U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

EVALUATION OF THE U.S. DEPARTMENT OF ENERGY RESEARCH AND DEVELOPMENT ACTIVITIES ON THE DISPOSITION OF COMMERCIAL SPENT NUCLEAR FUEL IN DUAL-PURPOSE CANISTERS

A REPORT TO THE U.S. CONGRESS AND THE SECRETARY OF ENERGY

February 2024

U.S. Nuclear Waste Technical Review Board

EVALUATION OF THE U.S. DEPARTMENT OF ENERGY RESEARCH AND DEVELOPMENT ACTIVITIES ON THE DISPOSITION OF COMMERCIAL SPENT NUCLEAR FUEL IN DUAL-PURPOSE CANISTERS

A Report to the U.S. Congress and the Secretary of Energy

February 2024

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201-3367

February 2024

The Honorable Mike Johnson
Speaker
United States House of Representatives
Washington, DC 20515

The Honorable Patty Murray
President Pro Tempore
United States Senate
Washington, DC 20510

The Honorable Jennifer Granholm
Secretary
U.S. Department of Energy
Washington, DC 20585

Dear Speaker Johnson, Senator Murray, and Secretary Granholm:

Congress created the U.S. Nuclear Waste Technical Review Board in the Nuclear Waste Policy Amendments Act of 1987 (NWPAA) (Public Law 100-203) to evaluate the technical and scientific validity of activities undertaken by the Secretary of Energy to implement the Nuclear Waste Policy Act. In fulfilling this mandate, the Board has completed an evaluation of the U.S. Department of Energy (DOE) research and development (R&D) activities related to the disposition of commercial spent nuclear fuel (SNF) stored inside U.S. Nuclear Regulatory Commission (NRC) approved dry-storage casks at independent spent fuel storage installations (ISFSIs). The Board's observations, findings, and recommendations are presented in this report to Congress and the Secretary of Energy titled *Evaluation of the U.S. Department of Energy Research and Development Activities on the Disposition of Commercial Spent Nuclear Fuel in Dual-Purpose Canisters*.

In the United States, commercial SNF is stored at more than 70 sites and continues to be generated at a rate of more than 2,200 metric tons of heavy metal per year. Much of the SNF inventory has been stored inside large, welded canisters known as dual-purpose canisters (DPCs) at ISFSIs associated with nuclear power plants. These DPCs have been designed for interim storage and transportation, but not for geologic disposal. The storage of SNF in DPCs will have significant implications for later stages of the SNF management and disposal system, for which DOE is responsible.

The Board's report examined three alternative approaches for managing commercial SNF stored in dry-storage casks, namely: (i) storing SNF at ISFSIs indefinitely, with none transported to a repository site or a consolidated interim storage facility, (ii) repackaging the SNF into smaller canisters prior to disposal in a geologic repository, and (iii) direct disposal of SNF in DPCs in a

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repository. Based on the information and findings developed in the report, the Board makes three recommendations:

1. *The Board recommends that DOE give higher priority to refining its systems analysis tools and completing comprehensive analyses that address issues (1) and (2) in Finding 1 (as well as the other variables and complexities noted in this report):*

    (1) *The implications (time, effort, and cost) of identifying and finding a resolution for commercial SNF canisters approved by the NRC for storage, but which include contents not currently approved by the NRC for transportation.*

    (2) *The implications for the design, construction, and operation of a geological repository of disposing of SNF in large DPCs versus disposing of SNF repackaged into smaller canisters, with a particular focus on waste package degradation, thermal management, postclosure criticality, and the engineering aspects of waste package emplacement in various rock types.*

    By doing so, decision-makers would be better informed of the pros and cons of the alternative approaches for implementing an integrated waste management system and better prepared to adopt one or a combination of alternative approaches that would be the most effective and efficient for the nationwide program.

2. *The Board recommends that DOE address the points related to modeling steady-state and transient criticality events noted in Finding 2b, in Section 4.2.1.1 of this report, regarding the ongoing consequence analysis of postclosure criticality.*

3. *The Board recommends that DOE establish a set of criteria for evaluating the various options for modifying fuel assemblies and baskets for DPCs to be loaded in the future. Using these criteria, DOE should assess the various options to determine the R&D priorities. In developing the criteria and in evaluating the various options, DOE consultation with fuel owners and cask vendors is recommended to gain industry insights on and acceptance of potential DPC modifications.*

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

Sincerely,

Nathan Siu
Chair

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ABBREVIATIONS AND ACRONYMS

BWR	boiling water reactor
CFR	Code of Federal Regulations
CSFP	Commercial Spent Fuel Projection tool
DOE	U.S. Department of Energy
DPC	dual-purpose canister
EPRI	Electric Power Research Institute, USA
GDSA	Geologic Disposal Safety Assessment
HBF	high burnup spent nuclear fuel
HLW	high-level radioactive waste
IAEA	International Atomic Energy Agency
ISFSI	independent spent fuel storage installation
MPC	multi-purpose canister
MTHM	metric ton of heavy metal
NGSAM	Next Generation System Analysis Model
NRC	U.S. Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
NWPAA	Nuclear Waste Policy Amendments Act of 1987
NWTRB	U.S. Nuclear Waste Technical Review Board (Board)
PASO	Performance Assessment of Strategy Options Model
PWR	pressurized water reactor
R&D	research and development
SNF	spent nuclear fuel
SNL	Sandia National Laboratories, USA
UNF-ST&DARDS	Used Nuclear Fuel Storage, Transportation & Disposal Analysis Resource and Data System

EXECUTIVE SUMMARY

Congress established the U.S. Nuclear Waste Technical Review Board (Board) in the Nuclear Waste Policy Amendments Act of 1987 (NWPAA)[1] and charged it to "...evaluate the technical and scientific validity of activities undertaken by the Secretary [of Energy], including…activities relating to the packaging or transportation of high-level radioactive waste or spent nuclear fuel." As recorded in the legislative history of the NWPAA, the Board is also to provide independent expert advice to Congress and the Secretary of Energy on technical and scientific issues related to the management and disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW).

