Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel

October 2014

[This page left blank.]

FOREWORD

In January 2012, the final report of the Blue Ribbon Commission on America's Nuclear Future urged the Administration to conduct a review of the current policy to dispose of defense and commercial high level radioactive waste and spent nuclear fuel in a single repository or repositories. Based on that recommendation, in January 2013, the Administration's *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* indicated that the current policy would be the subject of analysis moving forward.

The following report was prepared for the Secretary of Energy by a team of federal and contractor personnel led by the Department's Office of Nuclear Energy. The report assesses the technical options for the permanent disposal of high-level radioactive waste (HLW) and spent nuclear fuel (SNF) managed by the Department of Energy. Specifically, it considers whether DOE-managed HLW and SNF should be disposed of with commercial SNF and HLW in one geologic repository or whether there are advantages to developing separate geologic disposal pathways for some DOE-managed HLW and SNF. This assessment draws heavily on a recently completed DOE report that summarizes the inventory of both commercial and DOE-managed radioactive wastes requiring geologic disposal, organizes that inventory into broadly defined waste groups with similar disposal characteristics, and qualitatively evaluates disposal options for each group of waste types.

The analyses of alternatives and options related to the treatment and disposal of HLW and SNF presented in this report are based on technical and programmatic considerations and do not include an evaluation of relevant regulatory and legal considerations. This report has been prepared for informational and comparison purposes only.

[This page left blank.]

Executive Summary

Overview

This report provides an assessment of options for the permanent disposal of high-level radioactive waste (HLW) and spent nuclear fuel (SNF) managed by the U.S. Department of Energy (DOE). Specifically, the assessment considers whether DOE-managed HLW and SNF should be disposed of with commercial SNF and HLW in one geologic repository, or whether there are advantages to developing a separate repository for some DOE-managed HLW and SNF.[1] Results of the assessment indicate that multiple disposal options are technically feasible and have the potential to provide excellent long-term isolation of DOE-managed HLW and SNF, and that there are programmatic advantages to a phased strategy that allows for flexibility in disposal pathways for some DOE-managed HLW and SNF. This report, therefore, recommends that DOE pursue 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. 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. This report also recommends 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.

The analyses of alternatives and options related to the treatment and disposal of HLW and SNF presented in this report are based on technical and programmatic considerations and do not include an evaluation of relevant regulatory and legal considerations. This report has been prepared for informational and comparison purposes only and should not be construed as a determination of the legal permissibility of specific alternatives and options.

Background

The DOE has planned since the mid-1980s to dispose of all HLW and SNF, regardless of origin, in one or more common mined geologic repositories. Multiple factors now indicate that consideration of options to allow flexibility in disposal pathways for some DOE-managed HLW and SNF is warranted, including the following:

- The implementation of a stepwise approach to repository siting and development, as described in the Administration's 2013 *Strategy for the Management and Disposal of Used Nuclear Fuel and High- Level Radioactive Waste*, provides an opportunity to evaluate alternative disposal options for the DOE-managed wastes. Consistent with the goals of the Strategy, a phased, adaptive, and consent-based approach will implement a flexible waste management system incrementally to

[1] A repository used exclusively for the disposal of DOE-managed HLW and SNF not of commercial origin could be sited and developed outside the framework of the Nuclear Waste Policy Act of 1982 (NWPA). Any such repository would be subject to licensing by the U.S. Nuclear Regulatory Commission and would have to comply with other NWPA requirements related to state and local participation in the siting process; those requirements are compatible with a consent-based process. The provisions of the NWPA would apply to any repository used for the disposal of HLW and SNF of commercial origin even though managed by DOE. Alternative disposal options for DOE-managed HLW and SNF of commercial origin are not analyzed in this report.

ensure safe and secure operations, gain trust among stakeholders, and adapt operations based on lessons learned. Experience in the U.S. and other nations indicates that a consent-based, negotiated siting process may have greater prospects for success than prior top-down approaches to site designation.

- An extensive body of knowledge has been developed in the U.S. and other countries relative to all aspects of geologic disposal, indicating that there are multiple viable options for geologic disposal.

- There are new perspectives on the DOE-managed wastes requiring disposal. Specifically, the inventory of DOE-managed HLW and SNF is now essentially fixed and known. Current plans for waste forms date from the early 1980s, when much less was known about the capabilities of repositories to isolate radioactive material. Based on today's understanding, selection of disposal options with suitable characteristics might allow DOE to simplify waste treatments, potentially accelerating cleanup activities and avoiding or reducing costs associated with projected treatments for some parts of the waste inventory. In addition, there is a growing disparity in terms of heat output between the DOE-managed HLW and some thermally cooler DOE-managed SNF and commercial SNF, which is a factor in repository siting, design, and performance analysis. This disparity could favor separate disposal of some DOE-managed HLW and thermally cooler SNF.

With these developments in mind, this report considers a broad range of potential options for the disposal of DOE-managed HLW and SNF not of commercial origin in light of today's understanding of waste management challenges and opportunities.

Inventory Considered

DOE-managed HLW and SNF consists of two principal waste streams: (1) HLW, mostly resulting from atomic energy defense activities but also including a small amount of HLW of commercial origin; and (2) SNF, primarily from atomic energy defense activities (weapons plutonium production reactors and naval propulsion reactors), but also including a smaller amount of SNF from DOE research and development activities and some DOE-managed SNF from commercial sources. A significant portion of the DOE-managed HLW has not yet been immobilized and might be suitable for different waste forms and disposal approaches than assumed in the mid-1980s. In that regard, this assessment draws heavily on a review of options for disposal of HLW and SNF recently completed by the DOE[2] that summarizes the inventory of both commercial and DOE-managed radioactive wastes requiring geologic disposal, groups that inventory into broadly defined waste groups with similar disposal characteristics, and qualitatively evaluates disposal options for each group of waste types.

Estimates of projected quantities and volumes of DOE-managed HLW and SNF used for cost analyses in this report are based on current planning assumptions about predisposal treatment. These estimates are shown in Table ES-1.

---

[2] *Evaluation of Options for Permanent Geologic Disposal of Used Nuclear Fuel and High-Level Radioactive Waste Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy*, FCRD-UFD-2013-000371; SAND2014-0187P; SAND2014-0189P, Revision 1.

Table ES-1. Sources and Projected Quantities and Volumes of DOE-Managed HLW and SNF

Storage Site	HLW Canisters		SNF Canisters	
	Number of Canisters	**Volume (m^3)**	**Number of Canisters**	**Volume (m^3)**
Savannah River, SC	7,824	5,230	3,542 DOE SNF canisters projected at all DOE sites combined, not including naval SNF. Approximately 2,450 of these canisters will contain SNF of non-commercial origin.[a]	2,685
Idaho National Laboratory, ID	4,391	3,221		
Hanford Site, WA	11,079	11,551		
West Valley, NY [a]	275	212		
Fort St. Vrain, CO [a]	0	0		
Naval Reactors Facility, ID	0	0	400	3,930
TOTALS	23,569	20,214	3,942	6,615

Note: Projections assume completion of currently planned treatment of all HLW at DOE-managed sites and packaging of DOE-managed HLW and SNF as described in Section 2.2.3. DOE-managed SNF (including naval SNF) is projected to 2035. Values are point estimates drawn from ranges reflecting uncertainty regarding final treatment and packaging decisions. Waste volumes do not include packaging.

[a] Commercial waste (e.g., HLW at West Valley and SNF at Fort St. Vrain) is not eligible for a repository exclusively for DOE-managed HLW and SNF from defense or DOE research and development activities.

Options Analyzed

This report considers three primary disposal options:

1. Disposal of all HLW and SNF, regardless of origin, in a common repository. This option is essentially unchanged from the approach taken by the DOE since the mid-1980s; it calls for disposing of all DOE-managed HLW and SNF together with commercial SNF in one or more repositories. If more than one repository is ultimately required to accommodate the full inventory of commercial SNF, as envisioned in the Nuclear Waste Policy Act of 1982 (NWPA), this option carries an implicit assumption that at least one repository would include a broad representation of all the waste types, both DOE-managed and commercial.

2. Disposal of some DOE-managed HLW and SNF in a separate mined repository. Flexible disposal options that allow for disposing of some DOE-managed HLW and SNF in a separate repository could lead to benefits in repository cost or performance based on different characteristics of the HLW and SNF such as thermal output, chemical characteristics, and fissile mass loading. For example, there could be advantages to separating thermally cooler DOE-managed SNF from thermally hotter DOE-managed SNF (e.g., hotter naval SNF) and disposing of the thermally cooler DOE-managed SNF with DOE-managed HLW.

3. Disposal of smaller waste forms in deep boreholes. Some DOE-managed waste forms are small enough to be candidates for disposal in deep boreholes drilled using currently available commercial drilling technology, as an alternative to emplacement in mined repositories. Preliminary evaluations of deep borehole disposal indicate a high potential for robust isolation of the waste, and the concept could offer a pathway for earlier disposal of some wastes than might be possible in a mined repository.

Stepwise Development of Repositories for HLW and SNF

Proceeding with a strategy to dispose of some portion of the DOE-managed HLW and SNF separately from commercial waste could allow nearer-term progress on geologic disposal. Focusing first on waste forms that have the potential to simplify both the design of the repository and the demonstration of compliance with long-term performance objectives (i.e., defense HLW and cooler DOE-managed SNF) would be consistent with the phased, adaptive, and consent-based approach recommended by the Blue Ribbon Commission and endorsed in the Administration's Strategy. The initial steps to implement this approach could include two parallel activities:

1. A repository development strategy that starts with a portion of the total inventory, specifically the defense HLW and cooler DOE-managed SNF, potentially including some naval SNF. As discussed in this report, focusing first on disposing of these wastes may present fewer challenges, requires little further technology development to support repository design and licensing, and may provide a greater degree of public acceptability.

2. A focused research, development, and demonstration program addressing technologies relevant to deep borehole disposal of small waste forms and the disposal of large waste packages with high thermal loads in mined repositories.

This assessment identifies potential benefits associated with these initial steps, including recognition that development of a separate repository for some DOE-managed HLW and SNF could:

- Provide a pathway for timely progress on the DOE cleanup mission within existing legislative authority, focusing on those portions of the DOE-managed HLW and SNF that are ready for disposal today. A significant amount of the HLW already exists in its final form at the Savannah River Site (3,339 canisters out of a projected total of 7,824 to be produced at that site), and existing and projected HLW canisters are of a size that is transportable by truck to allow disposal to begin as soon as possible.

- Support national security objectives. Delays in removing naval SNF from the State of Idaho could potentially impact naval operations beginning in 2035 because of a binding settlement agreement entered into by the DOE and the Navy with the State of Idaho to remove SNF from the state by that time. Near-term progress on disposing of a portion of the DOE-managed HLW and SNF could help expedite a process for ultimately removing all naval SNF from Idaho. Near-term progress could also increase support for the continued receipt and storage of highly enriched SNF from foreign research and test reactors.

- Potentially create savings to taxpayers from avoided costs for safely storing inventories of immobilized tank waste if a separate repository for DOE-managed HLW and SNF is available earlier. The resulting savings could be redirected to focus work scope and resources on other high-priority cleanup activities at the three defense HLW sites: the Savannah River Site in South Carolina, the Hanford Site in Washington, and the Idaho National Laboratory. In addition, the earlier availability of a repository for some DOE-managed HLW and SNF could help keep tank waste disposition costs and schedules within the baseline estimates by reducing uncertainty in final waste form treatment approaches, reducing the extent of maintenance and repairs to infrastructure, and accelerating the work.

- Simplify design and licensing for the repository, primarily because of the lower thermal output and lower overall radionuclide inventory of the DOE-managed HLW and SNF under consideration.

- Support the cleanup mission at the DOE sites, promote improved cooperation between DOE and state regulators, help enhance public acceptability of DOE's mission with the local communities around the DOE complex, allow other priority cleanup activities to receive additional funding, and increase the likelihood of DOE meeting consent and compliance agreements.

- Provide an opportunity to develop and test a consent-based repository siting process in consultation with stakeholders.

Conclusions

Two considerations lead to a recommendation that DOE pursue separate disposal options for some DOE-managed HLW and SNF. First, there are multiple viable options that could use technologies available today to dispose of the heterogeneous DOE-managed HLW and SNF. Second, there are potentially significant benefits from beginning a stepwise approach to disposing of the nation's HLW and SNF; such an approach could focus first on DOE-managed HLW and cooler DOE-managed SNF. Disposal of this HLW and SNF poses the fewest challenges, potentially allowing for a simpler repository design and licensing process, while helping meet DOE's environmental management goals and building confidence in waste management practices.

