8E+02	1.1E+01	3.7E-01	5.9E+01	2.0E+01	2.2E+01	9.2E+00	9.2E+01	6.2E+01	3.6E+00	1.5E+00
uranium-232	2.2E+04	6.0E-02	1.1E-02	2.1E+01	1.4E+03	2.0E+04	1.1E-01	1.8E+00	5.8E-01	9.5E-01	1.6E-02
uranium-233	1.8E+04	5.8E-01	4.9E-06	3.4E+01	1.9E+03	1.6E+04	4.3E-01	1.4E+00	2.0E-02	8.7E+01	1.4E-02
uranium-234	7.3E+03	1.5E+03	3.6E-02	1.2E+03	2.7E+02	4.6E+02	1.6E+03	1.5E+03	7.6E+02	4.4E+00	2.1E-01
uranium-235	1.4E+02	2.0E+00	2.1E-04	5.4E+01	3.8E+00	5.6E-01	4.8E+01	1.1E+01	2.2E+01	2.1E-01	8.4E-01
yttrium-90	2.3E+07	4.7E+05	4.1E+03	1.8E+06	1.1E+06	8.0E+05	4.7E+06	3.4E+06	1.0E+07	1.2E+05	2.1E+05

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Table A1-4. Nominal non-naval U.S. Department of Energy spent nuclear fuel inventory, in curies, in 2030 *(continued from page 196)*

Radionuclide	Total (1)	DG2 (2)	DG3	DG4	DG5	DG6 (3)	DG7	DG8	DG9	DG10	DG11
Others (4)	3.5E+07	5.2E+05	1.2E+04	6.3E+06	1.1E+06	9.3E+05	6.8E+06	5.3E+06	1.4E+07	1.4E+05	2.6E+05
Total	1.3E+08	2.1E+06	5.4E+04	1.9E+07	4.5E+06	3.5E+06	2.6E+07	2.0E+07	4.9E+07	5.3E+05	1.0E+06

Notes

(1) Inventory is in curies. Radionuclides that are dominant on a curie basis or are important to public dose calculations are listed. DOE (2007c) documents the total values for all radionuclides. Other values are from DOE (2004a, Volume 3, pp. D-577 to D-586).

(2) Degradation groups (DGs) are those in Table 2-3. DOE SNF groups described in Table A1-1 are listed here for each degradation group number. DG2 (plutonium/uranium alloy) includes DOE SNF Groups 3 and 4. DG3 (plutonium/uranium carbide) is DOE SNF Group 21. DG4 (mixed oxide and plutonium oxide) includes DOE SNF Groups 22, 23, and 24. DG5 (thorium/uranium carbide) includes DOE SNF Groups 19 and 20. DG6 (thorium/uranium oxide) includes DOE SNF Groups 25 and 26. DG7 (uranium metal) includes DOE SNF Groups 1 and 2. DG8 (uranium oxide) includes DOE SNF Groups 5, 6, 7, 8, 9, 10, 11, 12, and 13. DG9 (aluminum-based SNF) includes DOE SNF Groups 14 through 18. DG10 (miscellaneous SNF) is DOE SNF Group 34. DG11 (uranium-zirconium hydride) includes DOE SNF Groups 27 through 30.

(3) Yellow highlighted values indicate that more than 50% of the total inventory of that radionuclide for DOE SNF is in SNF of that waste degradation group. For example, Shippingport Light Water Breeder Reactor fuel is the dominant fuel, by mass and by radioactivity, in waste degradation group 6 (DG6). That fuel was 95% thorium oxide with the balance uranium oxide, which consisted of high-enriched uranium (98% uranium-233). The composition of the fuel and the fuel blanket and nuclear reactions during reactor operations lead to SNF with large inventories of uranium-232 and uranium-233. The large inventory of protactinium-231 was produced from thorium-232 during reactor operations that occurred between 1979 and 1982 (Olson *et al.* 2002). The large inventory of actinium-227, in 2030, is due to radioactive in-growth from its parent, protactinium-231.

(4) Summary tables for each waste degradation group did not list nickel-59 separately, but it and other non-listed radionuclides were summed in the "Others" category (DOE 2004a, Volume 3, pp. D-577 to D-586).

Appendix 2. Comparison of Commercial and U.S. Department of Energy Spent Nuclear Fuel

This appendix discusses differences between commercial spent nuclear fuel (SNF) and U.S. Department of Energy (DOE) SNF in terms of several factors: the size of the inventory, where and how the SNF is stored, and requirements for transport and disposal. Some of the characteristics of DOE SNF that are described in Appendix 1, such as fuel compound, cladding, cladding condition, and enrichment, are described here for commercial SNF. These parameters correspond to fuel characteristics that DOE has determined will have a major impact on the release of radionuclides from a geologic repository and contribute to nuclear criticality scenarios. This appendix also compares the physical size of individual handling units of commercial and DOE SNF because handling size affects options in terms of packaging the fuel for storage, transportation, and disposal.

A2.1 Characteristics of Spent Nuclear Fuel

The physical characteristics of commercial and DOE SNF differ substantially (Figure A2-1). Commercial SNF comes in two types based on whether it was generated by a pressurized water reactor (Figure A2-2) or a boiling water reactor (Figure A2-3). By contrast, there are over 250 different types of DOE SNF that vary in size, length and width, and cross-sectional shape, which may be circular, square, or hexagonal.

In general, DOE SNF is smaller than commercial SNF.[246] Commercial SNF is generally handled in assemblies, whereas DOE SNF may be handled in different forms, including assemblies, subassemblies, fuel elements, and single pieces of fuel.

[246] About 85% of the DOE SNF inventory by mass is N Reactor fuel. The diameter of this fuel is 2.5 inches and its length varies from 15 inches to 26 inches. The heaviest N Reactor element contains approximately 22.7 kilograms (50 pounds) of uranium.

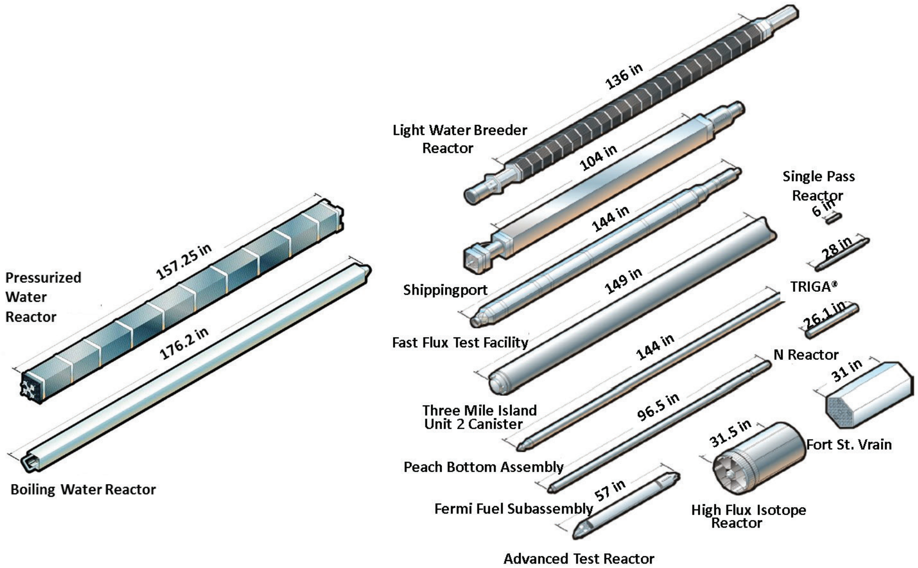

Figure A2-1. The two types of commercial fuel assemblies and a few types of the more than 250 types of U.S. Department of Energy spent nuclear fuel.
The length in inches for each type of SNF is given directly above the image of the fuel. (Source: INL 2007).