In the United States, commercial SNF is stored at more than 70 sites and continues to be generated at a rate of more than 2,200 metric tons of heavy metal per year.[2] Much of the commercial SNF inventory has been stored inside dry-storage casks at independent spent fuel storage installations (ISFSIs) associated with nuclear power plants because the spent fuel pools at the plants do not have the storage capacity to accommodate all the SNF discharged from the reactors. As of June 1, 2023, almost 4,000 dry-storage casks are in service at ISFSIs.[3] This number is projected to increase to about 10,000 by 2080 when all SNF discharged from nuclear power plants will be transferred from spent fuel pools into dry storage.[4,5] In the absence of a clearly defined disposition pathway for commercial SNF (i.e., disposal in a geologic repository), long-term dry storage has become the de facto SNF management program in the United States for the foreseeable future.

The design of most dry-storage casks relies on large, welded canisters[6] known as dual-purpose canisters (DPCs). These DPCs have been designed for interim storage and transportation, but not for their potential use for geologic disposal. The storage of SNF in DPCs and the trend toward larger DPCs will have significant implications for the later stages of the SNF management and disposal system, for which the U.S. Department of Energy

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[1] Public Law 100-203, Title V, Subtitle A. December 22, 1987.

[2] Freeze, G., E.J. Bonano, P. Swift, E. Kalinina, E. Hardin, L. Price, S. Durbin, R. Rechard, and K. Gupta. 2021. *Integration of the Back End of the Nuclear Fuel Cycle*. SAND2021-10444. Albuquerque, New Mexico: Sandia National Laboratories. August.

[3] UxC. 2023. *StoreFUEL and Decommissioning Report*. Vol. 25, No. 298. June 6, 2023. Roswell, GA: UxC, LLC.

[4] Freeze et al. *Integration of the Back End of the Nuclear Fuel Cycle*.

[5] The projected 10,000 dry-storage casks by 2080 accounts for SNF that have been or would be discharged from reactors that were shut down or operating as of the end of 2020 and assumes no new nuclear power reactors are constructed and operated. See footnote 86 for other assumptions used in the analysis.

[6] A number of different terms are used in the commercial nuclear industry, and by the U.S. Department of Energy, to refer to the large engineered systems used for dry storage of SNF. Apart from when differences in the designs of these systems make it necessary to distinguish between them, or it is necessary to refer to specific system components, this report uses the term "dry-storage cask" generically to refer to any of these systems and the term "canister" to refer to the welded internal system component that contains the SNF in many of these systems. Appendix A explains the terminology used in this report for SNF containers.

(DOE) is responsible. The size and weight of the casks in which the canisters are stored and transported, and the overpacks into which they will be loaded for disposal, may present physical handling challenges for emplacement in a repository. The higher fissile content, radiation level, and heat output of larger DPCs may present challenges for both transportation and emplacement in a repository. There may also be additional implications for repository performance, including the potential for and consequences of criticality events[7] that might occur during the postclosure period from lack of inclusion of long-lived materials in DPCs that prohibit criticality. The degradation rate of engineered barriers during the postclosure period could also be higher due to the increased temperatures resulting from the higher heat output of larger DPCs. On the other hand, repackaging the SNF from large canisters into smaller canisters prior to transportation or disposal would require additional fuel handling operations, with the potential for increasing the radiation dose to operations personnel, inadvertent damage to the SNF, and/or generating large quantities of low-level radioactive waste.

This report presents a historical context of how the nation's commercial SNF came to be stored in DPCs and examines three alternative approaches for managing commercial SNF: (1) storing SNF at ISFSIs indefinitely,[8] (2) repackaging the SNF into smaller canisters before disposal, and (3) direct disposal of SNF in DPCs in a geologic repository. The report discusses the implications of each alternative approach and presents the Board's observations, findings, and recommendations regarding these alternatives. Among these three alternatives, recent DOE research and development (R&D) has been focused largely on direct disposal of SNF in DPCs. Therefore, the Board has also focused its review on this alternative. Chapter 4 of this report documents the Board's evaluation of DOE's R&D on direct disposal of SNF in DPCs and provides the Board's observations, findings, and recommendations on those activities.

Alternative Approaches for the Management of Commercial Spent Nuclear Fuel and DOE Research on Direct Disposal of Spent Nuclear Fuel in Dual-Purpose Canisters

As discussed above, there are three possible alternatives for managing commercial SNF, and simplified descriptions of the alternatives are provided here (more detailed descriptions can be found in the main body and appendices of this report). One alternative is to store the SNF at ISFSIs indefinitely, with none transported to a repository site or a consolidated interim storage facility[9] for the foreseeable future. This approach would be employed in the case of a

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[7] A nuclear criticality event refers to an unintended and potentially hazardous situation that occurs when a mass of fissile material, such as uranium or plutonium, reaches a critical state. In this context, "critical" means that there is a self-sustaining chain reaction of nuclear fission taking place, which could result in the release of a significant amount of energy in the form of heat, radiation, and potentially explosive force.

[8] For the purposes of this report, "indefinite" storage means storage for more than 80–120 years.

[9] Under the NWPA, a monitored retrievable storage facility is to be designed, constructed, and operated by DOE. However, NRC also licenses consolidated interim storage facilities, which can be designed, constructed, and operated by a private commercial entity. For the purposes of this report, the term "consolidated interim storage facility" means a DOE monitored retrievable storage facility, a commercial storage facility, or both.

long (or indefinite) delay in the development of a deep geologic repository, a consolidated interim storage facility, or both. A second alternative is repackaging the SNF from existing dry-storage casks into new SNF canisters, which would involve unloading the SNF from a dry-storage cask and loading it into a new, typically smaller, canister. The repackaging operation may be performed at a nuclear power plant site, an interim storage facility, or a repository site and may be performed in a spent fuel pool or dry transfer facility. A third approach is direct disposal in a geologic repository of the SNF in DPCs. In this alternative, DOE would transport SNF in welded DPCs directly from SNF storage locations to a repository site for disposal without repackaging the SNF into smaller standardized canisters or into disposal canisters. Intermediate storage of the DPCs at one or more consolidated interim storage facilities may also be considered as part of this alternative.