Specifically, this report recommends that the DOE begin implementation of a phased, adaptive, and consent-based strategy with development of a separate mined repository for some DOE-managed HLW and cooler DOE-managed SNF, potentially including some portion of the inventory of naval SNF. This report notes that, in addition to early development of a separate repository for cooler DOE-managed HLW and SNF, effective implementation of a strategy for management and disposal of all HLW and SNF would also include a focused research, development, and demonstration program addressing technologies relevant to deep borehole disposal of smaller DOE-managed waste forms and the disposal of large DOE-managed waste packages with high thermal loads in mined repositories.

Beginning with a separate repository for some DOE-managed wastes would be consistent with a phased, adaptive approach that has been endorsed by the National Academies and the Blue Ribbon Commission on America's Nuclear Future and is incorporated in the Administration's *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste*. Focusing initially on DOE-managed HLW and the cooler DOE-managed SNF not of commercial origin could build greater confidence that HLW and SNF can be safely disposed of, and it would provide technical and institutional experience that could facilitate development of disposal capacity for the remainder of the inventory of HLW and SNF, including commercial SNF.

[This page left blank.]

CONTENTS

Figures

Tables

ACRONYMS

DOE	U.S. Department of Energy
HLW	high-level radioactive waste
INL	Idaho National Laboratory
MTHM	metric tons of heavy metal
NWPA	Nuclear Waste Policy Act of 1982
R&D	research and development
SNF	spent nuclear fuel
SRS	Savannah River Site
WIPP	Waste Isolation Pilot Plant

[This page left blank.]

1 INTRODUCTION

Overview

This report provides an assessment of options for the permanent disposal of high-level radioactive waste (HLW) and spent nuclear fuel (SNF) managed by the U.S. Department of Energy (DOE). Specifically, the assessment considers whether DOE-managed HLW and SNF should be disposed of with commercial SNF and HLW in one geologic repository, or whether there are advantages to developing a separate repository for some DOE-managed HLW and SNF.[1] Results of the assessment indicate that multiple disposal options are technically feasible and have the potential to provide excellent long-term isolation of DOE-managed HLW and SNF, and that there are programmatic advantages to a phased strategy that allows for flexibility in disposal pathways for some DOE-managed HLW and SNF. This approach is consistent with the phased, adaptive strategy recommended by the Blue Ribbon Commission on America's Nuclear Future (BRC 2012) and incorporated in the Administration's *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* (DOE 2013a). This report, therefore, recommends that DOE pursue 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. 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. This report also recommends 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.

The analyses of alternatives and options related to the treatment and disposal of HLW and SNF presented in this report are based on technical and programmatic considerations and do not include an evaluation of relevant regulatory and legal considerations. This report has been prepared for informational and comparison purposes only and should not be construed as a determination of the legal permissibility of specific alternatives and options.

Background

The DOE has planned since the mid-1980s to dispose of all HLW and SNF, regardless of origin, in one or more common mined geologic repositories. Multiple factors now indicate that consideration of options to allow flexibility in disposal pathways for some DOE-managed HLW and SNF is warranted. Those factors include:

- The implementation of a stepwise approach to repository siting and development, as described in the Administration's Strategy (DOE 2013a), provides an opportunity to evaluate alternative disposal options for the DOE-managed wastes.

[1] A repository used exclusively for the disposal of DOE-managed HLW and SNF not of commercial origin could be sited and developed outside the framework of the Nuclear Waste Policy Act of 1982 (NWPA). Any such repository would be subject to licensing by the U.S. Nuclear Regulatory Commission and would have to comply with other NWPA requirements related to state and local participation in the siting process; those requirements are compatible with a consent-based process. The provisions of the NWPA would apply to any repository used for the disposal of HLW and SNF of commercial origin even though managed by DOE. Alternative disposal options for DOE-managed HLW and SNF of commercial origin are not analyzed in this report.

- An extensive body of knowledge has been developed in the U.S. and other countries relative to all aspects of geologic disposal, indicating that there are multiple viable options for geologic disposal.

- There are new perspectives on the DOE-managed wastes requiring disposal. Specifically, the inventory of DOE-managed HLW and SNF is now essentially fixed and known. Current plans for waste forms date from the early 1980s, when much less was known about the capabilities of repositories to isolate radioactive material. Based on today's understanding, selection of disposal options with suitable characteristics might allow DOE to simplify waste treatments, potentially accelerating cleanup activities and avoiding or reducing costs associated with projected treatments for some parts of the waste inventory. In addition, there is a growing disparity between the DOE-managed HLW and some thermally cooler DOE-managed SNF and commercial SNF in terms of heat output, which is a factor in repository siting, design, and performance analysis. This disparity could favor separate disposal of some DOE-managed HLW and thermally cooler SNF.

With these developments in mind, this report considers a broad range of potential options for the disposal of DOE-managed HLW and SNF not of commercial origin in light of today's understanding of waste management challenges and opportunities.

Elements of a Stepwise Development Approach

The Administration's Strategy (DOE 2013a) proposes a phased, adaptive approach to siting and developing waste management facilities. The objective of this approach is to implement a flexible waste management system incrementally to ensure safe and secure operations, gain trust among stakeholders, and adapt operations based on lessons learned. Experience in the U.S. and other nations indicates that a consent-based, negotiated siting process may have greater prospects for success than prior top-down approaches to site designation.

This approach is consistent with the recommendations of the Blue Ribbon Commission on America's Nuclear Future (BRC 2012) and draws on the concept of "adaptive staging" recommended in a 2003 report from the National Academies as "a promising approach to successful repository development…" (National Research Council 2003, p. 3). The 2003 report described adaptive staging as "a cautious, deliberate decision and management process that emphasizes continuous learning, both technical and societal, includes scientific and managerial re-evaluations and responses to new knowledge, and is also reversible by design," and recommended that "adaptive staging should be the approach used in geologic repository development." In contrast to previous plans to implement transportation, storage, and disposal for all components of the entire waste stream concurrently, a phased, adaptive approach would "focus more strongly on achieving the degree of technical and societal consensus needed to begin waste emplacement, rather than on the emplacement of all waste" (National Research Council 2003, p. 7). The Nuclear Energy Agency of the Organisation for Economic Co-operation and Development reported in 2004 that staged development (adaptive staging) is attracting increasing attention internationally as a means to increase the societal acceptability of waste management activities (NEA 2004).

A phased, adaptive approach to waste management and disposal that reflects these features could begin with two parallel activities:

1. A repository development strategy that starts with a portion of the total inventory, specifically the defense HLW and cooler DOE-managed SNF, potentially including some naval SNF. As discussed in this report, focusing first on disposing of these wastes may present fewer challenges, requires little further technology development to support repository design and licensing, and may provide a greater degree of public acceptability.

2. A focused research, development, and demonstration program addressing technologies relevant to deep borehole disposal of small waste forms and the disposal of large waste packages with high thermal loads in mined repositories.

Scope and Organization of the Report

Consistent with the range of DOE-managed waste types, this assessment considers three primary options: (1) disposal of all HLW and SNF, regardless of origin, in a common repository; (2) disposal of some DOE-managed HLW and SNF in a separate mined repository; and (3) disposal of smaller waste forms in deep boreholes.

Section 2 of this report summarizes the characteristics of the DOE-managed HLW and SNF that are relevant to the assessment of disposal options.

Section 3 describes the disposal options considered in this assessment.

Section 4 summarizes potential benefits of proceeding with initial development of a separate repository for some DOE-managed HLW and SNF.

Section 5 describes the DOE's plans for a research, development, and demonstration program to address disposal of the remaining DOE-managed HLW and SNF.

Section 6 provides the overall conclusions of the report.

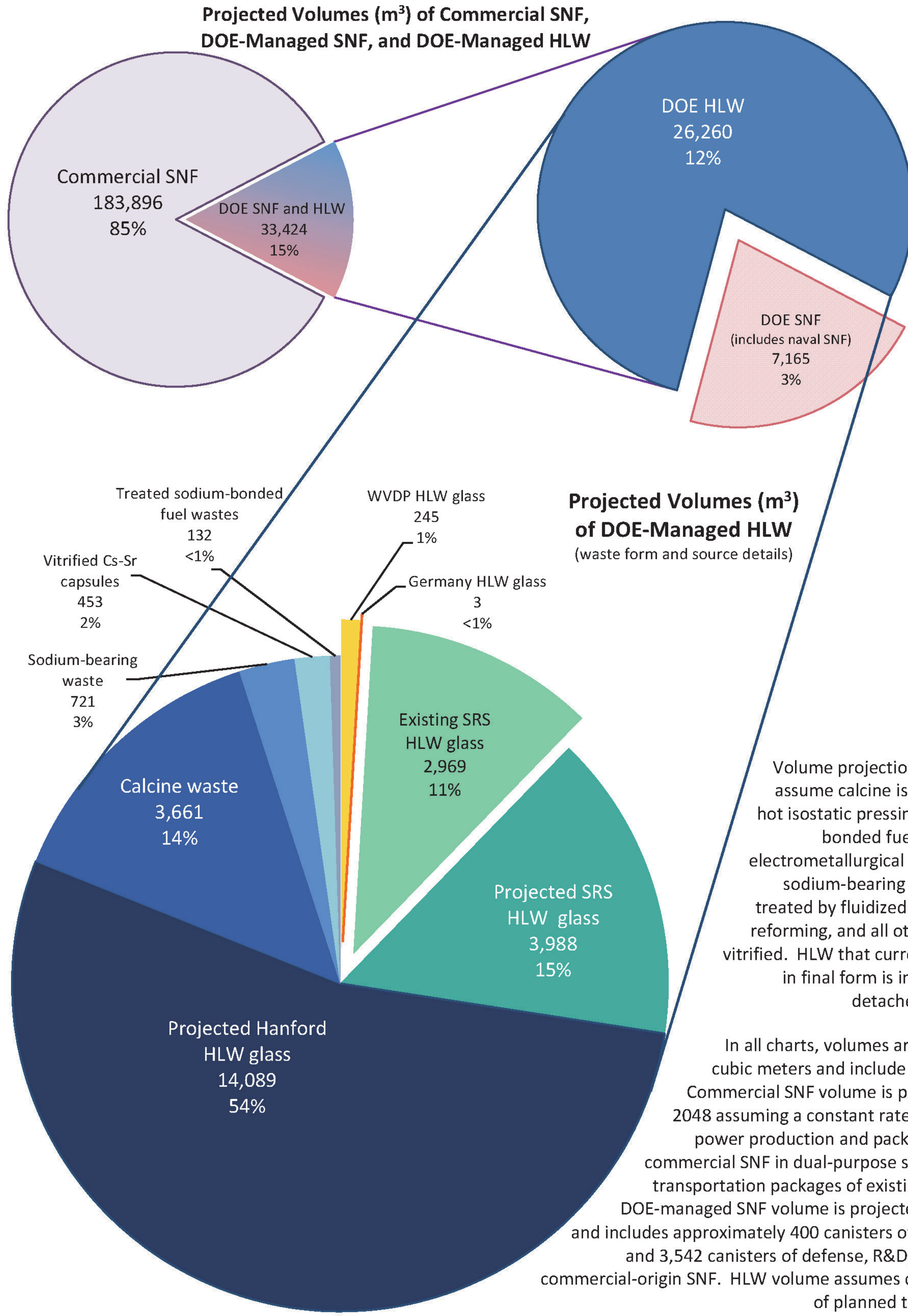
2 CHARACTERISTICS OF THE DOE-MANAGED HLW AND SNF

2.1 Overview of the DOE-Managed HLW and SNF

As described in more detail in supporting documents (SNL 2014; Wagner et al. 2012), DOE-managed HLW and SNF consists of two principal waste streams: (1) HLW, mostly resulting from atomic energy defense activities but also including a small amount of HLW of commercial origin; and (2) SNF, primarily from atomic energy defense activities (weapons plutonium production reactors and naval propulsion reactors), but also including a smaller amount of SNF from DOE research and development activities and some DOE-managed SNF from commercial sources. As shown in Figure 1, the DOE-managed HLW and SNF represents approximately 15% of the total volume (after treatment and packaging) of HLW and SNF projected to be ready for deep geologic disposal when existing commercial nuclear power plants are decommissioned and treatment of DOE's wastes is complete. After currently projected treatments, defense HLW will represent approximately 80% of the total volume of DOE-managed HLW and SNF. Unlike the commercial SNF, which will continue to increase in volume throughout the operational life of the existing nuclear power plants, the inventory of DOE-managed HLW and SNF is essentially fixed and known. With the exception of relatively small volumes of SNF from naval and research reactors that will continue to operate, all DOE-managed HLW and SNF is derived from past activities.