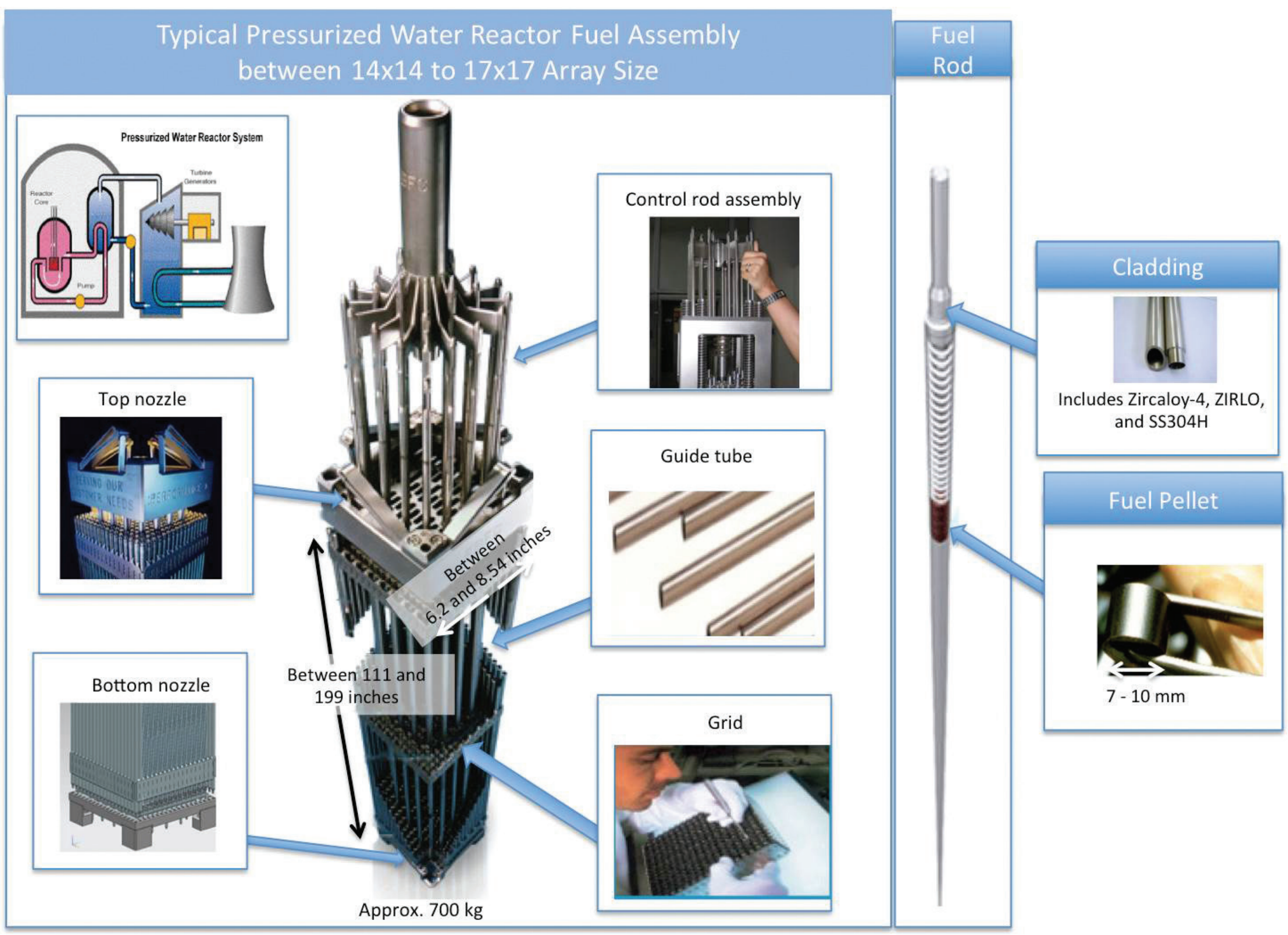

Figure A2-2. Typical pressurized water reactor fuel assembly.[247]
(Source: Wagner *et al.* 2012, Figure A-1).

[247] Wagner *et al.* (2012) described the characteristics of assemblies that were discharged from reactors prior to 1999. Nearly all assemblies are square (*e.g.*, 14 x 14) but a few are uneven arrays (*e.g.*, Yankee Rowe used 15 x 16 and 16 x 17 arrays and Indian Point-1 used a 13 x 14 array; Table A-1 in Wagner *et al.* 2012).

Although Figure A2-1 depicts a single length for each type of commercial fuel assembly, both pressurized water reactor and boiling water reactor fuel assemblies come in varying lengths and widths (see Figure A2-2 and Figure A2-3). Figure A2-2 identifies the components of a typical pressurized water reactor fuel assembly. This type of assembly is generally manufactured in square arrays of fuel rods (Wagner *et al*. 2012), ranging from 14 x 14 to 17 x 17 arrays of rods. Each fuel rod is composed of fuel pellets and the cladding that surrounds the fuel pellets. Almost all of the pressurized water reactor fuel rods ever produced (approximately 99%) are clad in zirconium-based cladding, such as Zircaloy-4™. The remaining fuel rods are clad in stainless steel (Wagner *et al*. 2012). Earlier fuel rods used stainless steel, but now only zirconium-based cladding is used.

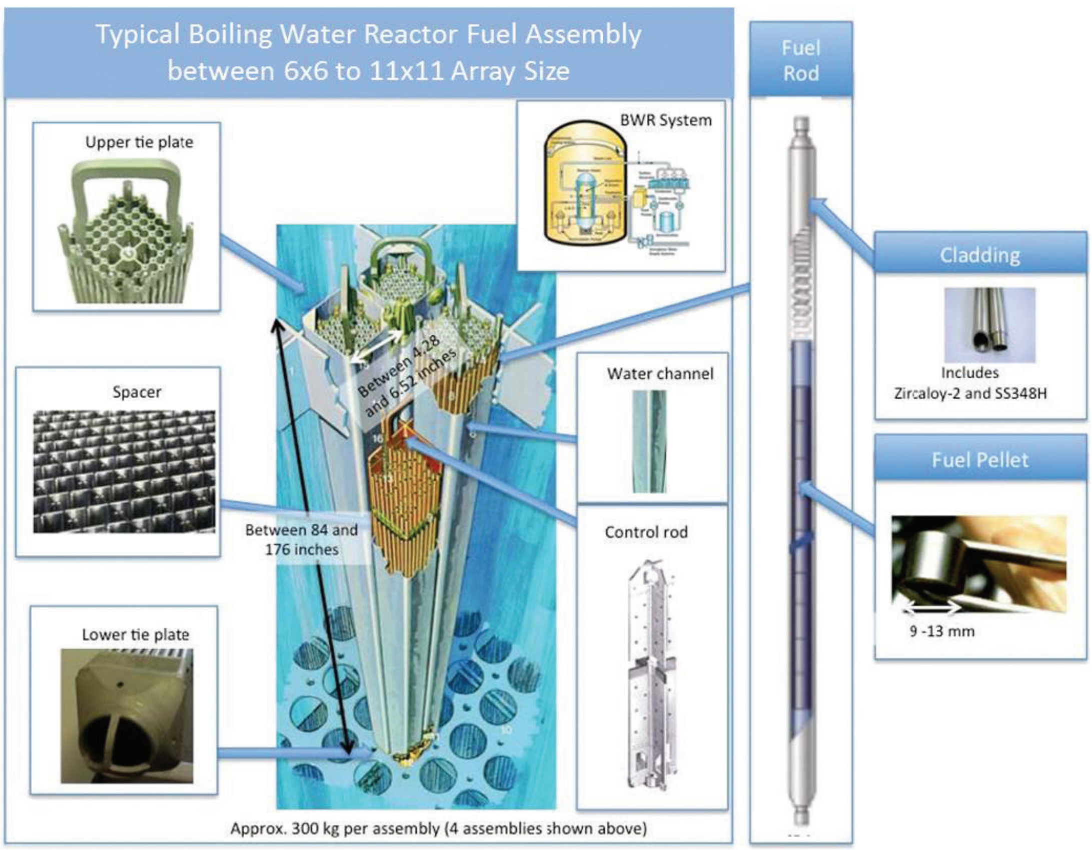

Figure A2-3. Typical boiling water reactor fuel assembly. (Source: Wagner *et al*. 2012, Figure A-2).

Figure A2-3 depicts the components of a typical fuel assembly from a boiling water reactor. These assemblies are likewise manufactured in square arrays of fuel rods (Wagner *et al*. 2012), but they are somewhat smaller, ranging from 6 x 6 rods arrays to 11 x 11 rods arrays. Although roughly similar in length, the typical boiling water reactor assemblies are about two times narrower and weigh less than half of typical pressurized water reactor assemblies. Almost all of the boiling water reactor fuel rods ever produced (approximately 99%) are clad in zirconium-based cladding, such as Zircaloy-2™. The remaining fuel rods are clad in stainless steel (Wagner *et al*. 2012). As in the case of pressurized water reactor fuel rods, earlier boiling water reactor fuel rods used stainless steel, but now only zirconium-based cladding is used.

Commercial and DOE SNF also differ with respect to other attributes, including the number and types of fuel compounds, cladding, cladding condition, enrichment, and burnup (Table 2-1). In general, commercial SNF has more uniform properties and is less damaged than DOE SNF. For example, all commercial fuel that is not managed by DOE is low-enriched (less than 5% uranium-235), composed of uranium dioxide, and clad in either zirconium-based or stainless steel cladding.[248]

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[248] Some early commercial fuel such as that at Fort St. Vrain and Shippingport was not low-enriched or composed of uranium dioxide, but this SNF is owned and managed by DOE and is not considered commercial in this report.