DOE R&D activities related to direct disposal of SNF in DPCs currently focus on three areas: (1) the consequences of potential criticality events on the long-term performance of a geologic repository after closure; (2) potential filler materials that could be injected as liquids into existing DPCs, where they solidify and prevent groundwater ingress into breached DPCs and thereby reduce the probability for nuclear criticality; and (3) modifications to future DPCs so they will remain subcritical in any repository setting.[10]

Board Observations, Findings, and Recommendations

Based on reviews of DOE documents, fact-finding meetings with national laboratory and DOE personnel, and the presentations and discussions at Board public meetings, the Board makes the following observations, findings, and recommendations.

Alternative Approaches for the Management of Commercial Spent Nuclear Fuel

DOE has examined, in a variety of past evaluations, the pros and cons of each of the three alternative approaches and has developed a number of useful analysis tools well-suited for these types of evaluations. The Board observes that while DOE's past evaluations have been informative, none has been fully comprehensive in considering all of the advantages and disadvantages of each alternative. The Board recognizes that DOE is aware of the issues that need to be addressed and commends DOE for working to address those issues in its integrated waste management and disposal R&D programs.

The Board observes that DOE has in place the proper tools to evaluate the alternative approaches for implementing an integrated waste management system (e.g., tools such as Next Generation System Analysis Model [NGSAM] and Performance Assessment of Strategy Options Model [PASO]) and to evaluate different repository concepts (e.g., the Geologic Disposal Safety Assessment [GDSA] Framework).

The Board commends DOE for supporting the development of systems analysis tools and encourages the continued refinement and application of those tools. The Board observes that

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[10] Sassani, D., J. Birkholzer, R. Camphouse, G. Freeze, and E. Stein. 2021. *SFWST Disposal Research R&D 5-Year Plan – FY2021 Update*. SAND2021-12491 R. Albuquerque, New Mexico: Sandia National Laboratories. August.

more work is necessary to focus the systems analysis tools on several key issues, as identified below, in order to advance meaningful comparative analyses.

Finding 1: The Board finds that DOE has not fully analyzed, in an integrated manner, all the key aspects of the alternative approaches for managing commercial SNF such that a meaningful comparison of the alternatives can be made. Particular issues that need to be addressed include:

(1) The implications (time, effort, and cost) of identifying and finding a resolution for commercial SNF canisters approved by the NRC for storage, but which include contents not currently approved by the NRC for transportation.

(2) The implications for the design, construction, and operation of a geological repository of disposing of SNF in large DPCs versus disposing of SNF repackaged into smaller canisters, with a particular focus on waste package degradation, thermal management, postclosure criticality, and the engineering aspects of waste package emplacement in various rock types.

Recommendation 1: *The Board recommends that DOE give higher priority to refining its systems analysis tools and completing comprehensive analyses that address issues (1) and (2) in Finding 1, as well as the other variables and complexities noted in this report. By doing so, decision-makers would be better informed of the pros and cons of the alternative approaches for implementing an integrated waste management system and better prepared to adopt one or a combination of alternative approaches that would be the most effective and efficient for the nationwide program.*

Criticality Consequence Analysis

The Board observes that the work DOE has completed to date can be characterized as preliminary with the objective of gathering sufficient information so that the scope of future analyses can be defined with increased confidence. DOE examined two hypothetical repositories—a saturated repository in shale and an unsaturated repository in alluvium—with regard to changes in isotopic composition, dose consequences, and material property alterations resulting from hypothesized steady-state criticality events. For hypothesized prompt critical transient events, the total energy released, fuel and coolant temperatures, and coolant quality in the two repositories were evaluated.

Finding 2a: The Board finds that sufficient work has been completed to define the path forward regarding analyzing hypothesized postclosure criticality events. There is now sufficient information to determine going forward what simulation codes to be used in the analyses, events to be analyzed, and the parameters of interest to evaluate.

Finding 2b: However, the Board finds that some of the DOE-sponsored evaluations of postclosure criticality may be based on assumptions that are not fully supportable, and some of the codes used in the criticality consequence analyses may not be appropriate. (See Section 4.2.1.1)

***Recommendation 2**: The Board recommends that DOE address the points noted in Finding 2b in Section 4.2.1.1 of this report regarding the ongoing consequence analysis of postclosure criticality.*

Development and Testing of Dual-Purpose Canister Fillers

The Board observes that DPC filling experiments cannot be done on all possible canister designs and fuel loadings. Thus, computational simulations are required to enable predicting canister filling and filler material solidification. The Board encourages DOE to continue with the development and validation of computational capabilities that can be used for predicting canister filling and solidification of DPC fillers (both metal alloys and phosphate-based cements) for the range of canister designs and fuel loadings.

The Board observes that filler materials, especially metal/metal alloy fillers, can add significant weight to DPCs. With filling completed at the repository site, the added weight to the DPCs will only impact repository handling of the DPCs, which could be significant. The Board acknowledges that DOE intends to seek solutions to issues that may arise, if any, due to the added weight from DPC fillers. The Board remains interested in this topic and looks forward to reviewing DOE’s progress in the future.

The Board also observes that using fillers for DPCs and the facilities that would implement the technology would require approval by the NRC. The Board acknowledges that DOE has taken steps to identify the regulatory considerations for the use of fillers to facilitate direct disposal of SNF in DPCs, including developing a high-level concept of operations report that could be used in future interactions with NRC.

Modification of Dual-Purpose Canisters to be Loaded in the Future

The Board observes that DOE is examining several options for modifying fuel assemblies and baskets for DPCs to be loaded to reduce the probability of criticality after the closure of a repository when waste packages may have been breached and flooding with groundwater may have occurred. These options include specialized control rods in pressurized water reactor assemblies going to disposal, control rods and fuel rechanneling in boiling water reactor assemblies, absorber plate replacements, chevron absorber inserts, zone loading of canisters, and rod consolidation.

