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A Review of U.S. DOE Activities to Manage, Package, Transport and Dispose of DOE Spent Nuclear Fuel

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ABSTRACT

The U.S. Nuclear Waste Technical Review Board (NWTRB) reviewed the U.S. Department of Energy's (DOE) efforts to manage the inventory of spent nuclear fuel (SNF) that is under its control at Hanford Site, the Idaho National Laboratory (INL), the Savanah River Site (SRS), and the Fort St. Vrain independent spent fuel storage installation (ISFSI). 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. Based on the information and findings developed as part of its review, the NWTRB made recommendations to Congress and the Secretary of Energy related to aging management, packaging, and disposal of DOE SNF. Outstanding packaging issues primarily are related to the DOE standardized canister. DOE has yet to finish research and development (R&D) activities for the DOE standardized canister that will be needed to design and operate any packaging facility it develops. 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. The Board recommended 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. The Board recommended that DOE conduct R&D 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 Board recommended that DOE complete R&D and licensing-related activities for the DOE standardized canister prior to completing the packaging facility's preliminary design.

INTRODUCTION

While disposal of SNF and HLW 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 a viable disposal solution is found, it is necessary that DOE manage its SNF in a manner that does not impede its eventual transportation and disposal.

DOE's SNF inventory comprises a broad range of fuels, resulting primarily from defense-related activities (Figure 1). DOE is responsible for packaging, storing, transporting, and eventually disposing of the SNF that it manages. DOE identified the DOE standardized canister, a type of multi-purpose (storage, transportation and disposal) canister, as the packaging it would use for non-naval SNF that is not already stored in a multi-purpose canister or is planned to be processed into high-level radioactive waste forms. Properly managing SNF in the near term is particularly important because, in the absence of a permanent geologic disposal option, 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 NWTRB has undertaken a review of the technical and scientific validity of DOE's SNF management activities. This paper summarizes the NWTRB's evaluation, findings, and recommendations on DOE SNF management activities related to the DOE standardized canister, which were documented in a report to Congress and the Secretary of Energy [1].