In contrast, DOE fuel includes both low-enriched fuel and high-enriched (greater than 20% uranium-235) fuel; contains more than ten types of fuel compounds, including uranium dioxide; includes some fuel that is embedded in a fuel matrix (for example, thorium-uranium carbide fuel particles in graphite); and is clad in more than five classes of material (for example, aluminum). In addition, some of the fuel has no cladding.

Commercial SNF and its cladding is in much better condition than DOE SNF. For instance, only a small fraction of commercial SNF is damaged—through 2002, this damaged fraction amounted to just 0.012 (12 thousandths) of the overall mass of the commercial SNF inventory (Wagner *et al*. 2012). DOE (2009a) estimated the expected failure rate for cladding of commercial SNF received at the proposed Yucca Mountain repository at 0.1%. The annual rate of failure for the cladding of fuel in commercial reactors has decreased with time to a current failure rate of about 1×10^{-6} per fuel rod per year (Sowder 2014). In contrast, the majority of DOE SNF has cladding that is in fair condition (*i.e.*, known or suspected defects are limited to hairline cracks or pinhole leaks) or worse. For example, Group 1 DOE SNF includes about 2,100 metric tons of heavy metal (MTHM) of N Reactor SNF at the Hanford Site and the condition of the cladding for this SNF is fair to poor. Also, a substantial amount of DOE SNF is damaged, including approximately 81.6 MTHM of nuclear reactor core debris from the Three Mile Island Unit 2 (TMI-2) reactor stored at the Idaho National Laboratory (INL).

Fuel enrichment (in percent uranium-235), extracted energy per unit mass of fuel (*i.e.*, burnup), and thermal output are less variable in commercial SNF than in DOE SNF. The current licensing limit of 5% uranium-235 for commercial reactors (Sandia National Laboratories 2014) also limits the range of burnup in commercial SNF. Fuel enrichment, burnup, and thermal output are higher for the average pressurized water reactor assembly than for the average boiling water reactor assembly (DOE 2009a, Tables 1.5.1-5 and 1.5.1-11). Although the range of burnup for DOE SNF is larger than the range for commercial SNF, about 85% of the DOE SNF (by mass) has a burnup of 2.4 GWd/MTU (Group 1). The approximate average thermal output per MTHM is about six times lower for DOE SNF than for commercial SNF.

A2.2 Inventory of Spent Nuclear Fuel

The commercial and DOE SNF inventories differ substantially in terms of mass, volume, and radioactivity. These differences will continue to grow in the future because of the continued operation of commercial nuclear power plants (Figure A2-4). The volume of SNF, both commercial and DOE, that is projected to be produced from 2012 to 2048 is roughly equivalent to the volume that had been produced through 2012. The commercial SNF inventory is increasing by 2,000–2,400 MTHM each year (Cummings 2014), depending on individual reactor refueling schedules. Figure A2-5 provides details on the inventory of commercial and DOE, SNF. Figure A2-6 shows the relative radioactivity of commercial SNF and DOE-managed high-level waste (HLW) and SNF for the dates cited in the figure notes. Almost all the radioactivity is from commercial SNF and more than 95% of the current radioactivity is from radionuclides that have half-lives less than 50 years (Table A2-1), primarily cesium-137 and strontium-90 and their short-lived radioactive daughters. The total radioactivity for each waste type, except commercial SNF, will decrease with time due to radioactive decay. For example, the radioactivity of the current HLW inventory (assuming no further additions) will decrease by about 20% in 10 years due to the decay of cesium-137 and strontium-90. The total radioactivity of the commercial SNF inventory, by contrast, will increase to about 33 billion curies (Ci) by 2048[249] because the decay of radionuclides in the existing inventory is more than offset by the addition of new commercial SNF.

[249] The value cited is from a worksheet ("WFDO__Evaluation_Rev_25.xlsx") used by Sandia National Laboratories to develop its disposal options report (Sandia National Laboratories 2014), provided by Timothy Gunter, DOE, e-mail message, with attachments, to Bret Leslie, NWTRB staff, April 24, 2015.

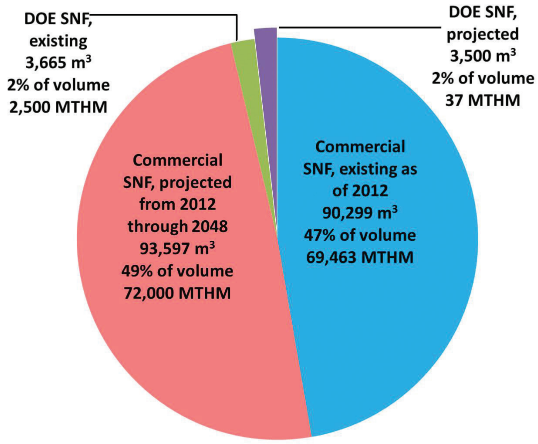

Figure A2-4. Quantities of commercial and U.S. Department of Energy spent nuclear fuel.
Spent nuclear fuel (SNF) volume and mass, in terms of metric tons of heavy metal (MTHM), of existing and projected inventory in 2048. DOE SNF includes naval SNF.[250]

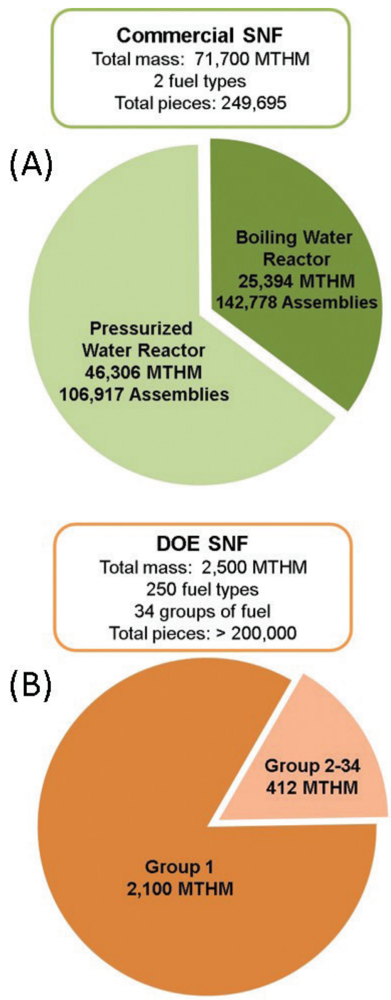

Figure A2-5. Quantities and types of commercial and U.S. Department of Energy spent nuclear fuel.
The diameter of the pie charts is not to scale relative to the quantity of SNF. A. The estimated mass, in metric tons of heavy metal (MTHM), of commercial SNF as of December 31, 2013 (Carter and Vinson 2014, Table 1-2), is depicted as well as the number of assemblies. B. The mass of the 34 groups of DOE SNF described in Appendix 1 and DOE (2009a) is depicted, as well as the number of fuel types and total number of pieces of DOE SNF. For Group 1 SNF, 99% of the mass is from the N Reactor at Hanford.

[250] Figure 6-1 of Sandia National Laboratories (2014) was revised to add the projected mass and volume of naval SNF. Approximately 3,500 cubic meters (m3) of naval SNF remains to be generated (Sandia National Laboratories 2014). The future addition of 37 MTHM of naval SNF reflects the existing inventory of 28 MTHM and the total expected inventory of 65 MTHM (McKenzie 2010a). Volume estimates assume constant nuclear power generation in commercial reactors and disposal of all commercial SNF in dual-purpose canisters. Masses of commercial SNF and DOE, existing and projected in 2048, also assume constant nuclear power generation in commercial reactors.