Finding 3: The Board finds that a set of criteria needs to be developed for use in assessing the various options for modifying fuel assemblies and baskets for DPCs to be loaded in the future and in prioritizing R&D activities. The criteria could include (1) how rapidly each option could be implemented in practice, (2) how many DPCs to be loaded in the future potentially could benefit, (3) the associated cost of implementation of each option per DPC, and (4) the criticality prevention effectiveness of each option.

***Recommendation 3:** The Board recommends that DOE establish a set of criteria to evaluate the various options for modifying fuel assemblies and baskets for DPCs to be loaded in the future. Using these criteria, DOE should assess the various options to determine R&D priorities. In developing the criteria and in evaluating the various options, the Board* *recommends DOE consultation with fuel owners and cask vendors to gain industry insights on and acceptance of potential DPC modifications.*

1. INTRODUCTION

Congress established the U.S. Nuclear Waste Technical Review Board (Board) in the Nuclear Waste Policy Amendments Act of 1987 (NWPAA)[11] and charged it to "...evaluate the technical and scientific validity of activities undertaken by the Secretary [of Energy], including…activities relating to the packaging or transportation of high-level radioactive waste or spent nuclear fuel." As recorded in the legislative history of the NWPAA, the Board is also expected to provide independent expert advice to Congress and the Secretary of Energy on technical and scientific issues related to the management and disposal of spent nuclear fuel (SNF)[12] and high-level radioactive waste (HLW).[13]

1.1 Background

In the United States, commercial SNF is stored at more than 70 sites, including operating and decommissioned nuclear power plant sites, and continues to be generated at a rate of more than 2,200 metric tons of heavy metal per year (Freeze et al. 2021). Much of the SNF has been stored inside dry-storage casks at independent spent fuel storage installations (ISFSIs)[14] because the spent fuel pools at nuclear power plants do not have the storage capacity to accommodate all the SNF discharged from the reactors. As of June 1, 2023, almost 4,000 dry-storage casks are in service at ISFSIs (UxC 2023a). This number is projected to increase to about 10,000 by 2080, when all SNF discharged from nuclear power plants will have been transferred from spent fuel pools into dry storage (Freeze et al. 2021).[15] The design of most

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[11] Public Law 100-203, Title V, Subtitle A. December 22, 1987.

[12] Nuclear fuel reaches the end of its useful life for the production of electricity after between three and five years of operation in a nuclear power plant. At that point, it is discharged from the nuclear power plant and is referred to as SNF. After discharge from the nuclear power plant, SNF is intensely radioactive and continues to produce heat through the radioactive decay of fission products and actinides, so it must be stored in a way that provides cooling and shielding to protect operations staff and sensitive plant components. (See the Board fact sheet on Commercial Spent Nuclear Fuel.) Spent nuclear fuel is also referred to as "used nuclear fuel."

[13] HLW is produced when SNF is processed to recover some or all of the contents for recycling or other purposes. Like SNF, it produces heat and is radioactive, so it must be stored in a way that provides cooling and shielding. Then it must be processed into a durable waste form, such as borosilicate glass, for permanent disposal in a geologic repository. (See the Board's fact sheets on Spent Nuclear Fuel and High-Level Radioactive Waste in the United States and Vitrified High-Level Radioactive Waste on the Board's website www.NWTRB.gov.) The management and disposal of HLW are not considered in this report.

[14] An ISFSI is a facility that is designed and constructed for the interim storage of SNF; solid, reactor-related, greater-than-Class-C waste; and other associated radioactive materials. An ISFSI may be considered independent even if it is located on the site of another facility licensed by the U.S. Nuclear Regulatory Commission (NRC 2021a).

[15] The projected 10,000 dry-storage casks by 2080 account for SNF that have been or would be discharged from reactors that were shut down or operating as of the end of 2020 and assume no new nuclear power reactors are constructed and operated. See footnote 86 for other assumptions used in the analysis.

dry-storage casks relies on large, welded canisters[16] known as dual-purpose canisters (DPCs). These DPCs have been designed for interim storage and transportation, but not for their potential use for geologic disposal (Freeze et al. 2021).

The Board has long recognized that the storage of SNF in DPCs by nuclear utilities[17] could have significant implications for later stages of the SNF management and disposal system (Garrick 2012). If SNF is to be disposed of in these large dry-storage canisters,[18] the size and weight of the casks in which the canisters are stored and transported and the overpacks into which they will be loaded for disposal may present physical (handling) challenges for emplacement in a repository. The higher fissile content, radiation level, and heat output of larger DPCs may present challenges for transportation and emplacement in a repository and additional implications for repository performance, including the potential for and consequences of criticality events[19] that might occur during the postclosure period due to the lack of inclusion of long-lived materials in DPCs that prohibit criticality. The degradation rate of engineered barriers during the postclosure period also could be higher due to the increased temperatures resulting from the higher heat output of larger DPCs. On the other hand, repackaging the SNF from large canisters into smaller canisters prior to transportation or disposal would require additional fuel handling operations, with the potential for additional radiation doses to operations personnel, inadvertent damage to the SNF, increasing the cost, and/or generating large quantities of low-level radioactive waste.

To explore the impacts of using DPCs on the future handling, storage, transportation, and geologic disposal of SNF in the United States, the Board held a workshop in November 2013 in Washington, DC.[20] that explored potential technical issues associated with (1) the direct

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[16] A number of different terms are used in the commercial nuclear industry and by DOE to refer to the large engineered systems used for dry storage of SNF. Unless differences in the designs of these systems make it necessary to distinguish between terms, or it is necessary to refer to specific system components, this report uses the term “dry-storage cask” generically to refer to any of these systems and the term “canister” to refer to the welded internal system component that contains the SNF in many of these systems. Appendix A explains the terminology used in this report for SNF containers.