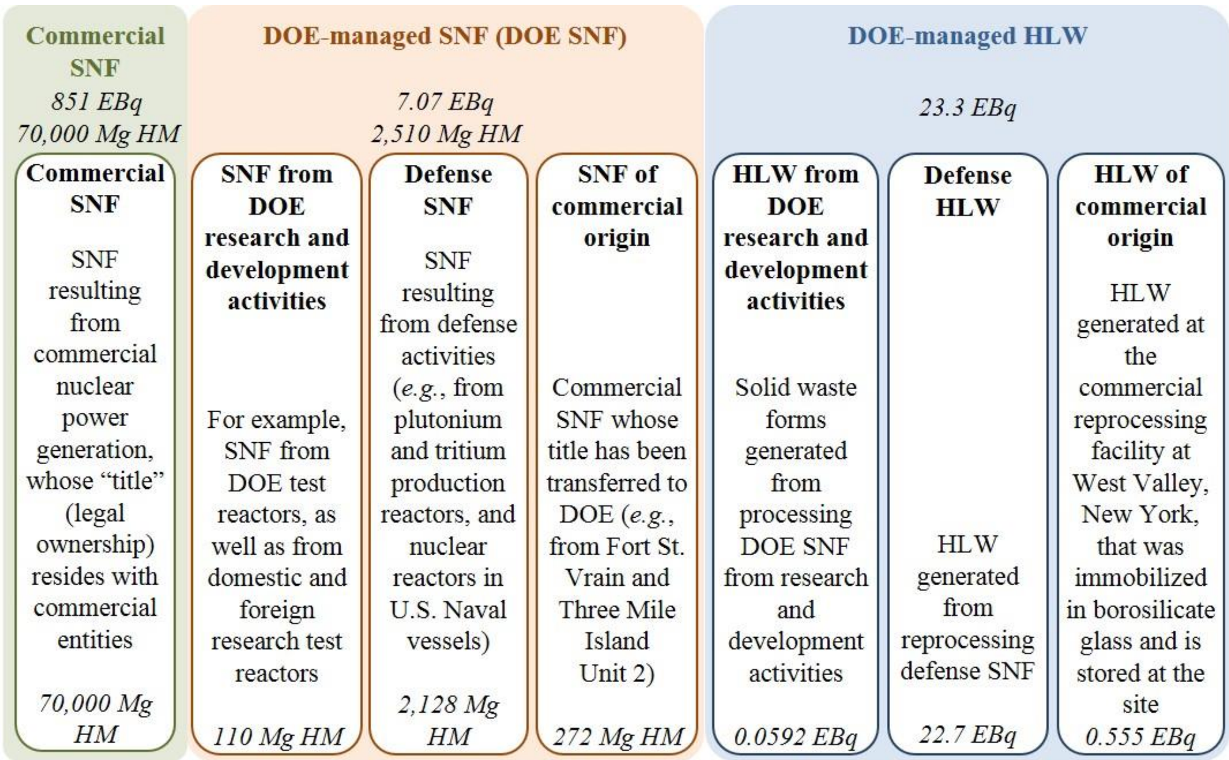

Figure 1. Wastes that require disposal in a geologic repository [1; see Figure A2-6 for data sources]

DISCUSSION

The NWTRB report [1] recorded the quantities and characteristics of DOE SNF by storage site and the evaluation of DOE's packaging and storage activities and plans related to DOE SNF. Figure 2 depicts the status of DOE management activities, as of August 2014, leading to disposal of DOE SNF. Figure 2 is a simplified depiction of DOE SNF management activities at the Hanford Site, the INL, the SRS, and the Fort St. Vrain ISFSI from on-site storage of DOE SNF through disposal of SNF in a geologic repository. In the figure, the mass of SNF in storage is depicted in italics. Undamaged SNF of commercial origin would be packaged and transported off site using bare fuel rail transport casks. Damaged fuel of commercial origin will be packaged into the DOE standardized canister (Figure 3). The NWTRB adopted 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 DOE standardized canister accommodate the wide dimensional variability of DOE SNF [2].

Quantities and Characteristics of DOE SNF

DOE currently manages about 2,500 Mg HM of SNF, most of which is stored at four locations (Figure 2 and Table 1): the Hanford Site in Washington State, INL in Idaho, SRS in South Carolina, and the Fort St. Vrain ISFSI in Colorado. At these sites, DOE stores about 50 Mg HM of SNF in storage pools—two located at INL and one at SRS (Figure 2). The remaining inventory of DOE SNF at the sites is stored dry in containers at 11 different dry storage facilities: two facilities at Hanford, eight facilities at INL, and one at Fort St. Vrain.