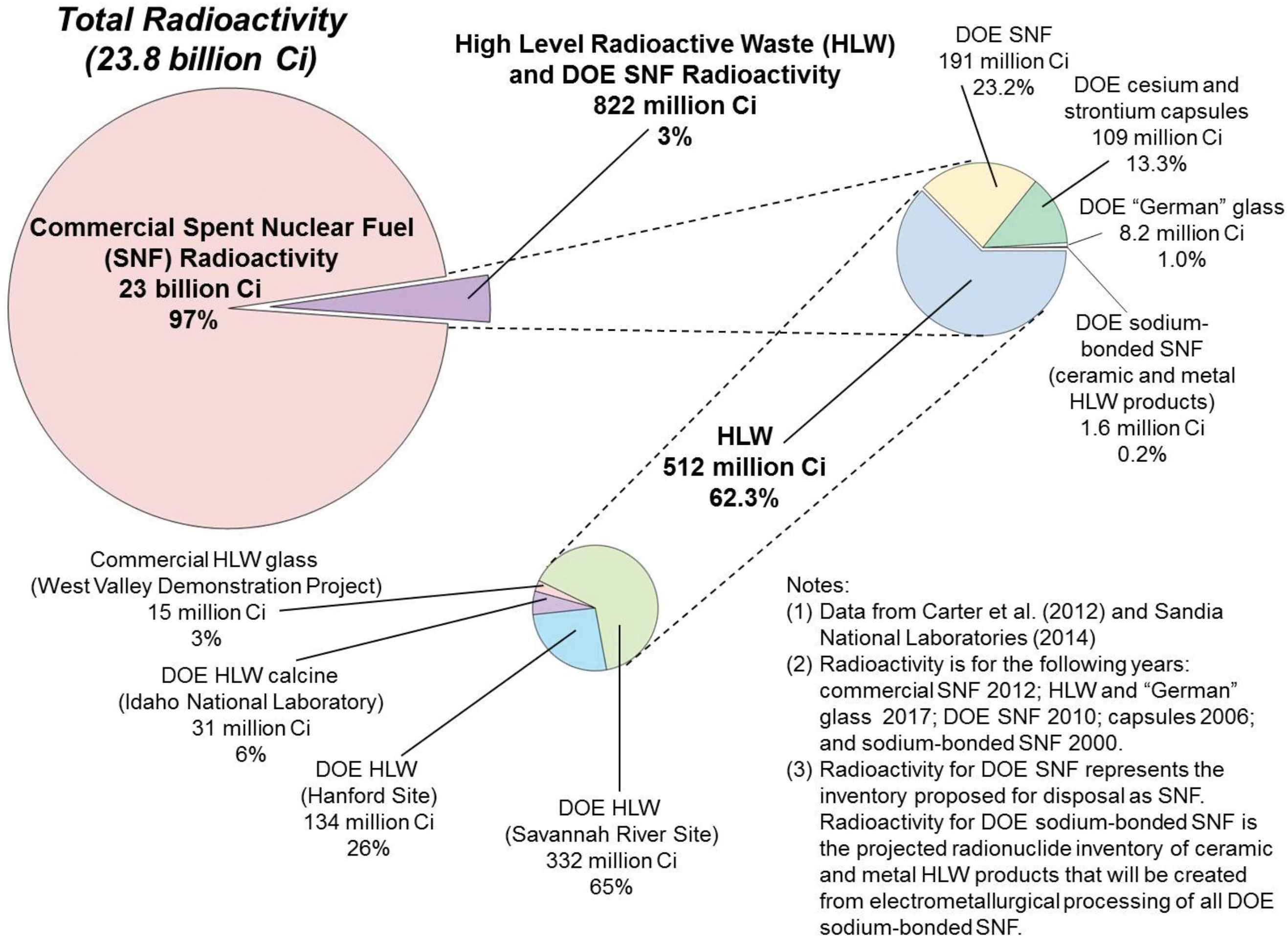

Figure A2-6. Relative radioactivity of United States spent nuclear fuel and high-level radioactive waste.
Over 99% of the SNF radioactivity [in curies (Ci)] is in commercial SNF assemblies. DOE SNF value does not include naval SNF. There are 1,335 cesium capsules, 600 strontium capsules, 34 canisters of glass created by DOE in the late 1980s for the German disposal program, and 275 glass canisters at West Valley, New York. DOE is vitrifying liquid HLW at the Savannah River Site and plans to solidify into disposable waste forms the remaining HLW radioactivity. For clarity purposes, an additional ~550,000 Ci, in 2012, present in sodium-bearing waste at the INL (Sandia National Laboratories 2014) are not depicted in the figure.

Table A2-1. Radioactivity of commercial and non-naval U.S. Department of Energy spent nuclear fuel inventory and of a representative canister of naval spent nuclear fuel[251]

Radionuclide	Commercial Total Ci	DOE Total Ci	Commercial Ci/MTHM	DOE Ci/MTHM	Navy Ci/Canister
actinium-227	2.03E+00	5.79E+01	3.22E-05	2.55E-02	2.12E-04
americium-241	3.02E+08	2.24E+06	4.79E+03	9.88E+02	3.56E+01
americium-242	1.01E+06	4.73E+03	1.60E+01	2.09E+00	3.84E-01
americium-242m	1.01E+06	4.75E+03	1.60E+01	2.09E+00	3.86E-01
americium-243	3.28E+06	4.05E+03	5.21E+01	1.79E+00	4.66E-01
antimony-125	1.50E+06	9.38E+04	2.38E+01	4.14E+01	4.13E+03
antimony-126	8.48E+03	3.93E+01	1.35E-01	1.73E-02	1.34E-01
antimony-126m	6.06E+04	2.81E+02	9.62E-01	1.24E-01	9.55E-01
barium-137m	6.13E+09	2.62E+07	9.73E+04	1.16E+04	2.93E+05
carbon-14	5.85E+04	1.82E+04	9.29E-01	8.02E+00	6.40E+00
cadmium-113m	1.18E+06	2.70E+03	1.87E+01	1.19E+00	2.33E+01
cerium-144	1.76E+01	1.44E+06	2.79E-04	6.35E+02	1.47E+04
cesium-134	3.78E+06	6.70E+05	6.00E+01	2.95E+02	4.95E+04
cesium-135	5.73E+04	3.13E+02	9.10E-01	1.38E-01	3.68E+00
cesium-137	6.50E+09	2.77E+07	1.03E+05	1.22E+04	3.11E+05
chlorine-36	1.14E+03	2.98E+02	1.81E-02	1.31E-01	1.36E-01
cobalt-60	4.40E+07	7.98E+05	6.98E+02	3.52E+02	1.18E+03
curium-242	8.34E+05	3.91E+03	1.32E+01	1.72E+00	9.70E-01
curium-243	1.53E+06	1.13E+03	2.43E+01	4.98E-01	4.68E-01
curium-244	1.96E+08	1.35E+05	3.11E+03	5.95E+01	4.40E+01
curium-245	4.25E+04	7.13E+01	6.75E-01	3.14E-02	3.85E-03
curium-246	1.45E+04	1.10E+01	2.30E-01	4.85E-03	1.20E-03
europium-152	2.15E+05	2.17E+03	3.41E+00	9.57E-01	3.71E+01
europium-155	8.06E+06	9.11E+04	1.28E+02	4.02E+01	2.12E+03
hydrogen-3	1.81E+07	1.06E+05	2.87E+02	4.67E+01	1.15E+03
iodine-129	3.48E+03	1.95E+01	5.52E-02	8.60E-03	8.03E-02
iron-55	1.18E+06	5.33E+04	1.87E+01	2.35E+01	1.68E+03
krypton-85	1.79E+08	9.54E+05	2.84E+03	4.21E+02	2.41E+04

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[251] The total commercial inventory [in curies (Ci)] 25 years after reactor discharge is calculated from the radioactivity (Ci per assembly) for the average pressurized water reactor and boiling water reactor SNF assemblies (DOE 2009a, Table 1.5.1-12) and percent of the total commercial assemblies (~221,000) that are from boiling water reactors (57%; Carter and Vinson 2014). The average pressurized water reactor and boiling water reactor assemblies represent the averaged characteristics of commercial SNF over the entire inventory that was to be emplaced in a proposed repository at Yucca Mountain (DOE 2009a). The average pressurized water reactor assembly has 4.0% initial enrichment of U-235, an initial uranium loading of 475 kilograms, a burnup of 48 gigawatt-days per metric ton of uranium (GWd/MTU), and 25 years' cooling time. The average boiling water reactor assembly has 3.5% initial enrichment of U-235, an initial uranium loading of 200 kilograms, a burnup of 40 GWd/MTU, and 25 years' cooling time. As described in Table 2-1 (note 8), the average age of the total commercial inventory will be about 25 years from reactor discharge in 2030. The total nominal fuel inventory for DOE SNF in the table is for the year 2030 and is from DOE (2007c, Table 3). The radioactivity per mass (Ci per MTHM of SNF) is calculated using the mass of commercial SNF (63,000 MTHM) and DOE SNF (2,268 MTHM) to be emplaced in the repository (DOE 2009a, Table 1.5.1-1). The radionuclide inventory for a representative naval SNF canister five years after reactor shutdown (DOE 2009a, Table 1.5.1-32) is also provided. Dashes reflect the lack of data for different radionuclides in the different fuels in the source tables.