HLW, as defined in the Nuclear Waste Policy Act of 1982 (NWPA), Section 2(12), is the highly radioactive material resulting from the reprocessing of SNF, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations, and other highly radioactive material that the U.S. Nuclear Regulatory Commission, consistent with existing law, determines by rule to require permanent isolation. Defense HLW is that which is owned and managed by the DOE, produced as a result of DOE's atomic energy defense activities, and is stored at three DOE sites: the Savannah River Site (SRS), the Idaho National Laboratory (INL), and the Hanford Site. Commercial HLW resulting from a demonstration of commercial reprocessing technology was generated at the West Valley Demonstration Project and is owned by New York State and managed by the DOE.

As shown in Figure 1, most of the HLW is from defense programs at the Hanford Site and SRS, and has either already been vitrified or is planned to be vitrified, as was expected in the 1980s when the plan was developed to dispose of defense and commercial waste together in a common repository (DOE 1983). DOE also manages defense HLW in granular calcine form at INL, and a small quantity of commercial HLW at the West Valley Demonstration Project, as noted above. Other smaller-volume defense wastes currently managed by the DOE at the Hanford Site that may be suitable for disposal as HLW include 34 canisters of glass containing cesium and strontium prepared in 1986 and 1987 to support thermal testing proposed at that time by the Federal Republic of Germany, and 1,936 capsules containing cesium and strontium separated from liquid defense HLW. The cesium and strontium capsules are noteworthy because of their small size (individual cylinders are less than 9 cm (3.5 inches) in diameter and less than 56 cm (22 inches) in length) and highly concentrated radioactivity. In aggregate, the 1,936 cesium and strontium capsules contain approximately one third of the total radioactivity (in curies) at the Hanford Site, but in their current form they occupy a total volume of less than 4 m^3 (140 ft^3), which is less than 0.03% of the total projected volume of approximately 14,000 m^3 (500,000 ft^3) of HLW at Hanford after vitrification is complete (SNL 2014).



Volume projections for HLW assume calcine is treated by hot isostatic pressing, sodium-bonded fuels undergo electrometallurgical treatment, sodium-bearing wastes are treated by fluidized bed steam reforming, and all other HLW is vitrified. HLW that currently exists in final form is indicated by detached wedges.

In all charts, volumes are shown in cubic meters and include packaging. Commercial SNF volume is projected to 2048 assuming a constant rate of nuclear power production and packaging of all commercial SNF in dual-purpose storage and transportation packages of existing designs. DOE-managed SNF volume is projected to 2035 and includes approximately 400 canisters of naval SNF and 3,542 canisters of defense, R&D, and some commercial-origin SNF. HLW volume assumes completion of planned treatments.

NOTE: WVDP = West Valley Demonstration Project. Source: SNL 2014.

Figure 1. Projected Volumes of Commercial SNF, DOE-Managed SNF, and DOE-Managed HLW

DOE also manages a diverse inventory of SNF, defined in Section 2(23) of the NWPA as fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing. In the 1980s, reprocessing operations were ongoing at the Hanford Site, SRS, and INL, and it was expected that DOE-managed SNF from all sources (weapons plutonium production reactors, naval propulsion reactors, and test reactors) would be reprocessed to recover usable materials, leaving HLW and transuranic waste for long-term disposal. The cessation of most reprocessing operations by the early 1990s left DOE with a heterogeneous inventory of what at that time was about 2,300 metric tons of heavy metal (MTHM) of SNF, now stored at SRS, INL, the Hanford Site, and the Fort St. Vrain site in Colorado. Most of the DOE-managed SNF (about 2,100 MTHM) is defense plutonium production fuel at the Hanford Site, but the inventory also includes fuel assemblies of various designs from a wide range of defense and DOE R&D activities. In addition, naval SNF is in storage at the Naval Reactors Facility at INL, and additional quantities are placed into storage as fuel is withdrawn from Navy vessels. The inventory of DOE-managed SNF has also been augmented by materials not contemplated in the early 1980s, including foreign research reactor fuel and several hundred tons of commercial SNF accepted by DOE under its Atomic Energy Act responsibilities (e.g., SNF from the Fort St. Vrain reactor in Colorado and the damaged core from the Three Mile Island Unit 2 reactor). Under the terms of the NWPA, this commercial-origin SNF is not a candidate for disposal in a separate repository for DOE-managed wastes.

Estimates of projected quantities and volumes of DOE-managed HLW and SNF that are used for cost analyses in Section 4.2 of this report are presented in Table 1; they include a total of 23,294 canisters of defense HLW from SRS, the Hanford Site, and INL. Cost estimates also include approximately 2,450 canisters of existing and projected DOE-managed SNF of non-commercial origin stored at SRS and INL and 400 canisters of naval SNF existing and projected to be stored at the Naval Reactors Facility at INL (Carter et al. 2012). These projections assume completion of all currently planned treatment of HLW at DOE-managed sites and packaging of DOE-managed HLW and SNF as described in Section 2.2.3. Cost estimates presented in this report do not include the 275 canisters of DOE-managed HLW of commercial origin stored at the West Valley Demonstration Project or approximately 1,100 canisters of DOE-managed SNF of commercial origin, including SNF stored at the Fort St. Vrain site in Colorado. Quantities of waste considered here are consistent with the methodology of the July 2008 Total System Life Cycle Cost estimate (DOE 2008a).

Table 1. Sources and Projected Quantities and Volumes of DOE-Managed HLW and SNF

	HLW Canisters		SNF Canisters	
Storage Site	**Number of Canisters**	**Volume (m^3)**	**Number of Canisters**	**Volume (m^3)**
Savannah River, SC	7,824	5,230	3,542 DOE SNF canisters projected at all DOE sites combined, not including naval SNF. Approximately 2,450 of these canisters will contain SNF of non-commercial origin.[a]	2,685
Idaho National Laboratory, ID	4,391	3,221		
Hanford Site, WA	11,079	11,551		
West Valley, NY [a]	275	212		
Fort St. Vrain, CO [a]	0	0		
Naval Reactors Facility, ID	0	0	400	3,930
TOTALS	23,569	20,214	3,942	6,615

Note: Projections assume completion of currently planned treatment of all HLW at DOE-managed sites and packaging of DOE-managed HLW and SNF as described in Section 2.2.3. DOE-managed SNF (including naval SNF) is projected to 2035. Values are point estimates drawn from ranges reflecting uncertainty regarding final treatment and packaging decisions. Waste volumes do not include packaging.

[a] Commercial waste (e.g., HLW at West Valley and SNF at Fort St. Vrain) is not eligible for a repository exclusively for DOE-managed HLW and SNF from defense or DOE R&D activities.

Source: Carter et al. 2012; SNL 2014.

2.2 Distinguishing Characteristics Relevant to Disposal Options

The review of options for disposal of HLW and SNF (SNL 2014) that supports this assessment summarized the inventory of commercial and DOE-managed HLW and SNF, grouped that inventory into broadly defined waste groups with similar disposal characteristics (Table 2), and qualitatively evaluated disposal options for each group of waste forms. The study considered multiple geologic media for disposal (mined repositories in salt, clay/shale, and crystalline rock, plus deep borehole disposal options), different packaging concepts for the waste (e.g., large dual-purpose storage and transportation canisters for commercial SNF versus new package designs engineered specifically for each repository concept) and aspects of the waste form itself (e.g., borosilicate glass forms versus salts and granular solids). Some existing wastes were evaluated for more than one treatment option, resulting in alternative waste forms. For example, cesium and strontium capsules were considered for disposal both in their current form and as part of the vitrified HLW group. The study was not tasked with identifying a preferred option for each type of waste; rather, it focused on identifying where generic and site-specific R&D might be needed before various disposal options can be implemented. The study concluded that all of the waste groups (other than the relatively small volume of untreated sodium-bonded fuels for which additional information is needed) could potentially be disposed of in any of the mined repository concepts considered, although some disposal concepts showed potential advantages over others. For example, salt repositories provide the greatest flexibility for managing high-thermal-output wastes. The study also concluded that, from a technical perspective, deep borehole disposal was potentially an option for small waste forms, including, for example, the cesium and strontium capsules at the Hanford Site.

Table 2. Waste Group Descriptions

Waste group	Description
WG1	All commercial SNF packaged in purpose-built disposal containers
WG2	All commercial SNF packaged in dual-purpose canisters of existing design
WG3	All vitrified HLW (all types of HLW glass, existing and projected, canistered)
WG4	Other engineered waste forms
WG5	Metallic and non-oxide DOE spent fuels
WG6	Sodium-bonded fuels (driver and blanket), direct disposed[a]
WG7	DOE oxide fuels
WG8	Salt, granular solids, and powders
WG9	Coated-particle spent fuel
WG10	Naval fuel

Notes: [a] Information was insufficient to identify a pathway for direct disposal of sodium-bonded fuels without further treatment.
Source: SNL 2014.

Four attributes of the HLW and SNF considered by SNL (2014) are discussed further here: the heterogeneity of the DOE-managed wastes, the composition of the wastes, the physical dimensions of specific waste forms, and the thermal output of the wastes.

2.2.1 Heterogeneity of the DOE-Managed HLW and SNF

As shown in Table 2, the DOE-managed HLW and SNF are remarkably diverse compared to the commercial SNF. Although the DOE-managed wastes are projected to represent only 15% of the total volume of HLW and SNF after packaging and treatment, they account for eight of the ten waste groups defined on the basis of disposal characteristics including radionuclide content; thermal, chemical, and physical properties; packaging; and security and safeguard considerations (SNL 2014). Commercial spent fuel presents a relatively homogenous set of material from a disposal perspective, despite a diverse range of fuel types (e.g., pressurized and boiling water reactor fuels) with different enrichment and burnup histories (Wagner et al. 2012). The two groups identified for commercial SNF differed only in the waste package size, allowing for evaluations of hypothetical endpoint scenarios in which either all commercial SNF is disposed of in large packages comparable to existing dual-purpose storage and transportation canisters, or in smaller purpose-built packages designed specifically for the chosen disposal concept. In contrast, diversity within the eight waste groups defined for the DOE-managed HLW and SNF is large, and, as discussed below, these groups could have been subdivided further.

DOE-Managed HLW. As shown in Figure 1 and discussed above, various forms of HLW are the largest component, by volume, of the DOE-managed wastes considered here. HLW can be divided into three broadly-defined groups based on disposal characteristics (SNL 2014).

- **Vitrified HLW.** Despite differences in radionuclide content, glass chemistry, canister size, and origin, the existing and projected glass waste forms represent the most homogeneous category of the DOE-managed HLW and SNF. Once vitrified, HLW presents a relatively uniform set of characteristics relevant to disposal. As shown in Figure 1, the large majority of the total projected volume of the DOE-managed HLW and SNF is in this group.

- **Other engineered HLW forms.** This group contains two different categories of engineered waste forms other than glass: ceramic and metal wastes projected to be created by the electrometallurgical treatment of sodium-bonded fuels from research reactors at INL, the Hanford Site, and the Fermi-1 reactor; and solid wastes resulting from the treatment of granular calcine wastes at INL by hot isostatic pressing. These waste forms are grouped together for the purposes of evaluating disposal options based on their robust physical properties.

- **Salts, granular solids, and powders.** The largest volume of waste in this group is the calcine HLW at INL, which exists in its current form as 4,400 m^3 of granular and powdered solids. The group also includes the cesium and strontium capsules at Hanford, in which the wastes are currently stabilized as solid cesium chloride and strontium fluoride salts, and two waste forms projected to result from future treatments: granular solids resulting from fluidized-bed steam reforming of sodium-bearing liquid wastes at INL, and salt waste forms derived from electrometallurgical treatment of sodium-bonded fuels. These wastes are grouped together because of their relatively high solubility and potentially corrosive chemistry; the waste form itself will contribute relatively little in a repository setting to the long-term isolation of the radioactivity, and the potentially corrosive nature of the salts may warrant physical separation between these wastes and other waste forms within a repository.

DOE-Managed SNF. The inventory of DOE-managed SNF (DOE 2007) includes fuels from over 500 different sources, including a broad range of physical and chemical forms, most of which exist in relatively small quantities. Based on characteristics relevant to disposal options, they are aggregated here into five of the ten waste groups shown in Table 2 (SNL 2014).