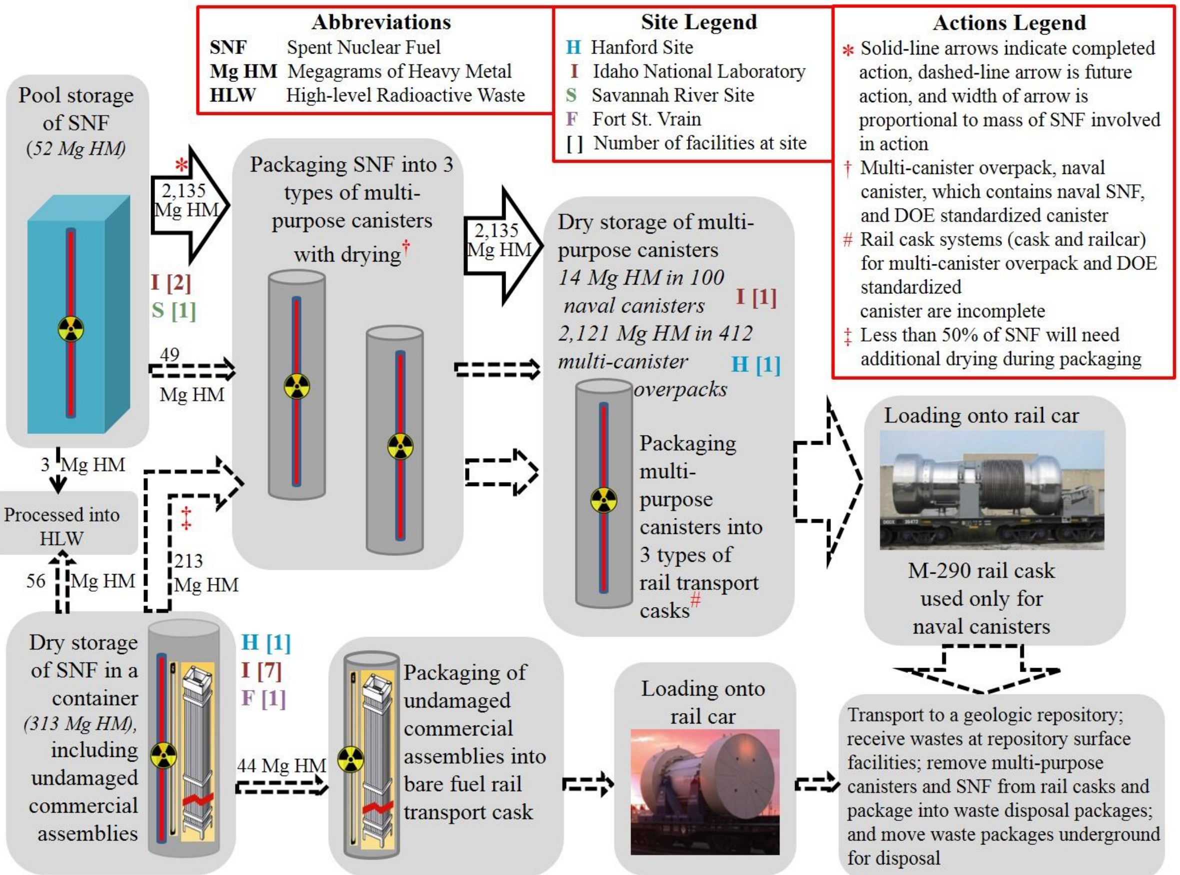

Figure 2. Status of activities that lead to disposal of DOE SNF

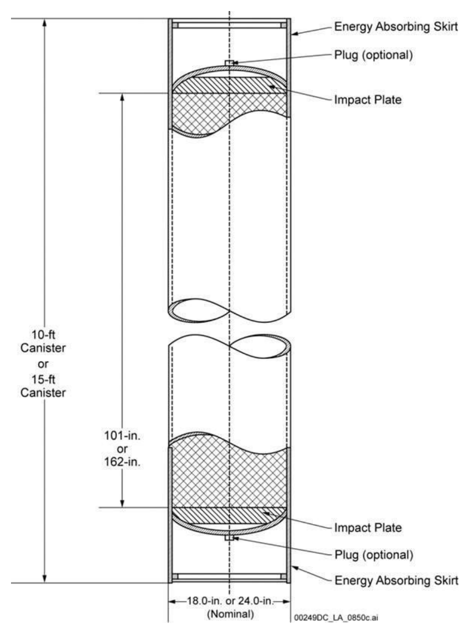

Figure 3. A cutaway perspective of a DOE standardized spent nuclear fuel canister [2; Figure 1.5.1-9]

As of December 2017, DOE had been using six storage facilities, including two pools, beyond their 40-year design lifetimes. The DOE SNF inventory consists of more than 250 types of SNF (Table 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.

Table 1. Mass and types of SNF stored at four locations

Storage Site	Mass of Stored Spent Nuclear Fuel (Megagrams of Heavy Metal)	Number of Types of Spent Nuclear Fuel
Hanford	2,130	20
INL	325	250
SRS	30	60
Fort St. Vrain	15	1
Total	2,500	>250

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. The majority of DOE SNF—about 85% of the mass, in terms of Mg HM—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 1).

Unlike commercial SNF, of which there are 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 different cladding compositions for DOE SNF is greater than for commercial SNF, including some compositions that can degrade during storage. Other characteristics of DOE SNF also vary. For example, DOE SNF has a wide-range of fissile material concentrations 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 less knowledge about the present physical state of the DOE SNF, including the extent of its degradation and the potential for further degradation.

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 increase with time because of deleterious aging effects on both the cladding and fuel. Requirements stipulated in legal agreements and regulations add to the challenges. For example, a 2035 deadline for DOE to remove SNF from the state of Idaho, affects SNF management at INL. Also, U.S. Nuclear Regulatory Commission (NRC) regulations related to storage, transport, and disposal to varying degrees limit DOE's use of multi-purpose canisters (i.e., canisters used for storage, transportation, and disposal). This creates a challenge because most DOE SNF, by mass, is either packaged in or planned for packaging in such canisters (Figure 2).

<u>Aging Management Issues</u>

As materials age, they can degrade. An aging management program manages degradation effects to ensure continued safe operations for extended periods. Different fuel materials—and the cladding that surrounds the fuel—have different rates of degradation in storage (Figure 4), 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 for disposal. Figure 4A [3] depicts pit-corrosion damage on fuel plate cladding over fuel material region in an aluminum-based Materials Testing Reactor type–assembly.

Different materials used in SNF storage systems (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.