Table A2-1. Radioactivity of commercial and non-naval U.S. Department of Energy spent nuclear fuel inventory and of a representative canister of naval spent nuclear fuel (continued from page 205)

Radionuclide	Commercial Total Ci	DOE Total Ci	Commercial Ci/MTHM	DOE Ci/MTHM	Navy Ci/Canister
lead-212	-	2.23E+04	-	9.83E+00	-
manganese-54	-	6.03E+02	-	2.66E-01	-
molybdenum-93	-	1.42E+02	-	6.26E-02	-
neptunium-237	3.77E+04	2.11E+02	5.98E-01	9.30E-02	1.17E+00
neptunium-238	4.54E+03	-	7.21E-02	-	1.74E-03
neptunium-239	3.28E+06	-	5.21E+01	-	4.66E-01
nickel-59	3.11E+05	4.56E+04	4.94E+00	2.01E+01	1.34E+01
nickel-63	3.73E+07	4.58E+06	5.92E+02	2.02E+03	1.63E+03
niobium-93m	1.67E+06	1.46E+03	2.65E+01	6.44E-01	2.27E+03
niobium-94	1.08E+05	2.37E+02	1.71E+00	1.04E-01	2.06E+02
palladium-107	1.31E+04	4.50E+01	2.08E-01	1.98E-02	4.42E-02
plutonium-236	1.43E+02	9.00E-01	2.27E-03	3.97E-04	6.63E-01
plutonium-238	3.44E+08	8.49E+05	5.46E+03	3.74E+02	7.80E+03
plutonium-239	2.74E+07	4.75E+05	4.35E+02	2.09E+02	9.87E+00
plutonium-240	5.09E+07	3.64E+05	8.08E+02	1.60E+02	1.04E+01
plutonium-241	3.76E+09	9.38E+06	5.97E+04	4.14E+03	2.56E+03
plutonium-242	2.55E+05	5.06E+02	4.05E+00	2.23E-01	5.65E-02
polonium-212	-	1.43E+04	-	6.31E+00	-
polonium-216	-	2.23E+04	-	9.83E+00	-
praseodymium-144	1.76E+01	1.44E+06	2.79E-04	6.35E+02	1.47E+04
promethium-145	-	2.92E+02	-	1.29E-01	-
promethium-147	1.88E+07	3.57E+06	2.98E+02	1.57E+03	9.20E+04
protactinium-231	5.06E+00	7.05E+01	8.03E-05	3.11E-02	7.77E-04
protactinium-233	-	2.10E+02	-	9.26E-02	-
radium-224	-	2.23E+04	-	9.83E+00	-
radium-226	-	7.98E-02	-	3.52E-05	1.50E-05
radon-220	-	2.23E+04	-	9.83E+00	-
rhodium-106	1.02E+08	2.60E+05	1.28E+02	1.48E+02	3.20E+03
ruthenium-106	1.83E+03	2.60E+05	2.90E-02	1.15E+02	3.20E+03
samarium-151	3.17E+07	5.28E+05	5.03E+02	2.33E+02	9.78E+02
selenium-79	7.27E+03	2.91E+02	1.15E-01	1.28E-01	2.67E-01
strontium-90	4.33E+09	2.27E+07	6.87E+04	1.00E+04	3.05E+05
technetium-99	1.44E+06	8.85E+03	2.29E+01	3.90E+00	5.11E+01
tellurium-125m	3.67E+05	2.29E+04	5.83E+00	1.01E+01	1.01E+03
thallium-208	1.12E+03	8.03E+03	1.78E-02	3.54E+00	8.76E-02
thorium-228	-	2.23E+04	-	9.83E+00	-
thorium-230	2.44E+01	4.89E+00	3.87E-04	2.16E-03	3.22E-03
thorium-231	-	1.62E+02	-	7.14E-02	-
thorium-232	-	8.01E+00	-	3.53E-03	1.19E-05

continued on page 207

Table A2-1. Radioactivity of commercial and non-naval U.S. Department of Energy spent nuclear fuel inventory and of a representative canister of naval spent nuclear fuel (continued from page 206)

	Commercial	DOE	Commercial	DOE	Navy
Radionuclide	**Total Ci**	**Total Ci**	**Ci/MTHM**	**Ci/MTHM**	**Ci/Canister**
thorium-234	-	4.95E+02	-	2.18E-01	-
tin-119m	-	2.10E+02	-	9.26E-02	-
tin-121m	2.57E+05	5.28E+02	4.08E+00	2.33E-01	-
tin-126	6.06E+04	2.81E+02	9.62E-01	1.24E-01	9.55E-01
uranium-232	3.02E+03	2.17E+04	4.79E-02	9.57E+00	5.29E-01
uranium-233	6.21E+00	1.82E+04	9.86E-05	8.02E+00	6.52E-02
uranium-234	1.09E+05	7.29E+03	1.73E+00	3.21E+00	1.86E+01
uranium-235	1.18E+03	1.43E+02	1.87E-02	6.31E-02	2.65E-01
uranium-236	2.76E+04	2.83E+02	4.38E-01	1.25E-01	1.84E+00
uranium-237	8.97E+04	1.96E+00	1.42E+00	8.64E-04	6.13E-02
uranium-238	2.46E+04	7.77E+02	3.90E-01	3.43E-01	9.20E-04
yttrium-90	4.33E+09	2.27E+07	6.87E+04	1.00E+04	3.05E+05
zinc-65	-	7.48E+02	-	3.30E-01	-
zirconium-93	1.45E+05	1.68E+03	2.30E+00	7.41E-01	8.69E+00
Total	2.64E+10	1.28E+08	4.19E+05	5.65E+04	1.45E+06

As of 2014, 100 nuclear power plants were licensed to operate in the United States. Of these, 65 are pressurized water reactors and 35 are boiling water reactors (NRC 2014c). In 2013, the number of pieces of commercial SNF was only 25% larger than the total number of pieces of DOE SNF; however, both the mass and number of commercial SNF assemblies will approximately double by 2048, while the mass and number of DOE SNF pieces will increase by less than 2% and less than 0.2%, respectively.

The radioactivity of SNF is a function of several factors. One factor is the fuel's composition (*e.g.*, whether the fuel compound is uranium-based versus thorium-based or whether the fuel compound or fuel matrix contain elements other than uranium, plutonium, or thorium that become radioactive during reactor operations). Other factors that affect radioactivity include enrichment, burnup, and the time that has elapsed after the SNF was discharged from the reactor. Table A2-1, which compares the radioactivity of commercial SNF, DOE SNF, and naval SNF, illustrates this point. For example, some DOE fuel originally consisted of uranium alloyed with metals, including molybdenum (3.9 MTHM; see Group 4). In the course of reactor operations, this type of fuel generated molybdenum-93, which is not found in commercial SNF. About 25 MTHM of DOE fuel originally contained thorium and now contains thorium-228 and other radionuclides that are not found in significant quantities in commercial SNF. The effects of enrichment on the inventory of individual radionuclides are most easily seen by comparing long-lived radionuclides in naval SNF to the radioactivity of the same nuclides in commercial SNF. For example, naval SNF contains much more uranium-235 relative to uranium-238 and plutonium-239 when compared with commercial SNF. This is consistent with naval fuel's high enrichment in uranium-235. In 2030, on average, commercial SNF will be about seven times more radioactive per unit mass than DOE SNF.

A2.3 Storage Locations and Systems for Spent Nuclear Fuel

SNF can be stored wet in pools or dry in a variety of physical configurations and in different states of readiness for transport away from the storage site. Commercial SNF is stored wet in spent fuel pools at reactors and at the GE Morris pool storage facility in Illinois (Figure A2-7). Commercial SNF is also stored dry, at 62 independent spent fuel storage installations (as of 2011) that are associated with operating reactors or shut-down reactor sites. Figure A2-7 shows the location and amounts of SNF discharged from commercial nuclear reactors as of 2011, as well as the locations and amounts of stored DOE SNF.

Figure A2-8 shows the quantity (in MTHM) of commercial and DOE SNF in dry and pool storage as of December 31, 2013. About 30% of commercial SNF is stored dry, and that percentage will increase with time as the SNF pools at almost all commercial nuclear reactors are filled to their licensed capacity. This means that as reactors are refueled, older SNF assemblies must be removed from pool storage and put into dry storage to make room for newer SNF as it is discharged from reactors. As of June 2014, the commercial SNF inventory included 1,947 loaded dry storage casks; approximately 200 additional dry storage casks are loaded each year (Cummings 2014). This rate of increase in the commercial SNF inventory that is in dry storage will remain approximately constant into the future. In contrast to commercial SNF, about 98% of DOE SNF (by mass) is already in dry storage in numerous storage configurations.