- **Metallic and non-oxide SNF.** By mass, this is the largest category of DOE-managed SNF, and is dominated by about 2,100 MTHM of plutonium-production fuels at the Hanford Site, most of which has been packaged in multicanister overpacks for disposal. The group also includes smaller quantities of a wide range of metallic and carbide fuels of both high and low uranium enrichment used in production and research reactors.

- **Sodium-bonded SNF.** This group contains a relatively small quantity (about 56 MTHM) of sodium-bonded fuels from research activities at the Fermi-1 reactor, the Hanford Site, and INL. These fuels are grouped separately from others because of the chemically reactive nature of the waste form, and they represent the only group of DOE-managed HLW and SNF for which information is insufficient to identify a disposal option for the waste form as it exists today, without further treatment (SNL 2014).

- **DOE-managed oxide SNF.** This group contains about 180 MTHM of a variety of fuel types all of which share the common attribute of containing oxides of uranium or plutonium, in both highly-enriched and low-enrichment forms. Some fuel in this group is originally of commercial origin, while other fuel in this group is derived from defense and DOE research activities. A small amount of SNF in this group will continue to be generated from future research activities.

- **Coated-particle SNF.** This group contains about 27 MTHM of SNF containing carbide-based fuel particles with graphite/carbon coatings, primarily derived from the Fort St. Vrain and Peach Bottom commercial reactors.

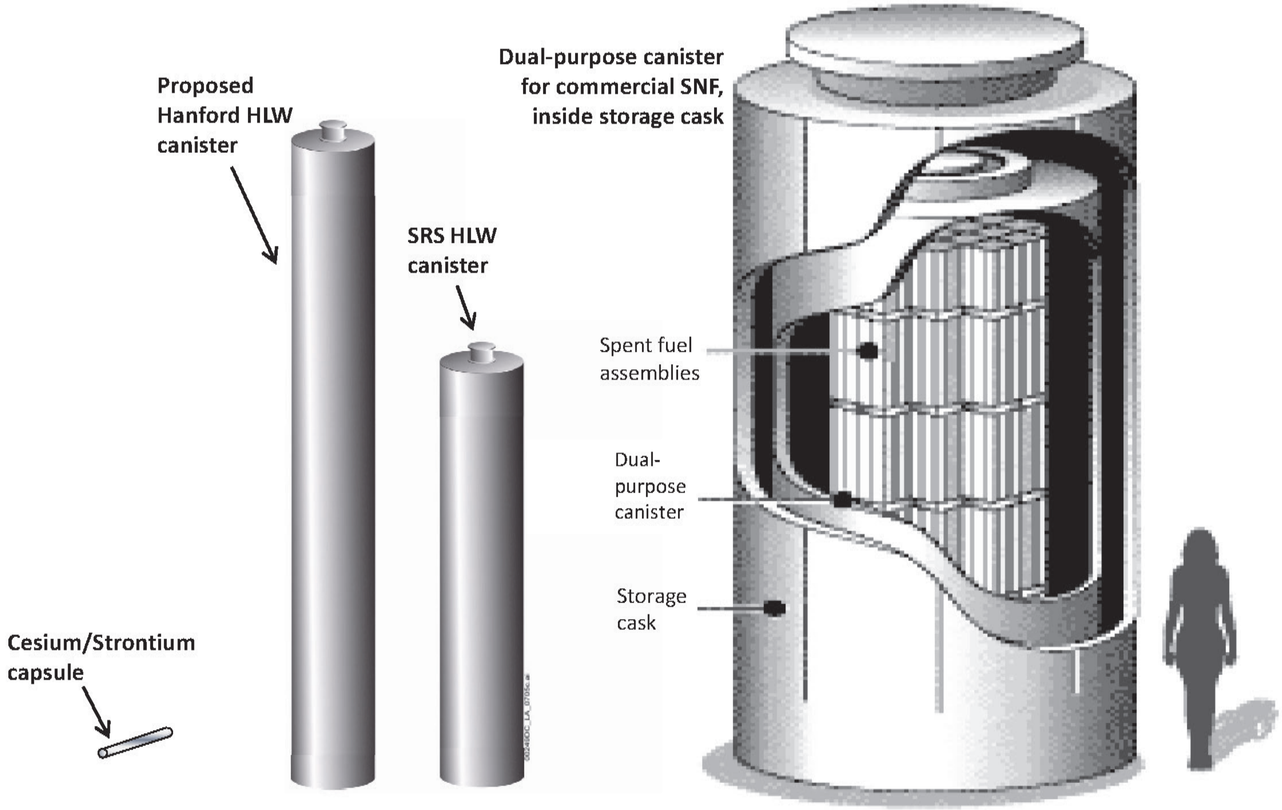
- **Naval SNF.** This group contains SNF derived from research and operational activities of the Navy. The group is projected to contain 65 MTHM of highly-enriched SNF in 2035; however, the inventory of naval SNF will continue to increase throughout the operational lifetime of the nuclear Navy.

2.2.2 Waste Composition

Although, as discussed in Section 3.1, all waste forms (with the possible exception of untreated sodium-bonded SNF) could potentially be disposed of in a broad range of mined repository concepts, the chemical and radioisotopic composition of the wastes can impact disposal system performance. For example, most types of SNF are less stable chemically in oxidizing environments than in reducing environments. Other waste forms, specifically those that contain chloride and fluoride salts, have the potential to create locally corrosive environments that could impact the durability of packages for wastes emplaced in close proximity, and may therefore warrant disposal separately. With respect to the radioactive inventory of the various waste forms, published safety assessments for mined repositories worldwide (see Section 3) indicate that, for most disposal concepts, the most chemically mobile species, and in particular the long-lived fission product iodine-129, pose the greatest challenges for long-term isolation. Waste forms, particularly SNF, that contain relatively larger amounts of iodine-129 and other long-lived mobile fission products are likely to be the largest contributors to overall releases from repositories that place primary reliance on the isolation provided by the geologic barriers. Waste forms that contain substantially fewer mobile fission products, including the HLW derived from the processing of DOE-managed SNF in the past, present fewer challenges for long-term isolation. Waste forms with simple chemistry and relatively less-mobile radioactive species, such as the cesium and strontium capsules, could present the fewest challenges for long-term isolation in appropriate disposal environments.

2.2.3 Waste Form Size

The size of the waste form has a potentially significant impact on disposal options for both the largest and smallest waste forms. The smallest forms of HLW and SNF, including both those that are already packaged in small-diameter canisters and those that are currently unpackaged but could fit in small-diameter canisters, could potentially be candidates for disposal in deep boreholes. At the other extreme, the largest waste forms, specifically the currently existing dual-purpose storage and transportation canisters used for dry storage of commercial SNF and the naval SNF currently loaded in storage, transportation, and disposal canisters at the Naval Reactors Facility in Idaho, have disposal attributes relevant to both emplacement operations and long-term performance that are unlike those of smaller waste packages. Figure 2 shows approximate sizes of representative examples of waste canisters, ranging from the small cesium and strontium capsules to the large dual-purpose canisters for commercial SNF.



Note: Canisters for DOE-managed SNF other than naval SNF are generally comparable in size to HLW canisters.
Source: modified from DOE 2008b Figure 1.5.1-8 and BRC 2012.

Figure 2. Approximate Sizes of Representative Packages for DOE-Managed and Commercial Radioactive Wastes

2.2.3.1 Standard Canisters for DOE-Managed HLW and SNF

The large majority of the DOE-managed HLW and SNF has been or is planned to be placed into canisters of a size that could potentially be disposed of in any of the mined repository concepts considered using emplacement systems that have currently been proposed for such repositories.

The existing and projected canisters for vitrified HLW are 0.61 m (24 inches) in diameter. SRS canisters are 3.0 m (10 feet) long and Hanford canisters are projected to be 4.6 m (15 feet) long (SNL 2014). Dimensions of canisters of immobilized HLW at INL remain to be determined, but for cost analyses presented in Section 4.2 they are assumed to be similar in size to those used at SRS.

DOE plans to package most of its SNF other than naval SNF (about 98% by mass) into standardized multicanister overpacks suitable for storage, transport, and disposal without the need to be re-opened (SNL 2014). As shown in Table 1, a total of 3,542 of these canisters are projected at all DOE sites combined. Some SNF has already been packaged into multicanister overpacks that are currently being stored at the Hanford site. Each multicanister overpack is nominally 0.61 m (24 inches) in diameter and 4.2 m (166 inches) long. The remaining portion of the DOE-managed SNF (not including intact commercial SNF from pressurized or boiling water reactors, SNF packaged in multicanister overpacks, and naval SNF) is planned to be placed into alternative standardized canisters prior to transport and disposal. These alternative standardized canisters will be of four sizes: 0.46 m (18 inches) or 0.61 m (24 inches) in diameter and either 3.0 m (10 feet) or 4.6 m (15 feet) long (SNL 2014).

2.2.3.2 Small Waste Forms

For the purposes of this discussion, small waste forms are those wastes that can be packaged in canisters small enough in diameter to be emplaced in a deep borehole drilled with commercially available technology. This corresponds approximately to waste forms that can be packaged in canisters 0.30 m (12 inches) or less in diameter, allowing emplacement in a borehole that could be drilled to a nominal depth of 5 km (3.1 miles) with a bottom-hole diameter of 0.43 m (17 inches) (SNL 2014). (See Section 3.3 for additional discussion of borehole disposal concepts.) The 0.30-m (12-inch) limit on canister diameter is not absolute, in the sense that technology exists to drill larger boreholes, but cost and complexity of borehole construction increase with diameter and depth, and the 0.43-m (17-inch) borehole diameter provides a reasonable basis for an initial identification of small waste forms. Future research, development, and demonstration activities have the potential to expand the dimensions considered for borehole disposal.

Waste forms that are currently packaged in canisters less than 0.30 m (12 inches) in diameter, or that are unpackaged and could readily be packaged in such canisters, include:

- Cesium and strontium capsules. As noted above, the 1,936 cesium and strontium capsules stored at the Hanford Site are all under 9 cm (3.5 inches) in diameter.

- Untreated calcine HLW. The waste is currently stored at INL in sets of stainless steel bins within concrete vaults, and final packaging has not been determined. Current plans call for treating the calcine HLW by hot isostatic pressing, producing a solid waste form roughly 1.5 m (5 feet) in diameter, but if the waste could be disposed of in its current granular form, it could be emplaced in canisters of essentially any diameter.

- Salt wastes from electrometallurgical treatment of sodium-bonded fuels. These wastes, which exist today only in small quantities, could be packaged in small canisters as they are produced.

- Some DOE-managed SNF currently stored in pools at INL and SRS without final packaging could potentially be packaged in canisters less than 0.30 m (12 inches) in diameter (DOE 2007; SNL 2014).

2.2.3.3 Large Waste Forms

For the purposes of this discussion, large waste forms include existing and projected waste packages that are significantly larger than packages typically proposed for mined repository concepts that rely on vertical shafts and hoists for access. (See Section 3 for additional discussion of disposal concepts.) All waste in this group is SNF; the overwhelming majority is commercial SNF packaged in existing or projected dual-purpose storage and transportation canisters, and there is a relatively small volume of naval SNF that has been packaged in large canisters. Commercial SNF is not part of the inventory of DOE-managed HLW and SNF that is the focus of this assessment, but it is included here for comparison with the DOE-managed waste forms.

- Dual-purpose storage and transportation canisters for commercial SNF. Multiple designs of dry storage cask systems are in use today in the U.S., and specific design details vary. All rely, however, on large canisters containing typically up to 32 pressurized water reactor fuel assemblies or 68 boiling water reactor fuel assemblies, and recent designs can hold even more. Representative dimensions are 2 m (78 inches) in diameter and 5 m (197 inches) or more in length. Fully loaded canisters may be up to 50 metric tons (110,000 pounds) in mass, without including the mass of a future disposal overpack (perhaps another 30 metric tons [66,000 pounds]) or a shielded transfer cask for use in emplacement operations (perhaps another 60 metric tons [132,000 pounds]) (Hardin et al. 2013).