[17] Not all nuclear power plant operators in the United States are utilities. For simplicity, this report uses the term “utility” to refer to all operators of nuclear power plants.

[18] DPCs are typically between 5 and 6 ft [between 1.5 and 1.8 m] in diameter, between 15 and 16 ft [between 4.6 and 5.0 m] in length, and, when loaded with SNF, weigh between 38 and 58 tons [between 34 and 53 metric tons] (Carter et al. 2016).

[19] A nuclear criticality event refers to an unintended and potentially hazardous situation that occurs when a mass of fissile material, such as uranium or plutonium, reaches a critical state. In this context, “critical” means a self-sustaining chain reaction of nuclear fission taking place, which could result in the release of a significant amount of energy in the form of heat, radiation, and potentially explosive force.

[20] The workshop on “The Implications of the Use of Large Dry-Storage Canisters for the Future Handling, Storage, Transportation, and Geologic Disposal of Spent Nuclear Fuel” was held on November 18-19, 2013. The agenda and presentations, plus a transcript of the discussion at the workshop, can be found on the Board’s website at http://www.nwtrb.gov/meetings/past-meetings/2013-board-technical-workshop. A summary of the main points from the workshop and the issues identified can also be found there.

disposal[21] of SNF in DPCs in a deep geologic repository and (2) the repackaging of SNF from DPCs into different containers for transport and/or disposal. Also in 2013, the U.S. Department of Energy (DOE) began research activities related to the potential direct disposal of SNF in DPCs. At a Board public meeting held in October 2018,[22] representatives from DOE and the national laboratories summarized DOE's evaluation of the technical feasibility of direct disposal of SNF in DPCs. The recommendations that came out of that evaluation and the planned research and development (R&D) activities to address some of the recommendations were described (Gunter and Hardin 2018). At a July 2020 Board public meeting,[23] the Board heard presentations from DOE and national laboratory staff on the results of those R&D activities. More recently, at a Board public meeting held in March 2022,[24] DOE and national laboratory staff provided an update on DOE's R&D activities related to the direct disposal of SNF in DPCs, in particular repository-scale evaluations that take account of hypothesized criticality events in a repository during the postclosure period. DOE's R&D on direct disposal of SNF in DPCs is discussed in Section 4.

1.2 About the Report

This report presents a historical context of how the nation's commercial SNF came to be stored in DPCs. The report then examines the following three alternative approaches to managing commercial SNF as the basis for considering the implications of the direct disposal of SNF in DPCs and the repackaging of the SNF into smaller canisters for transportation or disposal:

- Storing SNF at ISFSIs indefinitely, with none transported to a repository site or a consolidated interim storage facility.[25]
- Repackaging SNF into smaller canisters before disposal.
- Direct disposal of SNF in DPCs in a geologic repository.

The report then summarizes DOE's R&D activities related to the direct disposal of SNF in DPCs based on the presentations and discussions at the Board's public meetings and follow up discussions, as well as from reports published by DOE and others (see References

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[21] The term "direct disposal" is used in this report to refer to the geologic disposal of SNF in a dry-storage canister without needing to be repackaged to meet transportation regulations or repository limitations.

[22] The agenda, presentations, and transcript of the October 24, 2018, meeting held in Albuquerque, New Mexico, can be found on the Board's web site at https://www.nwtrb.gov/meetings/past-meetings/fall-2018-board-meeting---october-24-2018.

[23] The agenda, presentations, and transcript of the meeting held virtually on July 27-28, 2020, can be found on the Board's website at https://www.nwtrb.gov/meetings/past-meetings/summer-2020-board-meeting.

[24] The agenda, presentations, and transcript of the meeting held virtually on March 1-2, 2022, can be found on the Board's website at https://www.nwtrb.gov/meetings/past-meetings/winter-2022-board-virtual-meeting---march-1-2-2022.

[25] Under the NWPA, a monitored retrievable storage facility is to be designed, constructed, and operated by DOE. However, NRC also licenses consolidated interim storage facilities, which can be designed, constructed, and operated by a private commercial entity. For the purposes of this report, the term "consolidated interim storage facility" means a DOE-monitored retrievable storage facility, a commercial storage facility, or both.

section). Further, the report presents the Board's observations, findings, and recommendations regarding those R&D activities.

While the report is focused on commercial SNF, the Board notes that some of the issues related to storage and direct disposal or repackaging also apply to DOE-managed SNF and other SNF that is stored at DOE sites. The Board report "Management and Disposal of U.S. Department of Energy Spent Nuclear Fuel" (NWTRB 2017) discusses issues related to the SNF stored at DOE sites.

This report does not make recommendations concerning the disposition path to be followed for commercial SNF, but it does recommend actions that could be taken to better assess and clarify the advantages and disadvantages of the different alternatives for managing commercial SNF. Any decision about the management and disposal of commercial SNF will necessarily involve policy and other non-technical considerations, which are beyond the Board's NWPAA mandate. This report is intended to offer recommendations to DOE and to inform U.S. policy makers as they make the critical decisions that will be required in developing a national program for the management and disposal of SNF and HLW.

2. HISTORICAL CONTEXT

In the 1960s and early 1970s, the first commercial nuclear power plants were constructed in the United States with the expectation that spent nuclear fuel (SNF) would be reprocessed,[26] enabling the recovered uranium and plutonium to be recycled into new fuel. Furthermore, it was envisioned that SNF would be taken away from the nuclear power plant sites within a few years of its discharge from the reactor for reprocessing. For these reasons, the SNF storage pools at the nuclear power plant sites were sized to accommodate SNF discharged over typically less than ten years.[27] In 1977, however, a change in U.S. government policy prohibited further reprocessing of commercial SNF.[28] In the 1980 *Environmental Impact Statement on Management and Disposal of Commercially Generated Radioactive Wastes*, DOE proposed the adoption of a national strategy to develop mined geologic repositories for disposal of commercially generated SNF and HLW and the conduct of an R&D program to develop such facilities (DOE 1980). In 1983, Congress passed the Nuclear Waste Policy Act (NWPA),[29] which assigned DOE the responsibility to site, build, and operate a deep geologic repository for the disposal of SNF and HLW.