The amount of DOE SNF stored in pools will decrease slightly with time as DOE and the Navy work to move SNF from wet storage to dry storage at INL to meet a 2023 milestone date stipulated in the 1995 Settlement Agreement between the state of Idaho, DOE, and the Navy (Idaho *et al.* 1995). Although the SNF storage pool (L Basin) at Savannah River Site is near its maximum storage capacity, it still receives SNF from domestic and foreign research reactors. Any SNF removed from that pool, rather than being stored dry, is being processed in the H Canyon facility to recover high-enriched uranium for down blending to low-enriched uranium for use in commercial reactors.

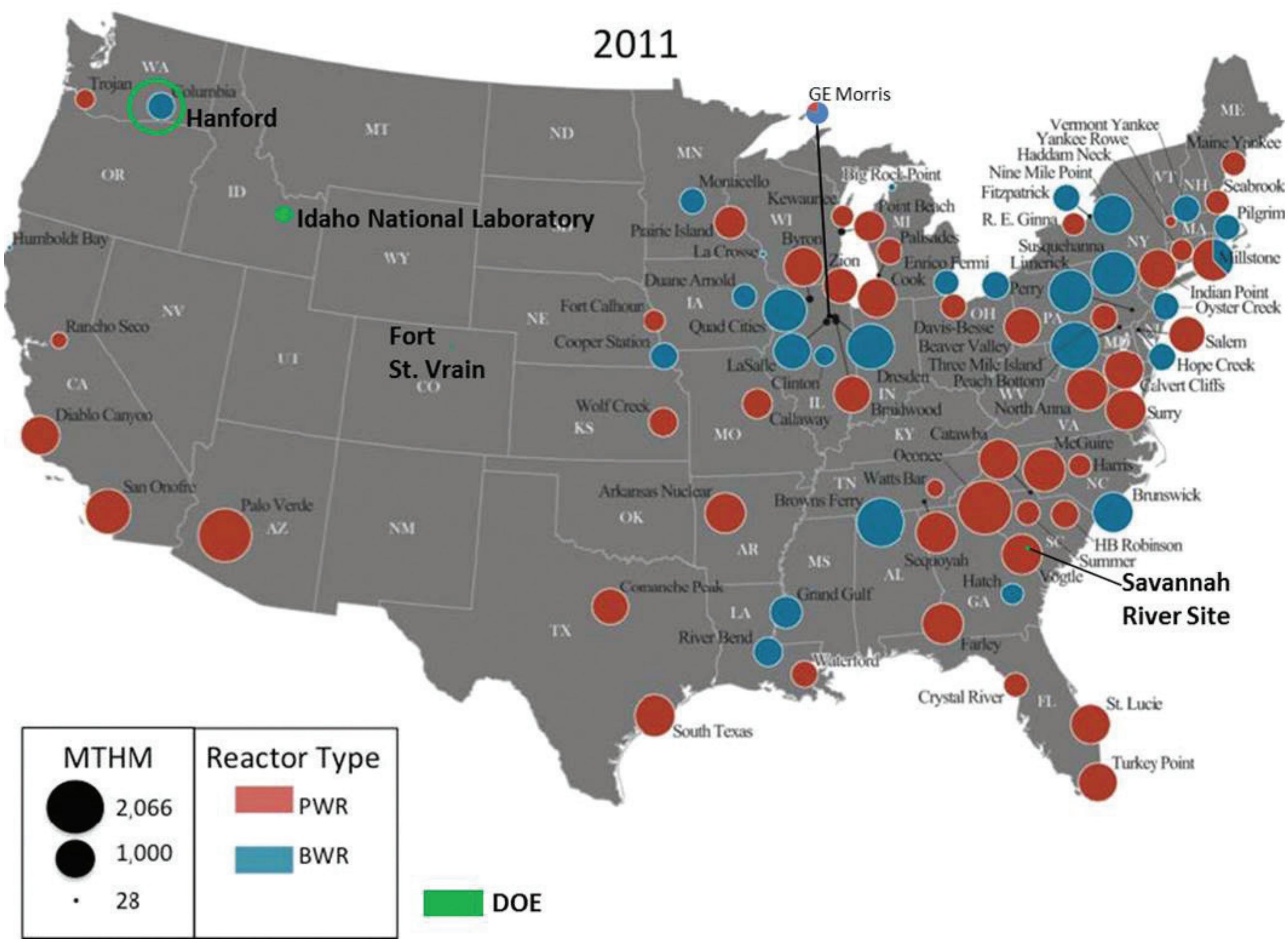


Figure A2-7. The location and quantity of discharged commercial spent nuclear fuel in the United States as of 2011. The source figure is revised here to depict the quantity and location of commercial SNF stored at the GE Morris pool storage facility and the quantity and location of DOE SNF at four sites. (Source: Sandia National Laboratories 2014, Figure 2-1).

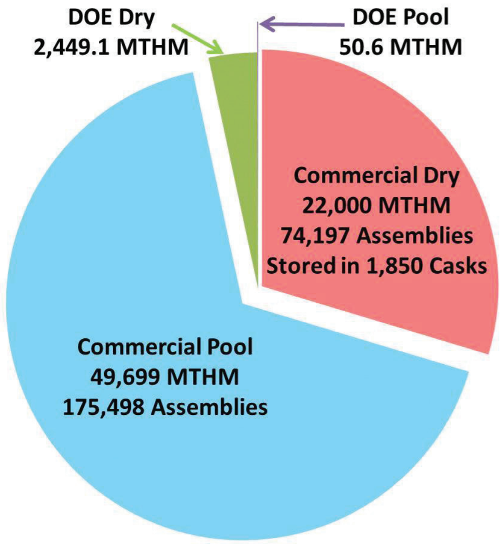


Figure A2-8. Quantities of commercial and U.S. Department of Energy spent nuclear fuel in dry and pool storage. The estimated inventory, in metric tons of heavy metal (MTHM), of commercial SNF shown in the figure is as of December 31, 2013 (Carter and Vinson 2014, Table 1-2).[252]

Just as SNF can exist in multiple physical configurations, dry storage systems for SNF come in multiple physical configurations and have different storage characteristics. There are three basic types of storage systems for commercial SNF; canister-based vertical systems, canister-based horizontal systems, and bare fuel (bolted) casks (Cummings 2014). All three types of systems store SNF outside and, in the vast majority of cases, aboveground. The capacity of individual storage canisters or casks varies from 7 to 37 pressurized water reactor assemblies and from 52 to 89 boiling water reactor assemblies (Greene *et al.* 2013). The commercial SNF in these canisters or casks is surrounded by an inert gas to inhibit degradation of the SNF and to allow effective heat transfer from the SNF to the cask. In contrast to commercial SNF, not all DOE SNF in dry storage is surrounded by inert gas; some stored DOE SNF is open to the ambient environment of the storage facility. In addition to the three types of storage systems used for commercial SNF, DOE SNF is also stored in vaults (both inside and outside buildings), in underground silos, inside a hot cell facility, and—in the case of naval SNF—in vertical canister-based systems inside buildings.

Different SNF dry storage systems provide different states of readiness for transport away from the storage site. Some systems are single-purpose, meaning they can be used for storage only, while other systems are dual-purpose (*i.e.*, suitable for storage and transportation), or multiple-purpose (*i.e.*, suitable for storage, transportation, and disposal). An example of a multi-purpose system is the naval canister system. Systems used to store and transport commercial SNF are regulated by the U.S. Nuclear Regulatory Commission (NRC), which can certify systems for storage only or for storage and transportation. As of June 2014, approximately 83% of the 1,947 loaded commercial SNF storage canisters and casks are transportable, meaning that they are NRC-certified for transportation (Cummings 2014). There are more than 20 NRC-certified dual-purpose storage systems (Greene *et al.* 2013). Additional dual-purpose systems are being designed, certified, and deployed; these new systems are increasing the capacity of canister-based systems (*e.g.*, capability for 37 pressurized water reactor or 89 boiling water reactor assemblies) and are evolving to address seismic, shielding, criticality, and thermal considerations (Cummings 2014).

In the case of DOE SNF, by contrast, none of the inventory is being stored in containers that are currently NRC-certified for transport. Naval SNF is stored in an NRC-approved (storage) multi-purpose canister system for off-site transportation. DOE SNF at the Hanford Site (approximately 2,100 MTHM) is stored in 412 multi-canister overpacks (MCOs) that were designed for storage, transportation, and disposal at the proposed Yucca Mountain repository. The MCOs are not NRC-certified for storage or transportation. DOE planned to transport a small number of intact commercial SNF assemblies from INL off site in NRC-certified bare fuel casks (Greene *et al.* 2013). DOE planned to package the remaining

[252] The amount of DOE SNF in pool storage consists of 30 MTHM at Savannah River Site and 20.6 MTHM at INL.