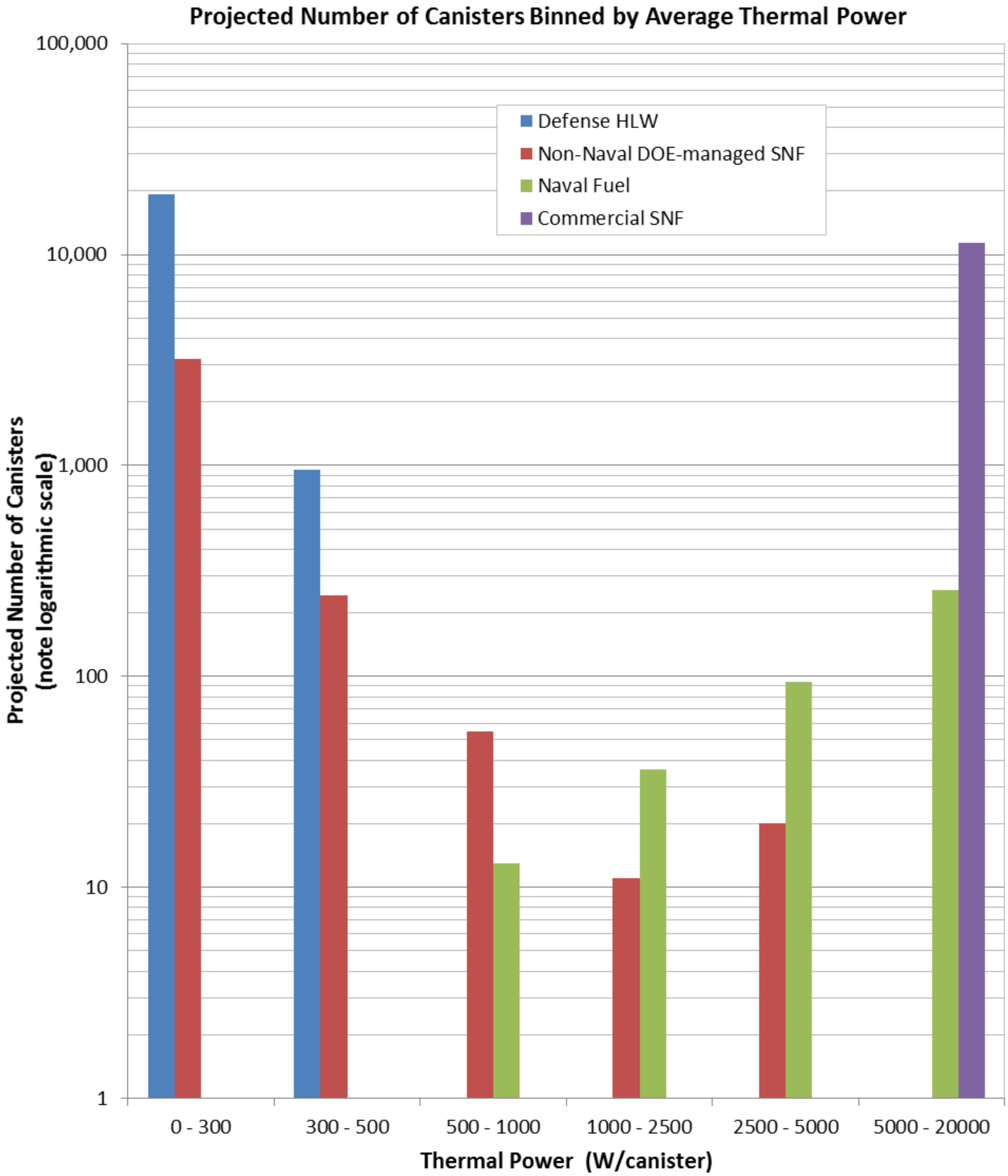
- Naval SNF currently stored in Idaho has been and continues to be packaged in canisters that are 1.7 m (66 inches) in diameter and either 4.7 m (185.5 inches) or 5.3 m (210.5 inches) long. Maximum design weight of the fully loaded naval canisters is approximately 45 metric tons (98,000 pounds) for the short canisters and 49 metric tons (108,500 pounds) for the long canisters (DOE 2008b, Section 1.5.1.4.1.2.1). As is the case for the commercial dual-purpose canisters, the additional mass of any future disposal overpacks and shielded transfer casks should be considered in evaluating options for disposal.

Approximately 1,700 commercial dual-purpose canisters were in use as of February 2013, and current practice indicates that this number will continue to grow at a rate of roughly 200 canisters per year (Carter and Leduc 2013). Assumptions used in this assessment allow for the possibility that all commercial SNF will eventually be packaged for disposal in large dual-purpose canisters if a suitable site and emplacement technology are available, or, alternatively, that all commercial SNF will need to be repackaged into smaller canisters designed specifically for a selected disposal concept (SNL 2014). As of December 2013, 93 canisters of naval SNF had been loaded at the Naval Reactors Facility in Idaho, and if naval SNF continues to be packaged in existing canister designs, approximately 400 are projected by 2035 (Table 1).

2.2.4 Thermal Output of the Waste

Thermal characteristics of the largest components (by volume) of the DOE-managed and commercial wastes (i.e., defense HLW, DOE-managed SNF with naval SNF shown separately, and commercial SNF) are shown in Figure 3. Defense HLW is assumed to be treated and packaged as planned at the three DOE sites. Dimensions of HLW canisters are assumed to be as described in Section 2.2.3.1. All SNF is assumed to be packaged for disposal in canisters of existing design, as described in Sections 2.2.3.1 and 2.2.3.3. Specifically, all naval SNF and commercial SNF, including SNF that has yet to be generated, is assumed for the purposes of this discussion to be packaged in large canisters, as described in Section 2.2.3.3.

As shown in Figure 3, HLW has relatively low thermal output, with the large majority of canisters falling below 300 W. Commercial SNF is significantly hotter (on the order of 10,000 W and greater for current dual-purpose storage and transportation canisters, with a large range depending on canister loading, age, and burnup of the fuel). The non-naval DOE-managed SNF overlaps in thermal output with the defense HLW, with most canisters falling below 300 W. The range of thermal output of naval fuel shown in Figure 3 represents differences in the type and age of fuel loaded in each canister. Seven of the 93 canisters currently loaded at the Naval Reactors Facility in Idaho have thermal outputs below 1,000 W, and the remainder are above 4,000 W. By 2025, 49 canisters are planned to be loaded with thermal outputs less than 2,500 W. The remaining canisters, including those loaded after 2025, will have significantly higher heat loads with most being above 8,000 W.



Note: Projections assume completion of currently planned treatment of all HLW at DOE-managed sites. DOE-managed SNF (including 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.
Sources: Carter and Leduc 2013; SNL 2014.

Figure 3. Number of Projected SNF and Defense HLW Canisters Binned by Average Thermal Power

The average thermal output of the existing wastes will decrease with age due to radioactive decay, while average thermal output of those wastes that continue to be produced at a constant rate, primarily commercial SNF, will remain essentially constant (or perhaps increase due to increased burnup) until production ceases. Packaging naval and commercial SNF in smaller canisters would lower the thermal output of individual canisters, but would not fundamentally change the observation that relatively young SNF, and in particular high-burnup SNF, has substantially higher thermal output than HLW or older and lower burnup SNF.

3 Options for Disposal of DOE-Managed HLW and SNF

The DOE has planned since the mid-1980s to dispose of all HLW and SNF, regardless of commercial, defense, or research origin, in a common mined geologic repository or repositories. This is not the only technical option available, however, and consistent with the diverse characteristics of the DOE-managed HLW and SNF, this report considers disposal options in which some DOE-managed HLW and SNF is disposed of separately from commercial SNF and DOE-managed HLW and SNF of commercial origin. Options for DOE-managed HLW and SNF could include a separate mined repository for some DOE-managed wastes and emplacement of other DOE-managed wastes in a repository for commercial HLW and SNF, as previously planned. In addition, deep borehole disposal may be an option for the smaller waste forms, including, for example, the cesium and strontium capsules stored at the Hanford Site.

Research done in the last 30 years in both the U.S. and other nations indicates that mined repositories could be designed and constructed in multiple geologic media, including salt, clay/shale rocks, and crystalline rocks. For example, license applications have been submitted for the construction of geologic repositories for SNF in crystalline rocks in Sweden (SKB 2011) and Finland (Posiva Oy 2013). France has completed a detailed safety assessment for disposal of both vitrified HLW and SNF in a mined repository in argillite (claystone) (ANDRA 2005). Germany has undertaken decades of research on a potential repository for both vitrified HLW and SNF in a salt dome at Gorleben (BMWi 2008). Switzerland and Belgium have conducted detailed safety assessments for proposed repositories in argillite (Switzerland: NAGRA 2002) and relatively soft clay (Belgium: ONDRAF/NIRAS 2011). In addition, DOE's Waste Isolation Pilot Plant (WIPP) was designed and constructed in bedded salt in southeastern New Mexico for the disposal of defense-related transuranic waste and certified for operation by the U.S. Environmental Protection Agency under 40 CFR Part 191 (DOE 1996, DOE 2004, and DOE 2009; 63 FR 27354, 71 FR 18010, and 75 FR 70584).[2]

Based on this experience, different geologic media will require different engineering approaches to repository and waste package design but the choice of a host rock is not likely to be a definitive or prescriptive discriminator in selecting disposal options. All commercial and DOE-managed HLW and SNF could potentially be disposed of, with appropriate treatment and packaging, in multiple mined repository concepts, and although additional research is needed to demonstrate the technology, deep boreholes appear to be a viable disposal option for smaller waste forms (SNL 2014). This report does not assume any specific geologic medium for disposal of commercial SNF or DOE-managed HLW and SNF in a mined repository, and conclusions are drawn at a high-enough level to apply broadly to a range of concepts. Three main options are described in more detail below: (1) disposal of all HLW and SNF regardless of origin in a common repository (or repositories), (2) disposal of some DOE-managed HLW and SNF in a separate repository, and (3) disposal of smaller waste forms in deep boreholes.

[2] The DOE suspended operations at the WIPP in February 2014 following two events—a fire involving an underground vehicle on February 5 and a subsequent, unrelated radiological release underground on February 14. Investigation of the causes of the radiological release is ongoing, but there is no indication that the events will have future impacts on the long-term performance of the repository. The DOE's recovery plan (DOE 2014) calls for the resumption of disposal operations in the first quarter of calendar year 2016.

3.1 Disposal of All HLW and SNF, Regardless of Origin, in a Common Repository

This option is essentially unchanged from the plan followed by the DOE since the mid-1980s, and calls for disposing of all DOE-managed HLW and SNF together with commercial SNF in one or more mined repositories. If more than one repository is ultimately required to accommodate the full inventory of commercial SNF (as envisioned by the NWPA), this option carries an implicit assumption that at least one repository would include a broad representation of all the waste types, both DOE-managed and commercial.

There are multiple ways to design and operate a single repository capable of accommodating a broad range of waste types. One approach is to emplace the different waste forms in separate regions within the repository, sharing common access shafts and drifts but not occupying the same disposal drifts. Repository design work conducted in the U.S. and other nations over the past 30 years has confirmed that this approach is viable. For example, the French radioactive waste management program conducted a detailed safety analysis in 2005 of a hypothetical mined repository in argillite (claystone) designed for disposal of high-level and long-lived radioactive wastes derived from nuclear power generation, research activities, and national defense activities (ANDRA 2005). The French design called for disposal of each major waste type in a separate region within the underground excavations, effectively isolating SNF, HLW, and intermediate-level wastes from each other. Alternatively, the design that had been proposed for a repository at Yucca Mountain in the U.S. took a different approach, specifying emplacement of DOE-managed wastes and commercial SNF in the same disposal drifts, in waste packages directly adjacent to each other in alternating sequences (DOE 2008b, Section 1.3.1.2.5).

Conclusions from the Yucca Mountain experience (DOE 2008b) relevant to the long-term performance impacts of disposing of all DOE-managed wastes and commercial SNF together in one or more repositories include:

- A repository can be designed such that DOE-managed HLW and SNF and commercial SNF can be disposed of in close proximity within the same emplacement areas.
- The disposal concept could have achieved safe isolation of any of the waste forms taken individually with minor modifications to the waste emplacement scheme (e.g., changes in waste package spacing).
- For repository concepts that include reliance on robust engineered barriers, waste package performance is likely to be an important factor in determining which components of the inventory provide the largest contribution to estimates of total dose.