The change in policy necessarily meant that SNF would remain at the nuclear power plant sites for much longer periods than previously envisioned. Initially, the operating utilities increased the on-site SNF storage capacity by replacing the racks in which the SNF was stored within the pools with racks of more advanced design that allowed denser SNF spacing. However, it was clear that SNF would eventually need to be removed from the pools, and the utilities started to consider construction of additional storage capacity. This eventually led to the development of dry cask storage systems, which are certified by the U.S. Nuclear Regulatory Commission (NRC) and stored at on-site ISFIs, which are licensed by NRC. The modular nature of dry cask storage at ISFSIs offered the possibility of increasing on-site storage capacity as needed without committing to the sort of major construction project that would be required to provide additional pool storage capacity. The first dry cask storage systems were put into operation at the Surry Nuclear Power Station in Virginia in 1986 (National Research Council 2006).

After the 1983 passage of the NWPA, DOE entered into contracts with the operators of commercial nuclear power plants for acceptance of SNF starting in 1998 and transportation of SNF to a federal storage facility or a repository site. There was reasonable confidence at

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[26] Reprocessing refers to the chemical separation of fissionable uranium and plutonium from SNF.

[27] In addition to the capacity required to store SNF until it is transported away from the site for reprocessing or disposal, utilities are also required to maintain enough capacity in the fuel storage pool to accommodate all of the fuel in the reactor, in case this is needed for routine operations or in the event of any problem requiring defueling of the reactor.

[28] On April 7, 1977, President Carter announced, "…we will defer indefinitely the commercial reprocessing and recycling of plutonium produced in the U.S. nuclear power programs." He vetoed S. 1811, the Energy Research and Development Administration Authorization Act of 1978, which was intended to provide the legislative authorization necessary for constructing a breeder reactor and a reprocessing facility (Andrews 2008).

[29] Public Law 97-425; 96 Stat. 2201. January 7, 1983.

that time that the use of dry cask storage systems would be limited to a relatively small number of sites for a limited period of time, and there was neither the requirement, nor the justification for designing new casks specifically for storage. Accordingly, the dry-storage casks[30] initially used for on-site storage had designs based closely on that of transport casks, with bolted lids and additional seals. At that time, the initial NRC licenses for ISFSIs and NRC certifications for storage casks were for twenty years.[31] The utilities that loaded the early dry-storage casks accepted that the SNF would have to be unloaded from the casks in the spent fuel pools of the nuclear power plants and loaded into transport casks for shipment to a repository site. However, with the bolted lids of the storage casks being loaded at that time and the limited number of casks expected to be used, the utilities did not foresee that the transfer of the SNF from storage casks to transport casks would have a significant impact on normal plant operations.

Since the NWPA was passed, the timescale for transporting SNF from nuclear power plant sites to a repository site has slipped considerably. By 2008, when DOE submitted the license application to the NRC for construction of a repository at the Yucca Mountain site, the earliest the utilities expected to see SNF being transported from their sites had moved to 2020, the year the repository was due to start operations. However, in 2010, DOE stopped work on the Yucca Mountain repository project. Since then, no schedule for transporting SNF from nuclear power plant sites has been defined.

As the timescale for SNF removal from nuclear power plant sites slipped, the nuclear utilities' view of dry storage changed. Instead of a short-term requirement at just a few sites, dry storage became generally accepted as a longer-term solution that would eventually be required at most, if not all, sites.[32] Both the cask vendors and the utilities saw justification for investing in the development of casks intended specifically for storage—and for much longer than the 20 years originally expected to be required. From the cask vendors' perspective, the justification was based on the projection of a large market for storage casks. From the utilities' perspective, there was an expectation that, in developing the design of new casks for storage, the cask vendors would introduce features resulting in significant reductions in both storage costs and the impact on the operation of their power plants.

Three modifications introduced into the designs of dry-storage casks intended for long-term storage are particularly relevant to this report. First, the capacities of the casks being loaded

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[30] As indicated in footnote 6, this report uses the term "dry-storage cask" generically to refer to any of the large engineered systems used for dry storage of SNF and uses the term "canister" to refer to the welded internal system component that contains the SNF in many of the dry storage systems.

[31] Currently, initial licenses for dry-storage facilities can be approved by NRC for periods of up to 40 years with options to renew in up to 40-year increments (10 CFR Part 72.42).

[32] As of January 2022, ISFSIs are in operation at all reactor sites with the exception of the Shearon Harris site in New Hill, North Carolina (UxC 2022). The Shearon Harris Nuclear Power Plant will not require dry storage of SNF because it has sufficient storage capacity in its spent fuel pools through the expiration of its renewed operating license in 2046 (Peters et al. 2022; UxC 2022).

by utilities today are often twice the capacity of the early casks.[33] Unless SNF is repackaged into smaller casks to meet either transportation or disposal requirements, this has significant implications in terms of requiring the handling of large, heavy loads at all stages of the SNF management program and meeting the temperature and radiation limits and criticality safety requirements during transportation and, possibly, disposal. Second, in order to reduce the cost of dry storage, the design was changed so that most dry-storage casks comprise two components, an inner canister and an outer overpack. Third, in order to reduce maintenance requirements, the canisters into which the SNF is loaded are now closed by seal-welding. As noted above, the original dry-storage casks had bolted lids, which required both periodic monitoring of the pressure of the gas inside the cask and periodic replacement of the lid seals. Changing the design so that the SNF is loaded into a canister that is welded closed removes both of these maintenance requirements, although it has significant implications if the SNF needs to be repackaged.