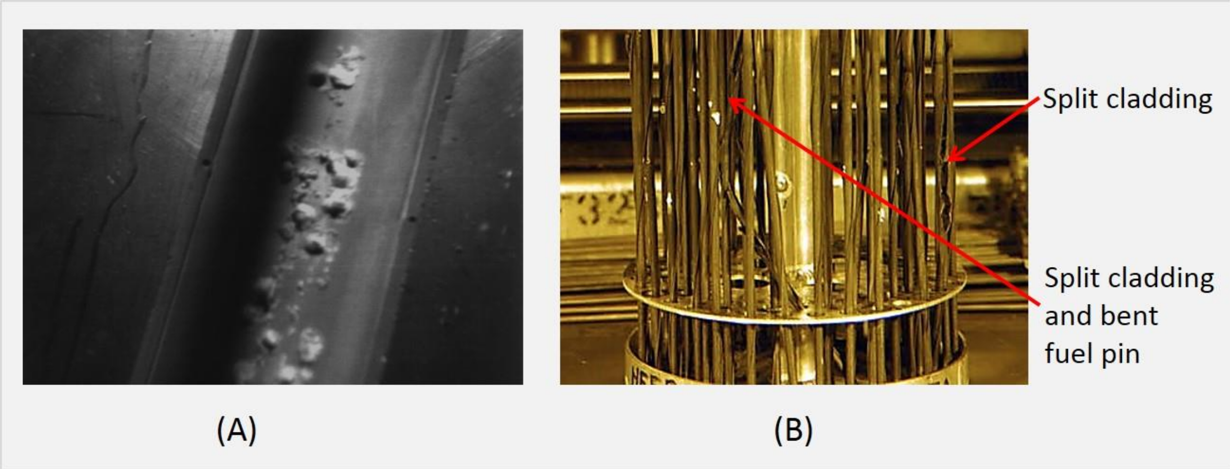

Figure 4. Examples of degradation that has occurred during extended storage of DOE SNF [3,4]

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 INL. Under both wet and dry storage conditions, the SNF degraded when moisture entered either the storage container or the cladding of the fuel (Figure 4B [4]). Moisture in dry storage containers penetrated small pinhole-sized holes in the 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. This reaction created hydrogen and sodium hydroxide, which split the cladding. Hydrogen was created due to the reaction of water with sodium and accumulated in the storage canisters. 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 (Figure 2).

Damaged metallic uranium SNF stored in pools at Hanford corroded, which made DOE’s retrieval and packaging process 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 multi-canister overpacks (MCOs; Figure 2) and drying it 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 monitored representative MCOs, which include a range of contents from 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. 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 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 to occur in canisters containing SNF with high fissile isotope concentrations. Finally, DOE also plans to add water-bearing pelletized supplemental neutron absorbers [3] to hundreds of DOE standardized canisters, but DOE has not decided the final composition of material that will surround the absorbers.

Defining and proving what is “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 of the canister for later 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.

NWTRB FINDINGS AND RECOMMENDATIONS

Based on the information developed in its multi-year review, the NWTRB developed four principal findings and recommendations on managing and disposing of DOE SNF [1] that are related to the DOE standardized canister.

Aging Management

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 the DOE SNF 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, 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.

The NWTRB recommended [1] 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 for 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.

Measuring and Monitoring Conditions During Storage

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 as was 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.

The NWTRB recommended [1] 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.

<u>Drying Procedures</u>

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 adequate. 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 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 storage, transport, and disposal operations. Predicting and monitoring gas composition and pressure of sealed multi-purpose canisters can confirm DOE's understanding of, and the basis for its conclusion that, proposed SNF drying procedures are adequate.

The NWTRB recommended [1] 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, transportation, and at a repository until it is closed. 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-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 are 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.

<u>Packaging Facilities</u>

Finding: technical and regulatory uncertainties complicate planning for packaging facilities. A key step in DOE's SNF management plans is developing packaging facilities at INL, Hanford, and SRS for DOE SNF that still needs to be placed into approximately 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 INL.

The NWTRB recommended [1] that to minimize complications in developing and operating a packaging facility for DOE SNF at INL, DOE should 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 to have 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 from 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.

CONCLUSIONS

The NWTRB has reviewed the technical and scientific validity of DOE activities related to the management and disposal of DOE SNF and documented its review in a report to the Secretary of Energy and Congress [1]. The diversity of DOE SNF, and the degraded condition of some of it, drive the technical challenges associated with DOE's SNF management activities. These challenges are increasing with time because of deleterious aging effects on both the cladding and fuel. 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. Based on its review, the NWTB made findings and recommendations on four main areas related to managing and disposing of DOE SNF that will be packaged into DOE standardized canisters: (i) aging management, (ii) measuring and monitoring conditions during storage, (iii) SNF drying procedures, and (iv) development of packaging facilities.

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