Conclusions from analyses of the Dossier 2005 argillite repository concept (ANDRA 2005) relevant to the long-term performance impacts of disposing of DOE-managed HLW and SNF and commercial SNF together in one or more repository include:

- A repository can be designed such that intermediate-level process wastes, vitrified HLW, and SNF are managed in separate disposal cells within the same underground facility.
- Performance of a disposal concept with separate waste emplacement areas is not dependent on disposal of the waste streams in a single repository, and the repository could achieve safe isolation of any of the waste streams taken individually. Thermal targets for high-thermal-output wastes are met in this example by keeping waste packages relatively small (maximum of four SNF assemblies per package).

- For repository concepts that rely primarily on robust isolation by the low-permeability host rock, engineered barrier performance may be less important than the time required for radionuclide transport through the surrounding rock. The relative abundance of mobile radionuclides in the initial inventory of each waste type may be a factor in determining relative contributions to estimates of total dose.

For both repository concepts, the largest contributions to the estimated peak radiation dose received by a hypothetical member of the public in the far future come from SNF (and specifically from the commercial SNF in the case of the design that had been proposed for a repository at Yucca Mountain), because SNF contains the largest inventory of mobile radionuclides. However, estimated peak doses from all waste types, including SNF, were well below regulatory limits in both analyses.

3.2 Disposal of Some DOE-Managed HLW and SNF in a Separate Mined Repository

As discussed above, multiple analyses have been conducted world-wide for mined repository concepts for commercial SNF and, in some cases, for repository concepts that include both commercial SNF and defense-related HLW and SNF. None of these analyses specifically addressed repository concepts limited only to DOE-managed HLW and SNF, but they provide strong support for concluding that it would be straightforward to modify any of the various designs proposed for commercial SNF repositories to accommodate the DOE-managed HLW and SNF. Furthermore, these modifications could result in a simpler design and potentially a more straightforward licensing case. Potential design modifications include:

- Size: a repository for DOE-managed HLW and SNF would be smaller than a repository for both commercial and DOE-managed wastes because of the smaller volume and lower heat output of DOE-managed HLW and SNF requiring geologic disposal.

- Thermal load management: as discussed in Section 2, much of the DOE-managed HLW and SNF generates significantly less heat than the commercial SNF, potentially simplifying aspects of repository design and operations, including:

  - The option of immediate waste emplacement and repository sealing without surface storage or ventilation.

  - Closer spacing of waste packages and greater flexibility in the use of backfill.

  - Shortened operational period and earlier permanent closure, consistent with the fixed quantity of the DOE-managed HLW and SNF.

- Criticality control considerations: DOE-managed HLW has had much of the fissile material removed and is not expected to need criticality controls, simplifying licensing considerations for these waste forms.

Flexible disposal options that allow for separating DOE-managed HLW and SNF from commercial SNF and HLW could lead to benefits in repository cost or performance based on different characteristics of radioactive wastes such as thermal output, chemical characteristics, and fissile mass loading. For example, there could be advantages to separating heat-generating components of DOE-managed SNF (e.g., hotter naval SNF) and disposing of them with the commercial SNF, while disposing of the other DOE-managed HLW and SNF in a separate repository. There are no recently published safety assessments available for a repository containing only DOE-managed HLW and SNF, but the safety analyses done for the repository that had been proposed at Yucca Mountain and for the Dossier 2005 argillite repository support a conclusion that overall long-term performance for a separate repository for HLW and small amounts of SNF would also meet regulatory limits. Estimated releases from such a repository could reasonably be expected to be smaller than from a repository that also included commercial SNF simply because of the smaller radionuclide inventory, and demonstrations of regulatory compliance could be simplified by the lower thermal output of such waste compared to commercial SNF. As shown in Figure 3, all of the defense HLW canisters and many of the DOE-managed SNF canisters are relatively cool (most projected to be less than 300 W per canister), and could be emplaced in a wide range of repository concepts without further aging or thermal load management considerations. For example, the Swedish concept for disposal in crystalline rock calls for emplacing SNF canisters with thermal power up to 1,700 W (SKB 2011), and the French argillite concept calls for emplacing commercial HLW canisters that may be up to several hundred watts and SNF packages up to several thousand watts in power (ANDRA 2005).

3.3 Disposal of Smaller Waste Forms in Deep Boreholes

As described in Section 2.2.3.2, some DOE-managed waste forms are small enough to be candidates for disposal in a deep borehole. For the purposes of this discussion, a representative reference design for borehole disposal (Arnold et al. 2011) calls for drilling a borehole to a total depth of approximately 5 km (3.1 miles), with at least 3 km (1.9 miles) of the lowest portion of the hole penetrating crystalline rock. The hole would have a nominal diameter of 0.43 m (17 inches) at depth (requiring larger hole diameters at shallower depth), and would accommodate emplacement of waste canisters with maximum external diameters of 0.30 m (12 inches). This design for a borehole was chosen because it is expected to be reliably achievable in crystalline rocks with currently available commercial drilling technology, and there are no known technical issues that present unreasonable barriers to drilling to this diameter at depth. Alternative designs for a borehole may also be appropriate. For example, the smallest waste forms, such as the cesium and strontium capsules, could be emplaced in a smaller diameter borehole that would be simpler and less costly to drill. Larger wastes forms could potentially also be candidates for borehole disposal if future developments in drilling technology allow for consideration of larger diameter boreholes.

Waste packages in this concept would be up to 4.2 m (166 inches) in length. The borehole would be lined with steel casing after drilling to facilitate emplacement of waste packages vertically in the lower 2 km (1.2 miles) of the borehole. Following emplacement, casing would be removed from the upper portion of the hole, and the hole would be sealed with alternating sections of concrete and compacted clay. Isolation of the waste would be provided by the extremely low permeability of crystalline rocks at these depths (significantly greater than the depths proposed for mined repositories), and by the long pathway for diffusive transport upward through the borehole seal system. Low permeability of the host rock and the absence of open fractures would need to be verified through borehole testing before waste was emplaced; testing would also confirm the absence of low-salinity or young groundwater. Because of the primary reliance on the geologic barriers and the long seal system, little long-term performance would be required from the waste packages, which could be constructed of standard drilling-industry steel pipe.

Although the deep borehole disposal concept has been investigated in the U.S. and other nations intermittently for decades, the concept has not been demonstrated through field testing (SNL 2014). Preliminary evaluations indicate a high potential for robust long-term isolation (e.g., Brady et al. 2009), and the DOE is proposing a multi-year deep borehole field test to confirm the safety and feasibility of the concept before proceeding further with implementation. This is discussed in more detail in Section 5.

3.4 Conclusions Regarding Disposal Options

This report recommends that DOE pursue options for disposing of some DOE-managed HLW and SNF separately from commercial SNF and HLW. Specifically, it recommends that DOE pursue options that allow for flexibility in disposing of HLW and cooler DOE-managed SNF (potentially including cooler naval SNF) in one repository, while disposing of other DOE-managed wastes, including HLW and SNF of commercial origin and naval SNF with relatively higher heat output, in another repository with commercial SNF and HLW. The report also recommends that DOE retain the flexibility to consider options for disposal of smaller DOE-managed waste forms in deep boreholes rather than in a mined repository, and that DOE conduct the deep borehole field test needed to confirm the safety and feasibility of the concept.

4 Benefits of Stepwise Development of a Repository for Defense HLW and Cooler DOE-Managed SNF

A primary benefit of proceeding with a strategy that allows for disposing of some DOE-managed HLW and SNF separately from commercial waste is that it could allow nearer-term progress on geologic disposal. Focusing first on waste forms that have the potential to simplify both the design of the repository and the demonstration of compliance with long-term performance objectives (specifically, defense HLW and cooler DOE-managed SNF, as described in Section 3) is consistent with the phased, adaptive, and consent-based approach outlined in Section 1. Furthermore, as described below, such an approach has potential benefits in cost efficiency and public acceptance, will help support national security goals, and will contribute to the likelihood of success in developing the overall solution to the entire waste management challenge.

4.1 Progress on Managing DOE's HLW and SNF

Timely Completion of the DOE Cleanup Mission—Timely completion of cleanup activities at the DOE sites was not a primary concern in the 1980s when DOE developed its plan to rely on a common repository for disposal of commercial wastes and DOE-managed HLW and SNF. At that time, nuclear weapons production activities were still a primary mission of the DOE, and the inventory of defense HLW was growing as nuclear fuel used for defense activities was being reprocessed. There were no legal requirements regarding specific dates for disposal of the resulting HLW, and the facilities to treat liquid HLW for disposal were not yet constructed. Furthermore, it was assumed that one or more repositories for commercial SNF and HLW would be available relatively quickly and could be used for the DOE-managed HLW and SNF as well. The recognition that a repository for commercial SNF and HLW may not be in operation until 2048 (DOE 2013a) makes options that allow for potentially earlier disposal of DOE-managed HLW and SNF more attractive.

Transportation and Disposal Readiness—A significant amount of defense HLW already exists in its final form at SRS (3,339 canisters out of a projected total of 7,824 to be produced at that site), and treatment of calcine at INL is planned to begin around 2024 and be completed by 2035. In accordance with the Tri-Party Agreement, immobilization of Hanford HLW would be complete by mid-century. While most DOE-managed SNF other than the remaining plutonium production fuel at the Hanford Site remains to be placed in canisters for disposal, such canisters have been designed, tested, and prototypes fabricated. Packaging of DOE SNF into standard canisters could begin well before the time a repository could be available. Existing and projected HLW canisters and the standard canisters for DOE-managed SNF are of a size that is transportable by truck if needed to allow disposal to begin as soon as possible. Existing and projected naval SNF canisters are transportable using available railcars.

4.2 Potential National Security and Cost Benefits

National Security Benefits—HLW and SNF are securely managed today and will continue to be securely managed in any approach taken for waste disposal. However, earlier progress on a repository for some DOE-managed HLW and SNF could benefit national security interests in two areas:

- First, delays in removing naval SNF from the State of Idaho could potentially impact naval operations beginning in 2035 because of a binding settlement agreement entered into by the DOE and the Navy with the State of Idaho to remove SNF from the state by that time. Shipments of

SNF to INL after this deadline may be suspended unless and until the parties agree or the Court determines that the substantive obligations or requirements of the agreement have been satisfied. Should Idaho refuse SNF from the Navy, the Navy could be unable to complete refueling operations of the nuclear fleet, raising national security concerns (GAO 2011). Near-term progress on disposing of some DOE-managed HLW and SNF (potentially including cooler naval SNF) could help expedite a process for ultimately disposing of all HLW and SNF, thereby facilitating removal of all naval SNF from Idaho.

- Second, progress in disposal of DOE-managed SNF could increase support for the continued receipt and storage of highly enriched SNF from foreign research and test reactors that is presently stored at DOE facilities at the SRS and INL under the Reduced Enrichment for Research and Test Reactors program. This ongoing program addresses the national security objective of global nuclear material threat reduction by allowing foreign reactor operators to return highly enriched SNF (which has a potential to be diverted and used for weapons material) of U.S. origin in exchange for low-enriched fuels.

Enhancing Overall Cost Effectiveness—Potential savings to taxpayers could be significant due to avoided costs for safely storing inventories of immobilized tank waste if a repository for some DOE-managed HLW and SNF is available earlier. For some repository concepts that rely primarily on geologic barriers to isolate the waste, additional potential savings could result from simplified treatment and packaging requirements. The resulting savings could be redirected to focus work scope and resources on other high-priority cleanup activities at the three defense HLW sites. In addition, the earlier availability of a repository for some DOE-managed HLW and SNF could help keep tank waste disposition costs and schedules within the baseline estimates by reducing uncertainty in final waste form treatment approaches, reducing the extent of maintenance and repairs to infrastructure, and accelerating the work. From these perspectives, a common repository for both commercial and defense waste may be the least cost-effective option. Proceeding with a stepwise approach that increases the likelihood of successfully addressing the needs of the entire nuclear waste management program may ultimately be a more cost-effective solution.

Uncertainties about the timing and characteristics of a repository have the potential to add significant costs that could affect the near-term management of DOE-managed HLW and SNF. These potential costs can be divided into three groups: (1) costs associated with extended storage of DOE-managed HLW and SNF at existing sites and/or siting and construction of alternative consolidated storage facilities; (2) programmatic impacts associated with delays in environmental remediation work at DOE-managed sites; and (3) costs associated with waste treatment decisions that the DOE must make in the near future without certain knowledge of the ultimate design and location of the repository.

For any specific geology and emplacement concept, Table 3 shows that a common mined repository containing both commercial SNF and DOE-managed HLW and SNF has a lower cost than two separate mined repositories. The longer a disposal facility is delayed, however, the less efficient a disposal option is with respect to achievement of the broad mission of completing the cleanup of the DOE sites.