With the lengthening timescale during which SNF will need to be in dry storage at nuclear power plant sites, the utilities have sought to increase the allowed duration of SNF dry storage at ISFSIs. To support this longer storage duration, significant R&D work has been undertaken by DOE and the NRC, as well as by commercial organizations in the United States and governmental organizations in other countries (e.g., Bryan et al. 2021, 2022; EPRI 2014; IAEA 2015; Larson 2022; Martínez et al. 2022; McManniman 2022; Saltzstein et al. 2020; Sanborn 2022; Vlassopoulos 2022; Waldrop et al. 2019). Based on increased confidence that any degradation of SNF and the dry-storage cask components will be limited during extended storage periods, the NRC has indicated it will be prepared to approve requests for initial licenses for dry-storage facilities for periods of 40 years, with the possibility of renewing the license in up to 40-year increments.[34] The NRC evaluated the environmental impacts of continued storage for periods of up to 160 years, and possibly even longer.[35] The ISFSIs for which licenses have been approved by the NRC as of June 2023 are shown in Figure 1.

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[33] Currently, the largest DPCs can hold 37 pressurized-water reactor assemblies or 89 boiling water reactor assemblies.

[34] Title 10 of the Code of Federal Regulations, Part 72.42.

[35] NUREG-2157, "Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel" (NRC 2014) analyzes three timeframes that represent potential storage periods before SNF is sent to a repository: (1) a short-term timeframe, which includes 60 years of continued storage after the end of a reactor's operating lifetime; (2) an additional 100-year timeframe (i.e., 60 years plus 100 years) to address the potential for delay in repository availability; and (3) an indefinite timeframe to address the possibility that a repository never becomes available.

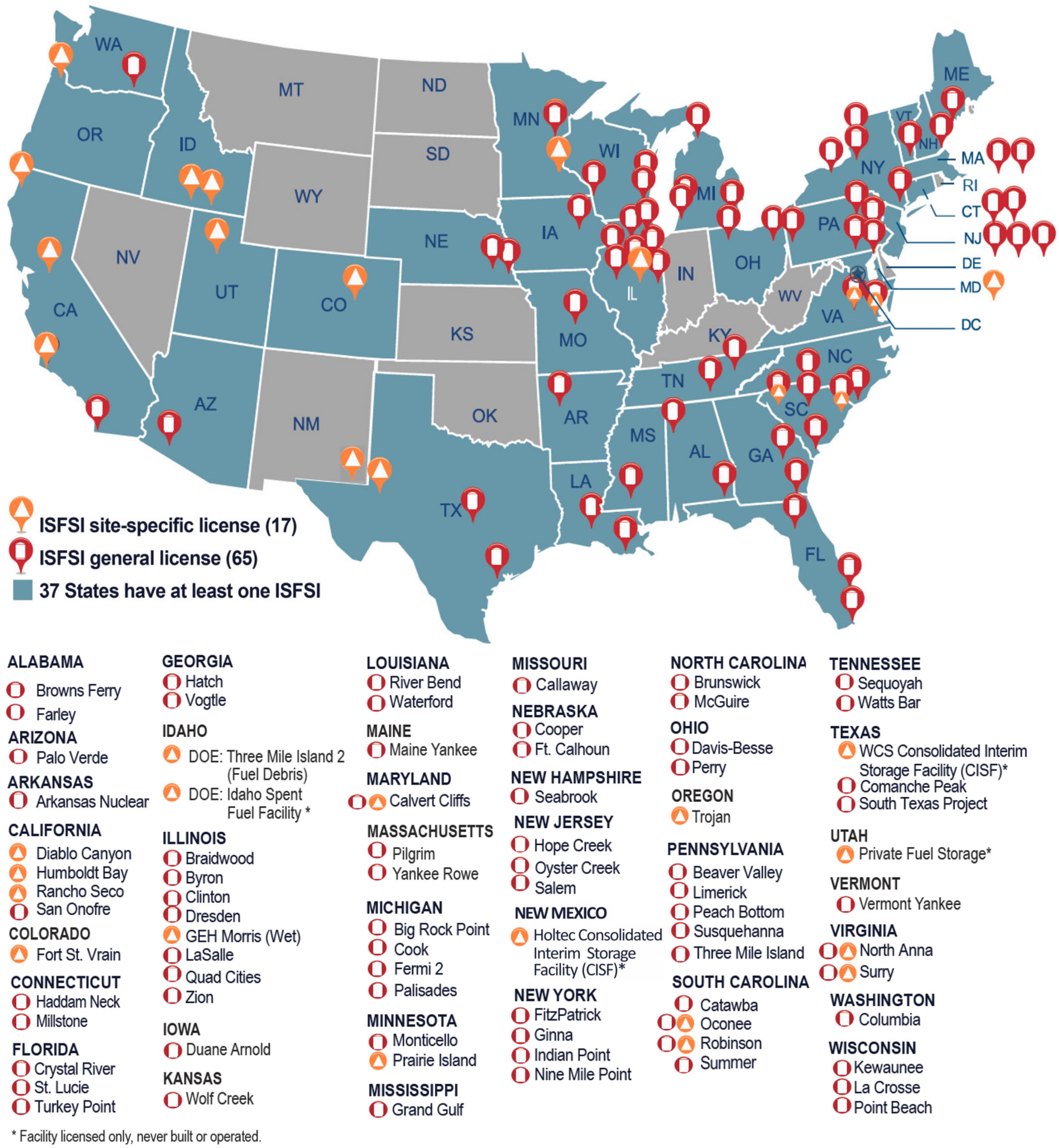

Figure 1. U.S. locations of independent spent fuel storage installations as of June 2023 (modified after NRC 2023a)

Notes: The Colorado and Idaho locations are managed by DOE. The Waste Control Specialists (WCS) location in Texas and Holtec location in New Mexico are planned consolidated interim storage facilities for commercial spent nuclear fuel. The General Electric (GE) facility at Morris, Illinois, is a pool built as part of a commercial reprocessing facility. Only the pool was put into operation.