SNF inventory, whether currently in wet or dry storage, in more than 2,100 multi-purpose DOE standardized canisters. Similar to the situation for MCOs, DOE will need to obtain NRC approval for transporting its standardized canisters in existing NRC-certified transportation casks or DOE will have to develop a separate transportation cask that will need to be certified by NRC. Figure A2-9 depicts the relative sizes of the MCO, the DOE standardized canister, the naval canister, and a potential commercial SNF canister that could hold up to 21 pressurized water reactor assemblies or 44 boiling water reactor assemblies.

A2.4 Transportation and Disposal Systems for Spent Nuclear Fuel

Because it remains unclear how and where commercial and DOE SNF will be disposed of, one way to compare the characteristics of potential transportation and disposal systems for commercial and DOE SNF is to look at DOE's plans for the proposed Yucca Mountain geologic repository (Figure A2-9 and Figure A2-10). For commercial SNF, DOE (2009a) had proposed to use a multi-purpose canister known as the transportation, aging, and disposal canister. DOE planned to use this canister, which could hold up to 21 pressurized water reactor assemblies or 44 boiling water reactor assemblies, to dispose of all commercial SNF.

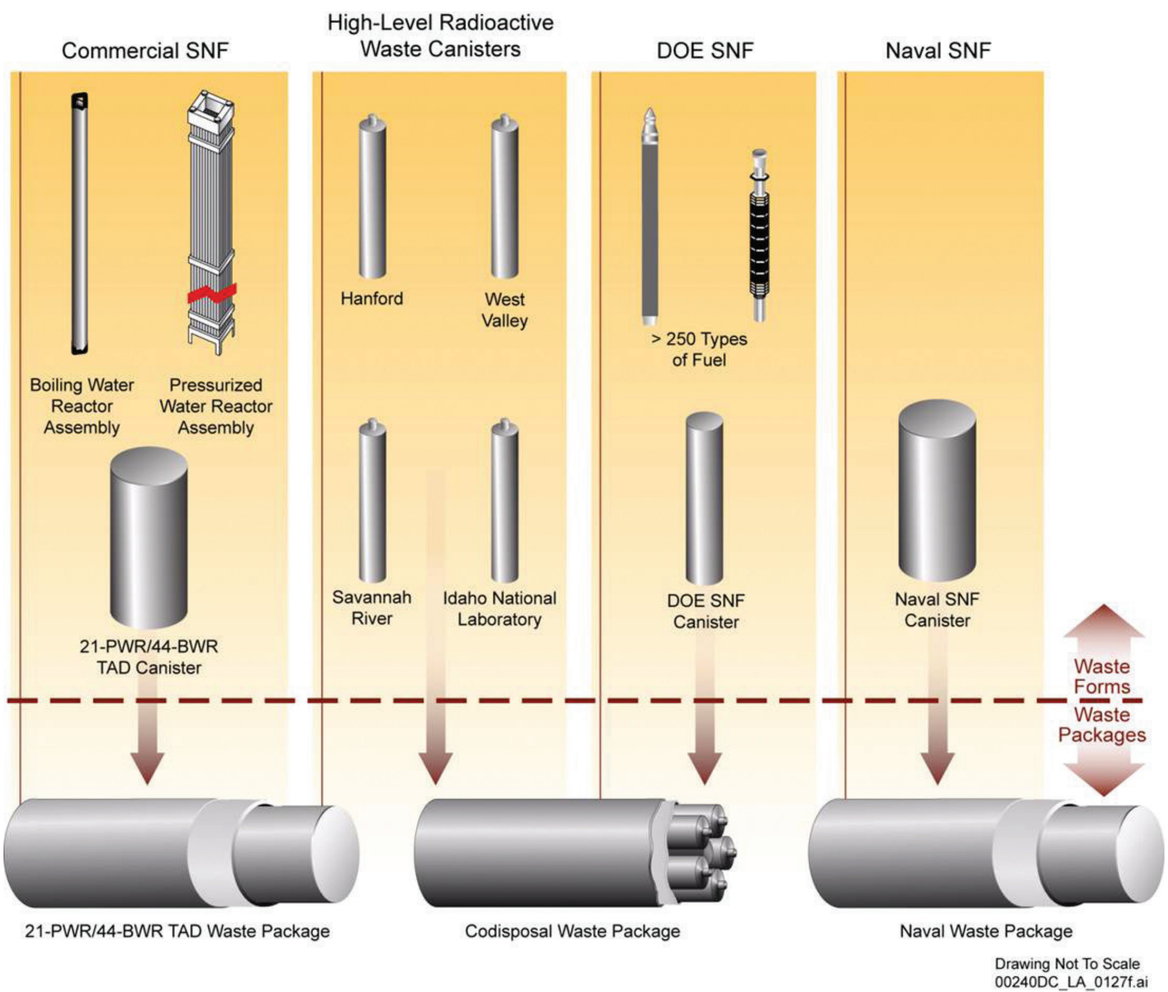


Figure A2-9. Waste form and waste package configurations.
The figure depicts the types of waste forms to be disposed of in the proposed Yucca Mountain repository and their representative waste package configurations. Assemblies of commercial spent nuclear fuel (SNF) would be packaged in a transportation, aging, and disposal (TAD) canister that could contain either 21 pressurized water reactor (PWR) or 44 boiling water reactor (BWR) assemblies. (Source: DOE 2009a, Figure 1.5.2-1).

DOE assumed that most, but not all, commercial SNF would be transported to the proposed Yucca Mountain repository in the transportation, aging, and disposal canister (DOE 2009a). According to DOE, the repository would have also accepted un-canistered SNF in bare fuel transportation casks and SNF shipped in NRC-certified dual-purpose canisters, as long as those NRC-certified dual-purpose canister systems were acceptable for use under the environmental conditions at the proposed Yucca Mountain repository (DOE 2009a). DOE would have repackaged any commercial SNF that was shipped in bare fuel transportation casks and dual-purpose canisters into the transportation, aging, and disposal canisters at the repository. All the commercial SNF in transportation, aging, and disposal canisters would have been placed in transportation, aging, and disposal waste packages for disposal (Table A2-2, note 3). No transportation, aging, and disposal canisters have been built or certified.

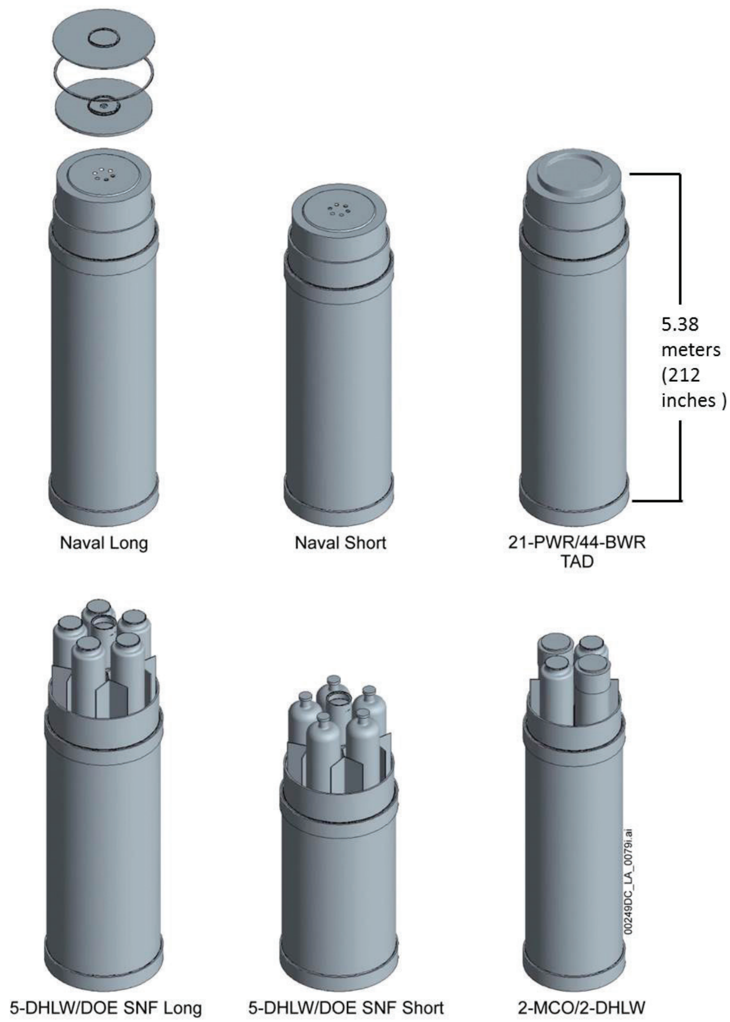


Figure A2-10. Waste package configurations. This depiction is close to scale and shows the waste-form configuration contained in each waste package design. Commercial spent nuclear fuel (SNF) would be disposed of in the transportation, aging, and disposal (TAD) waste package which contains a TAD canister that holds either 21 pressurized water reactor (PWR) or 44 boiling water reactor (BWR) assemblies. U.S. Department of Energy (DOE) waste configurations included both short and long canisters of DOE SNF, DOE SNF in multi-canister overpacks (MCOs), and short and long canisters of defense high-level radioactive waste (DHLW). (Source: DOE 2009a, Figure 1.5.2-2).