Table 3. Rough Order of Magnitude Costs for Repositories for Commercial and DOE-Managed SNF and HLW

Scenario		Repository Costs (Billions of 2013$): Repository for Commercial SNF and HLW, Low Range	Repository for Commercial SNF and HLW, High Range	Repository for DOE-managed HLW and SNF, Low Range	Repository for DOE-managed HLW and SNF, High Range
Common Repository. All HLW and SNF regardless of origin disposed of in a common repository	Crystalline	$73	$96	N/A	N/A
	Bedded Salt	$29	$39	N/A	N/A
	Clay/Shale	$71	$95	N/A	N/A
	Shale Unbackfilled	$30	$40	N/A	N/A
	Sedimentary Backfilled	$38	$51	N/A	N/A
Separate Commercial and Defense Repositories. All commercial origin HLW and SNF in one repository; all DOE-managed HLW and SNF not of commercial origin in a separate repository.	Crystalline	$63	$84	$35	$47
	Bedded Salt	$25	$33	$14	$19
	Clay/Shale	$62	$82	$34	$46
	Shale Unbackfilled	$26	$35	$15	$20
	Sedimentary Backfilled	$33	$45	$19	$25
Separate Repository limited to Defense HLW. Other DOE-managed wastes (DOE defense SNF, DOE-managed commercial/R&D SNF, naval SNF and commercial HLW) disposed of in a repository for commercial SNF.	Crystalline	$64	$85	$33	$44
	Bedded Salt	$25	$34	$13	$18
	Clay/Shale	$63	$84	$32	$43
	Shale Unbackfilled	$27	$36	$14	$18
	Sedimentary Backfilled	$34	$45	$17	$23
Separate Repository limited to Defense HLW and low-thermal-output DOE-managed SNF. High-thermal-heat DOE-managed commercial/R&D SNF, naval SNF, and commercial HLW disposed of in a repository for commercial SNF.	Crystalline	$63	$84	$33	$44
	Bedded Salt	$25	$33	$13	$18
	Clay/Shale	$62	$82	$33	$43
	Shale Unbackfilled	$26	$35	$14	$18
	Sedimentary Backfilled	$33	$45	$18	$24

Notes: The rough order of magnitude costs include design, construction, startup, operations, closure, and monitoring but are not complete repository system life cycle costs (e.g., transportation and repository siting costs are not included). Source: derived from DOE 2013b and Hardin et al. 2012.

In addition, some observations applicable to cost efficiency include:

- A primary driver for repository cost is the host rock, engineered barrier configuration (e.g., waste package), and treatment criteria required to meet regulatory requirements.
- A repository limited to low-thermal-output waste would generally be less expensive and would better utilize subsurface disposal capacity in terms of the quantity of waste disposed of per square meter of emplacement area.
- A common repository for commercial and DOE-managed HLW and SNF could cost between ~$29 billion and ~$96 billion, depending on the geologic host rock selected. Costs for such a repository are estimated assuming all commercial SNF would be emplaced in a single repository, consistent with the 2013 Fee Adequacy Assessment (DOE 2013b).
- A separate repository for some DOE-managed HLW and SNF could cost between ~$14 billion and ~$47 billion, depending on the geologic host rock selected. In general, mined repositories in salt and shale without backfill are estimated to be less expensive, and repositories in crystalline rock and clay/shale media with backfill are estimated to be more expensive.

- Disposing of all DOE-managed HLW and SNF separately from the commercial wastes could result in estimated costs about 10% lower for the repository for commercial SNF and HLW.

- Uncertainty in finalization of waste acceptance and disposal criteria required to meet regulatory performance requirements could add to the costs at DOE sites due to the application of unnecessary treatment requirements and inappropriate waste forms or packaging.

The common factor affecting all of these potential costs and impacts is the anticipated timing of a separate repository for some DOE-managed HLW and SNF. Availability of a repository could reduce the uncertainty in DOE's cleanup mission, avoid costs of delay in immobilization of tank wastes, and demonstrate to state regulators that DOE is making progress in cleaning up its tank wastes.

4.3 Little Requirement for Further Technology Development to Support Repository Design and Licensing

As shown in Figure 3, all of the defense HLW and much of the DOE-managed SNF is relatively cool and could be emplaced in the wide range of repository concepts discussed in Section 3.2 without further aging or thermal load management considerations. Furthermore, the planned and existing canisters for defense HLW and most of the DOE-managed SNF described in Section 2.2.3 are compatible in size with any mined repository concept under consideration, including those that rely on hoists in vertical shafts for access to the underground workings.[3] No significant technological advances (e.g., in the capability to emplace very large waste packages underground) are needed to support a design and license application for a repository limited to defense HLW and DOE-managed SNF packaged in those canisters.

As discussed in Section 3.2, both repository operations and the demonstration of compliance with regulatory limits on long-term radionuclide releases may be easier for a repository containing low thermal output waste packages (i.e., all of the defense HLW canisters and a substantial portion of the canisters of DOE-managed SNF) than for a repository that includes commercial SNF, independent of repository design considerations. Specifically, the safety case for such a repository would be simplified by the lower thermal output and overall lower radioactivity of the waste, and by the very low potential for criticality in the defense HLW because of the recovery and removal of fissile material during reprocessing.

4.4 Public Acceptability: Early Progress Will Help Meet DOE's Goals and Build Confidence in the Process

Early progress on a repository for some DOE-managed HLW and SNF will support the achievement of DOE's mission of completing the cleanup of the DOE sites, and will promote improved cooperation between DOE and state regulators, help enhance public acceptability of DOE's mission with the local communities around the DOE complex, allow limited funds to be shifted to other priority cleanup activities, and increase the likelihood of DOE meeting consent and compliance agreements.

Early progress could also ease concerns that any potential interim storage of waste could become *de facto* permanent storage because of lack of a path to a repository. The Administration's *Strategy for the*

---

[3] Cooler naval fuel that has already been placed into large canisters for storage and disposal, as described in Section 2, might require repackaging to be disposed of in repository concepts that rely on existing operational techniques for vertical hoist access to the repository.

Management and Disposal of Used Nuclear Fuel and High- Level Radioactive Waste (DOE 2013a, p. 7) notes that:

> "…the linkage between storage and disposal is critical to maintaining confidence in the overall system. Therefore, efforts on implementing storage capabilities within the next 10 years will be accompanied by actions to engage in a consent-based siting process and begin to conduct preliminary site investigations for a geologic repository."

Early progress will facilitate development of additional repository capacity for disposal of the full inventory of DOE-managed HLW and SNF and for commercial SNF and HLW for which DOE is responsible by:

- Developing experience on large scale operations of a repository for highly radioactive waste that can benefit the design and operation of future repositories;

- Potentially increasing public acceptance for a repository for commercial SNF and the remaining DOE-managed wastes.

Although there is no definitive basis to predict the public acceptance of any specific approach to developing a repository, available information supports a conclusion that there is a greater likelihood of public acceptance of a repository limited to DOE-managed HLW and SNF not of commercial origin than a repository that includes commercial wastes, particularly if such a repository incrementally addressed defense HLW and the cooler DOE-managed SNF.

Significant research has been conducted in the last 30 years on the factors that impact public acceptance during siting of a repository and other nuclear facilities. Experience has shown that public familiarity with the site and proposed facility contributes to public acceptance (Jenkins-Smith et al. 2012a). Greenberg (2009) found that familiarity with existing nuclear facilities at a site by residents within 50 miles (80 km) gave the strongest correlation with likely acceptance of new nuclear facilities at that site. In addition, both Jenkins-Smith et al. (2012b) and Greenberg (2013) found that with respect to nuclear power and nuclear waste management activities, federal agencies are trusted significantly more than private owners and operators.

The communities and states currently storing DOE-managed HLW and SNF are doing so largely as a result of federal eminent domain processes to site facilities used for the benefit of the entire country. Clearly these sites derived the benefit of the economic activity from the large federal expenditures, but they also have borne the burdens of hosting Cold War facilities that now require significant expenditures to clean up. Availability of a repository, including final waste acceptance criteria to inform needed treatment and packaging approaches, for DOE wastes can build public and regulator acceptance for all cleanup activities at these sites. This would be achieved through:

- Increased confidence by helping to demonstrate that DOE can meet enforceable agreements and that DOE-managed HLW and SNF will not be stranded indefinitely at these sites.

- Increased cooperation between DOE and host communities. Specifically, progress in disposal of DOE-managed HLW and SNF can help DOE in negotiating milestones related to other aspects of its cleanup mission and support interactions with the public and regulators in pursuing alternative treatment and packaging approaches.

- Reducing overall risks associated with DOE facilities, through accelerating the closure of aging infrastructure and avoiding costly and/or unnecessary treatment approaches, will also help build public acceptance.

Available information indicates that a repository limited to DOE-managed HLW and SNF not of commercial origin could be more likely to gain public acceptance than a repository that includes commercial waste, all other factors being equal. In the case of WIPP, the restriction of the facility to transuranic waste of defense origin was an essential condition to the public and state acceptance of the repository (Downey 1985; Stewart and Stewart 2011). In contrast to a repository for commercial SNF, siting a repository for DOE-managed HLW and SNF may be viewed as a national responsibility whereby all states have a share in the benefits and responsibilities.

Characteristics of the DOE-managed HLW and SNF that may also contribute to public acceptance include the same points summarized in Section 3.2 regarding the demonstration of compliance with long-term regulatory requirements: lower thermal output, lower total radioactivity, and, for HLW, the relative lack of fissile content may contribute to greater confidence in waste isolation. In addition, the lack of economic or resource value associated with HLW may contribute to public acceptance of options for its permanent disposal.

4.5 Developing and Testing a Consent-Based Repository Siting Process

The Administration's *Strategy for the Management and Disposal of Used Nuclear Fuel and High- Level Radioactive Waste* (DOE 2013a) identifies the establishment of a consent-based siting process as one of the critical elements for successful implementation of the proposed strategy. Development of a separate repository for some DOE-managed HLW SNF provides an opportunity to develop and test a consent-based siting process in consultation with stakeholders.

Recent progress using consent-based siting processes in Spain, where a central storage facility for commercial SNF and HLW has been sited, and in Canada, where so many communities became actively engaged in their repository siting process that the program suspended acceptance of further expressions of interest (NWMO 2012), suggest that DOE could implement a comparable process successfully in the U.S.

4.6 Conclusions Regarding the Stepwise Development of Repositories for HLW and SNF

Early action to develop a separate repository for some DOE-managed HLW and SNF will support timely completion of the cleanup mission at the DOE sites and will contribute to the resolution of issues associated with management and disposal of all HLW and SNF (both DOE-managed and commercial). A stepwise and staged approach of proceeding first with the easiest waste to transport and dispose of will help to develop the public confidence that is essential to a successful waste management program. Coupled with a focused research, development, and demonstration program that evaluates deep borehole disposal options for the smaller waste forms and supports disposal of high-thermal output waste packages and very large waste packages, as described in Section 5, this approach provides a pathway for disposal of all DOE-managed HLW and SNF of non-commercial origin, and will contribute to solving the entire waste management challenge.

5 Research, Development, and Demonstration Program to Address Disposal of the Full Inventory of DOE-Managed HLW and SNF

DOE is currently conducting R&D on multiple concepts for geologic disposal of HLW and SNF (e.g., evaluation of design concepts for mined repositories in multiple rock types and deep boreholes in crystalline rock). To complement the proposed development of a separate repository for some DOE-managed HLW and SNF, additional R&D efforts could focus on information needs specific to the field-scale demonstration of deep borehole disposal concepts and disposal of high thermal-output naval SNF in mined repositories.

5.1 Research and Development on Deep Borehole Disposal

As discussed in Section 3.3, the deep borehole disposal concept has been investigated intermittently for decades, but the concept has not been demonstrated through field testing (SNL 2014). DOE is proposing a multi-year deep borehole field test to confirm the safety and feasibility of the concept before proceeding further with implementation. For example, challenges exist in the development of remote handling equipment needed for emplacement operations in a deep borehole disposal system, although engineering for such equipment is clearly within the realm of current technology. If fielded, such a test would include construction of a full-scale borehole allowing testing of downhole characterization tools, confirmation of geologic, chemical, and hydrologic controls on waste isolation, demonstration of emplacement operations using non-radioactive surrogate wastes, and in situ testing of technology for sealing the borehole. Technologies developed during a borehole field test could also support broader DOE objectives relevant to characterization of the subsurface environment, including research in enhanced recovery of geothermal and fossil energy. Such a field test would be a first of its kind worldwide. DOE proposes to seek international collaboration with other nations that have expressed interest in deep borehole disposal concepts.