DOE and the Navy had planned to use a few types of standardized multi-purpose canisters and transportation casks. For example, DOE had planned to use a standardized canister of two different diameters and two different lengths to accommodate the wide variety of shapes and sizes of DOE SNF that remains to be packaged. Table A2-2 provides information on the size and weight of loaded disposal canisters and the current, largest-capacity, NRC-certified storage canister. Heavy, dual-purpose, commercial SNF canisters, as well as the naval canisters, present an engineering challenge in terms of being moved underground from the surface at the repository site (Bonano 2013).

Table A2-2. Dimensions and weight of loaded disposal canisters for the proposed Yucca Mountain repository

Type of canister (1 - see Notes below)	Outer diameter centimeters (inches) (2)	Height meters (inches) (2)	Maximum weight loaded metric ton (pounds) (3)
21-PWR/44-BWR TAD (4)	169 (66.5)	5.38 (212.0)	49.21 (108,500)
Naval long	168 (66)	5.35 (210.5)	44.45 (98,000)
Naval short (5)	168 (66)	4.71 (185.5)	44.45 (98,000)
MCO (5)	61 (24)	4.22 (166)	9.16 (20,200)
DOE standardized (5)	61 (24)	4.57 (180)	4.54 (10,000)
DOE standardized	61 (24)	3.05 (120)	4.08 (9,000)
DOE standardized (5)	45.7 (18)	4.57 (180)	2.72 (6,000)
DOE standardized	45.7 (18)	3.05 (120)	2.27 (5,000)
MPC-89 (6)	197 (75.5)	4.83 (190)	52.80 (116,400)

Notes
(1) Information from DOE (2009a).
(2) Dimensions for diameter and height are nominal. For example, DOE's plans constrain the height of the transportation, aging, and disposal (TAD) canister to not less than 4.72 meters (186.0 inches) and not greater than 5.38 meters (212.0 inches).
(3) The table shows the design limit for the maximum weight of a loaded canister in pounds. The maximum loaded weight for the TAD and naval long waste packages is 162,000 pounds. The maximum loaded weight for the naval short waste package is 157,000 pounds. The maximum loaded weights for the five short co-disposal, five long co-disposal, and 2-MCO/2DHLW waste packages [a package that contains 2 multi-canister overpacks (MCOs) and 2 canisters of defense high-level radioactive waste (DHLW)] are 90,000 pounds, 127,900 pounds, and 112,500 pounds, respectively.
(4) A TAD canister contains either 21 pressurized water reactor (PWR) or 44 boiling water reactor (BWR) assemblies.
(5) NRC identified that DOE could not accept these canister types at the Yucca Mountain repository without prior NRC review and approval (NRC 2015a, pp. 2-110 and 7-102) because DOE did not include the necessary design analyses that demonstrated the canisters could be safely received and handled. For example, DOE did include structural and thermal finite element analyses that evaluated worst-case impact loads and a hypothetical fire event. For these canisters, NRC requires DOE to provide information "that either (i) confirms that the current pre-closure safety analysis bounds the intended performance of these ... canisters at the geologic repository operations area or (ii) demonstrates, through the pre-closure safety analysis, that ... canisters can be safely received and handled at the repository during the pre-closure period."
(6) Although the MPC-89 was not among the canister types proposed for disposal at the proposed Yucca Mountain repository, this canister—which is certified for storage and is undergoing a transportation certification review by NRC—is designed to store 89 boiling water reactor assemblies and is currently the largest-capacity certified SNF storage canister. Its characteristics are described by Greene et al. (2013).

DOE's plans for the proposed Yucca Mountain repository called for packaging all DOE SNF in co-disposal waste packages with canisters of HLW from the Hanford Site, Savannah River Site, INL, and West Valley, New York (DOE 2009a; Figure A2-9 and Figure A2-10). Table A2-3 summarizes the planned inventory for the proposed Yucca Mountain repository in terms of the estimated number of canisters and mass of nuclear waste slated for disposal at this site.

Table A2-3. Summary of inventory for the proposed Yucca Mountain repository

Type of Waste	Estimated Number of Canisters	Metric Tons of Heavy Metal
Commercial SNF and HLW (West Valley, New York)	~7,500 transportation, aging, and disposal canisters 275 HLW canisters	63,000
DOE HLW	~9,300 canisters	4,667
DOE SNF	~2,500 to ~5,000 canisters	2,268
Naval SNF	~400 canisters	65

Information from DOE (2009a, Table 1.5.1-1).

A2.5 Key Observations

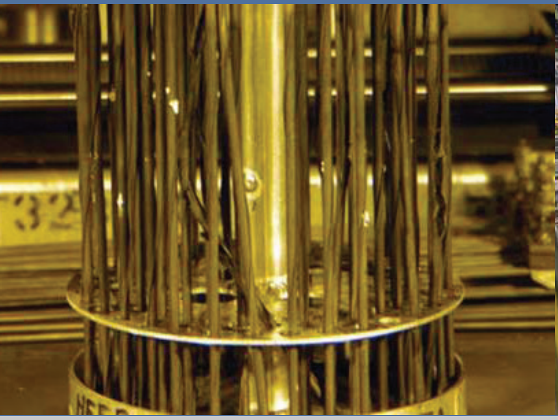
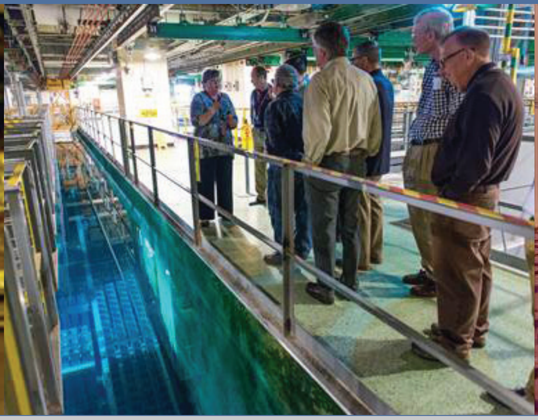
1. As of December 31, 2013, about 30% of the mass of commercial SNF is in dry storage in three basic types of storage systems that include 1,850 filled canisters or casks (this number increases by about 200 each year). Of the canisters or casks being used for the dry storage of commercial SNF, 83% are certified for off-site transport. By comparison, 98% of DOE SNF (by mass) is currently in dry storage in numerous types of storage systems, but none of the DOE SNF multi-purpose canister storage systems have been certified for off-site transport of SNF.

2. Commercial SNF handling units (*i.e.*, assemblies) come in a limited range of sizes and the cladding and fuel in these handling units are predominantly in good condition. By contrast, DOE SNF has much more diverse physical characteristics and the cladding and fuel are more damaged. For these reasons, drying and packaging DOE SNF for off-site transport will be more difficult than drying and packaging commercial SNF, and this diversity affects storage, transport, and disposal efforts.

3. The seven types of DOE and naval canisters that were planned or that are already in use (to date, approximately 500 canisters—including naval canisters and MCOs—have been filled) were designed for storage, transport, and disposal in a proposed geologic repository at Yucca Mountain; however, commercial SNF is currently stored in more than 20 types of dry storage canisters or casks that were not designed for disposal in any geologic repository. The large size and weight of commercial dual-purpose canisters, as well as naval canisters, could limit disposal options at potential repository sites due to current engineering limitations that could prevent physically emplacing these heavy packages underground in a geologic repository.

4. The radioactivity of DOE SNF will be less than 1% of the total radioactivity in a repository that contains all commercial SNF and HLW and DOE SNF and HLW. The radioactivity of non-commercial-origin DOE SNF could be about 20% of the total radioactivity to be disposed of in a defense HLW repository.

5. DOE needs to complete analyses to demonstrate that the naval short canister, MCO, and DOE long standardized canisters can be safely received and handled at a repository. DOE also needs to complete analyses to demonstrate that commercial dual-purpose canisters can be safely received, handled, and stored at a repository.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