5.2 Research and Development on High Thermal-Output Waste Packages

As noted in Section 3.1, some existing repository design concepts call for meeting postclosure temperature constraints in the repository by, among other things, limiting the size of waste packages. Additional research will investigate design alternatives that allow for other approaches to managing heat in the repository that facilitate permanent disposal of the high-thermal-output naval waste packages. R&D will evaluate the technical basis for postclosure temperature constraints in various repository design concepts, and will investigate alternative approaches to meeting those constraints, including waste aging strategies, ventilation approaches, increased spacing between packages, and the use of heat-tolerant backfill materials. Results of this R&D would also help support disposal of commercial SNF.

5.3 Research and Development to Support Emplacement of Large Packages in Mined Repositories

As noted in Section 2.2.3, the largest waste packages managed by the DOE, which contain naval SNF currently stored at INL, have disposal attributes unlike the smaller packages. R&D could include development and operation of appropriate test facilities that would support development and demonstration of technologies to transport large waste packages to repository depth (either by hoist or by inclined ramps), emplace them in the disposal region, and recover them if required. This would show demonstrable progress towards development of the capability to dispose of large canisters without requiring repackaging of naval SNF into smaller canisters, and would provide operational experience and data to support first-of-a-kind licensing of emplacement systems that exceed current capabilities and have not been used in regulated nuclear applications. As in the case of R&D for disposal of high thermal-output waste, results of this work would also support disposal of commercial SNF.

6 CONCLUSIONS

Two considerations lead to a recommendation that DOE pursue separate disposal options for some DOE-managed HLW and SNF. First, there are multiple viable options that could use technologies available today to dispose of the heterogeneous DOE-managed HLW and SNF. Second, there are potentially significant benefits from beginning a stepwise approach to disposing of the nation's HLW and SNF; such an approach could focus first on DOE-managed HLW and cooler DOE-managed SNF. Disposal of this HLW and SNF poses the fewest challenges, potentially allowing for a simpler repository design and licensing process, while helping meet DOE's environmental management goals and building confidence in waste management practices.

Specifically, this report recommends that the DOE begin implementation of a phased, adaptive, and consent-based strategy with development of a separate mined repository for some DOE-managed HLW and cooler DOE-managed SNF, potentially including some portion of the inventory of naval SNF. This report notes that, in addition to early development of a separate repository for cooler DOE-managed HLW and SNF, effective implementation of a strategy for management and disposal of all HLW and SNF would also include a focused research, development, and demonstration program addressing technologies relevant to deep borehole disposal of smaller DOE-managed waste forms and the disposal of large DOE-managed waste packages with high thermal loads in mined repositories.

Beginning with a separate repository for some DOE-managed wastes would be consistent with a phased, adaptive approach that has been endorsed by the National Academies and the Blue Ribbon Commission on America's Nuclear Future and is incorporated in the Administration's *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* (DOE 2013a). Focusing initially on DOE-managed HLW and the cooler DOE-managed SNF not of commercial origin could build greater confidence that HLW and SNF can be safely disposed of, and provide technical and institutional experience that could facilitate development of disposal capacity for the remainder of the inventory of HLW and SNF, including commercial SNF.

7 REFERENCES

40 CFR Part 191. Protection of Environment: Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes.

63 FR 27354. Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance With the Disposal Regulations: Certification Decision. May 18, 1998.

71 FR 18010. Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance With the Disposal Regulations: Recertification Decision. April 10, 2006.

75 FR 70584. Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance With the Disposal Regulations: Recertification Decision. November 18, 2010.

ANDRA (Agence nationale pour la gestion des déchets radioactifs [National Radioactive Waste Management Agency]) 2005. *Dossier 2005: Argile. Tome: Safety Evaluation of a Geological Repository*. Châtenay-Malabry, France: ANDRA.

Arnold, B.W.; P.V. Brady; S.J. Bauer; C. Herrick; S. Pye; and J. Finger 2011. *Reference Design and Operations for Deep Borehole Disposal of High–Level Radioactive Waste.* SAND2011-6749. Albuquerque, New Mexico: Sandia National Laboratories.

Brady, P.V.; B.W. Arnold; G.A. Freeze; P.N. Swift; S.J. Bauer; J.L. Kanney; R.P. Rechard; and J.S. Stein 2009. *Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2009-4401. Albuquerque, New Mexico: Sandia National Laboratories.

BMWi (Federal Ministry of Economics and Technology, Germany) 2008. *Final Disposal of High-Level Radioactive Waste in Germany—The Gorleben Repository Project.* Berlin, Germany: Federal Ministry of Economics and Technology (BMWi). Available at http://bmwi.de/EN/Service/search.html.

BRC (Blue Ribbon Commission on America's Nuclear Future) 2012. *Report to the Secretary of Energy*. http://brc.gov/sites/default/files/documents/brc_finalreport_jan2012.pdf

Carter, J., and Leduc, D. 2013. *Nuclear Fuels Storage and Transportation Planning Project Inventory Basis*. FCRD-NFST-2013-000263, Rev 0. Washington, DC: U.S. Department of Energy.

Carter, J.T.; A.J. Luptak; J. Gastelum; C. Stockman; and A. Miller 2012. *Fuel Cycle Potential Waste Inventory for Disposition*. FCRD-USED-2010-000031, Rev 5. Washington, DC: U.S. Department of Energy.

DOE (U.S. Department of Energy) 1983. *The Defense Waste Management Plan*. DOE/DP/0015. Washington, DC: U.S. Department of Energy.

DOE 1996. *Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant*. DOE/CAO 1996-2184. Carlsbad, New Mexico: Department of Energy Carlsbad Area Office.

DOE 2004. *Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2004*. DOE/WIPP 2004-3231. Carlsbad, New Mexico: Department of Energy Carlsbad Area Office.

DOE 2007. *General Description of Database Information Version 5.0.1.* DOE/SNF/REP-094, Rev. 1. National Spent Nuclear Fuel Program, Idaho National Laboratory, Idaho Falls, ID, prepared for the U.S. Department of Energy Office of Environmental Management.

DOE 2008a. *Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007 (July 2008)*. DOE/RW-0591. Washington, DC: U.S. Department of Energy, Office of Civilian Radioactive Waste Management.

DOE 2008b. *Yucca Mountain Repository License Application*. DOE/RW-0573, Rev.1. Washington, DC: U.S. Department of Energy, Office of Civilian Radioactive Waste Management.

DOE 2009. *Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2009*. DOE/WIPP-09-3424. Carlsbad, New Mexico: U.S. Department of Energy. http://www.wipp.energy.gov/Documents_EPA.htm.

DOE 2013a. *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste.* Washington, DC: U.S. Department of Energy.

DOE 2013b. *U.S. Department of Energy Nuclear Waste Fund Fee Adequacy Assessment Report, January 2013.* Washington, DC: U.S. Department of Energy.

DOE 2014. *Waste Isolation Pilot Plant Recovery Plan*. Revision 0. Washington, DC: U.S. Department of Energy.

Downey, G.L. 1985. "Politics and Technology in Repository Siting, Military versus Commercial Nuclear Wastes at WIPP 1972–1985." *Technology in Society*, *7* (1), 47–75. New York, New York: Elsevier.

GAO (U.S. Government Accountability Office) 2011. *DOE Nuclear Waste: Better Information Needed on Waste Storage at DOE Sites as a Result of Yucca Mountain Shutdown*. GAO-11-230. Washington, DC: Government Accountability Office.

Greenberg, M.R. 2009. "NIMBY, CLAMP, and the Location of New Nuclear-Related Facilities: U.S. National and 11 Site-Specific Surveys." *Risk Analysis*, *29* (9), 1242–1254. New York, New York: Plenum Press.

Greenberg, M.R. 2013. *Nuclear Waste Management, Nuclear Power and Energy Choices: Public Preferences, Perceptions and Trust*. New York, New York: Springer.

Hardin, E.; T. Hadgu; D. Clayton; R. Howard; H. Greenberg; J. Blink; M. Sharma; M. Sutton; J. Carter; M. Dupont; and P. Rodwell 2012. *Repository Reference Disposal Concepts and Thermal Load Management Analysis*. FCRD-UFD-2012-00219, Rev. 2. Washington DC: U.S. Department of Energy, Office of Used Nuclear Fuel Disposition.

Hardin, E.L.; D.J. Clayton; R.L. Howard; J.M. Scaglione; E. Pierce; K. Banerjee; M.D. Voegele; H.R. Greenberg; J. Wen; T.A. Buscheck; J.T. Carter; T. Severynse; and W.M. Nutt 2013. *Preliminary Report on Dual-Purpose Canister Disposal Alternatives (FY13).* FCRD-UFD-2013-000171 Rev. 1, Washington DC: U.S. Department of Energy, Office of Used Nuclear Fuel Disposition.

Jenkins-Smith, H.C.; C.L. Silva; K.G. Herron; S.R. Trousset; and R.P. Rechard 2012a. "Enhancing the Acceptability and Credibility of a Repository for Spent Nuclear Fuel." *The Bridge*, *42* (2), 49–58. Washington, DC: National Academy of Engineering.

Jenkins-Smith, H.C.; C.L. Silva; K.G. Herron; E. Bonano; and R.P. Rechard 2012b. "Designing a Process for Consent-Based Siting of Used Nuclear Fuel Facilities-Analysis of Public Support." *The Bridge*, *42* (3), 28–39. Washington, DC: National Academy of Engineering.

NAGRA (Nationale Genossenschaft für die Lagerung Radioactiver Abfälle [National Cooperative for the Disposal of Radioactive Waste]) 2002. *Project Opalinus Clay Safety Report: Demonstration Of Disposal Feasibility for Spent Fuel, Vitrified High-Level Waste and Long-Lived Intermediate-Level Waste (Entsorgungsnachweis)*. Technical Report 02-05. Wettingen, Switzerland: National Cooperative for the Disposal of Radioactive Waste.

National Research Council 2003. *One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste.* Washington, DC: National Academies Press.

NEA (Nuclear Energy Agency) 2004. *Stepwise Approach to Decision Making for Long-term Radioactive Waste Management: Experience, Issues, and Guiding Principles*. NEA 4429, Paris, France: Organisation for Economic Cooperation and Development.

NWMO (Nuclear Waste Management Organization) 2012. "Suspension of Expressions of Interest," backgrounder. Toronto, Canada: Nuclear Waste Management Organization. www.nwmo.ca/uploads_managed/MediaFiles/1918_suspensionofexpressionsofinterest_backgrounder.pdf

ONDRAF/NIRAS (Belgian Agency for Radioactive Waste and Enriched Fissile Materials) 2011. *Waste Plan for the Long-Term Management of Conditioned High-Level and/or Long-Lived Radioactive Waste and Overview of Related Issues*. NIROND 2011-02 E. Brussels, Belgium: ONDRAF/NIRAS.

Posiva Oy 2013. *Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto—Performance Assessment 2012*. POSIVA 2012-04. Eurajoki, Finland: Posiva Oy.

SKB (Svensk Kämbränslehantering AB [Swedish Nuclear Fuel and Waste Management Company]) 2011. *Long-Term Safety for the Final Repository for Spent Nuclear Fuel at Forsmark.* Technical Report TR-11-01. Three volumes. Stockholm, Sweden: Svensk Kärnbränslehantering AB.

SNL (Sandia National Laboratories) 2014. *Evaluation of Options for Permanent Geologic Disposal of Used Nuclear Fuel and High-Level Radioactive Waste Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy.* FCRD-UFD-2013-000371. SAND2014-0187P; SAND2014-0189P. Revision 1. Albuquerque, New Mexico: Sandia National Laboratories.

Stewart, R.B. and J.B. Stewart 2011. *Fuel Cycle to Nowhere: U.S. Law and Policy on Nuclear Waste*. Nashville, Tennessee: Vanderbilt University Press.

Wagner, J.C.; J.L. Peterson; D.E. Mueller; J.C. Gehin; A. Worral; T. Taiwo; M. Nutt; M.A. Williamson; M. Todosow; R. Wigeland; W.G. Halsey; R.P. Omberg; P.N. Swift; and J.T. Carter 2012. *Categorization of Used Nuclear Fuel Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy*. ORNL/TM-2012/308. FCRD-FCT-2012-000232. Oak Ridge, Tennessee; Oak Ridge National Laboratory.

[This page left blank.]