The changes described above and the absence of a definitive plan for permanent disposal of SNF have led to long-term on-site storage becoming the de facto SNF management program in the United States for the foreseeable future. The safe and secure management of SNF in dry storage remains a priority for the nuclear industry; however, the industry also seeks to minimize the impact of SNF dry storage on routine operations at nuclear power plant sites. Without a clearly defined SNF disposition route, the utilities have had no basis for taking any different course of action to accommodate the requirements that will eventually be needed for SNF transportation away from their sites and disposal in a repository. Consequently, the incorporation of commercial SNF, which is stored in dry-storage casks with different designs at a multitude of utility sites, into an integrated program for the management and disposal for SNF and HLW has now become the crux of a problem that DOE must face.

3. ALTERNATIVE APPROACHES FOR THE MANAGEMENT OF COMMERCIAL SPENT NUCLEAR FUEL

There are three principal alternative approaches for managing commercial SNF in an integrated waste management system (Bonano et al. 2018; Freeze et al. 2021):

- Storing SNF at ISFSIs indefinitely, with none transported to a repository site or a consolidated interim storage facility.
- Repackaging SNF into smaller canisters before disposal.
- Direct disposal of SNF in DPCs in a geologic repository.

Although reprocessing of commercial SNF to recover fissile materials (such as uranium-235) is another alternative for SNF management and is in use in other countries, most notably France, this approach is not currently being pursued in any significant way by DOE or the U.S. nuclear industry and will not be discussed further in this report.

This chapter provides a summary of each of the three alternatives listed above and the implications of each one. DOE has conducted R&D in the past to examine some aspects of all three alternatives, but as of June 2023, the most active DOE R&D related to these alternatives is on the direct disposal of SNF in DPCs.

The three alternatives are summarized below in Sections 3.1, 3.2, and 3.3, where Board evaluations are also included. Board findings and recommendations regarding the alternative approaches to managing commercial SNF are included in Section 3.4.

3.1 Indefinite Dry Storage of Spent Nuclear Fuel

One approach to managing commercial SNF discharged from nuclear power plants is to store the SNF at ISFSIs indefinitely, with none transported to a repository site or a consolidated interim storage facility for the foreseeable future. For this report, “indefinite” means more than 80−120 years. This approach would be employed in the case of a long (or indefinite) delay in the development of a deep geologic repository, a consolidated interim storage facility, or both. Additional discussion of this approach is provided in Appendix B.

From 2008 through 2022, an average of more than 190 dry-storage casks per year were loaded at nuclear power plant sites (Freeze et al. 2021; UxC 2022, 2023b). As of June 1, 2023, almost 4,000 dry-storage casks are in service at ISFSIs (UxC 2023a). Freeze et al. (2021) estimated that about 10,000 dry-storage casks will be needed to store SNF discharged from nuclear power plants by 2080, when all SNF from the final shutdown reactors will have been transferred to dry storage.[36]

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[36] See footnote 15.

Indefinite dry storage of SNF at ISFSIs has several implications. First, to accommodate the increase in the number of dry-storage casks with time, the capacity of ISFSIs at nuclear power plant sites may need to be increased. Although some utilities have ISFSIs with sufficient capacity to accommodate all the SNF discharged from their reactors through the end of their operating lifetimes, other utilities would need to increase the capacity of their ISFSIs. Second, if SNF remains at ISFSIs indefinitely, it will be necessary to anticipate the eventual need to repackage the SNF. In preparing its generic analysis of the environmental impact of continued storage of SNF (NRC 2014), the NRC assumed that spent fuel canisters and casks would be replaced approximately once every 100 years. To support this repackaging requirement, the NRC also assumed a dry transfer facility would be built at each ISFSI location for fuel repackaging (NRC 2014). Repackaging the SNF would have other implications, discussed in Section 3.2. Third, indefinite dry storage of SNF at ISFSIs would prevent the release of the sites for other purposes (e.g., converting to "greenfield" sites) following the decommissioning of the facilities and the removal of waste materials generated during their operation and decommissioning. It also would require the utilities to maintain security staff and systems at the sites, as well as maintain site licenses and capabilities for responding to emergencies. Fourth, if the SNF is eventually disposed of in a repository, the overall lifetime system costs of SNF management would be significantly higher due to the costs of maintaining the ISFSIs (e.g., Freeze et al. 2019). Finally, on the positive side, continued storage of SNF at ISFSIs would allow much more time for the SNF decay heat and radiation levels to decrease, which could result in reduced costs by making future operations easier and reducing repository footprint due to closer placement of disposal packages.

Key technical considerations for indefinite dry storage of SNF at ISFSIs are aging effects on the SNF, including the SNF cladding, and aging effects on the dry-storage casks (NWTRB 2010; NWTRB 2021). Degradation of canister materials over long periods of storage may eventually lead to the need for canister repair or repackaging of the SNF they contain, while degradation of SNF may eventually impact the ability to retrieve SNF assemblies from canisters for repackaging, if needed. Consequently, the potential for degradation during storage of SNF and the canisters used in canistered dry-storage casks has been the subject of research programs undertaken by several organizations, including DOE (e.g., Bryan et al. 2021, 2022; Duncan et al. 2021), NRC (e.g., He et al. 2014; Oberson et al. 2013), and EPRI (e.g., EPRI 2013, 2014).

3.1.1 DOE Research

As of June 2023, there is no DOE R&D activity specifically addressing indefinite storage (more than 80–120 years) of SNF at ISFSIs. However, there is ongoing DOE R&D on extended storage (60–80 years) of high burnup SNF (HBF) (see Box C-1) and on the potential for chloride-induced stress corrosion cracking of dry-storage canisters and the consequences if it occurs (Bahr 2022). These two R&D programs can provide data relevant to an assessment of indefinite storage of SNF. Descriptions of these programs can be found in DOE's "gap analysis" of technical information needs for the storage and transportation of commercial SNF (Teague et al. 2019) and in its storage and transportation 5-year R&D plan (Saltzstein et al. 2020).

3.1.2 Board Evaluation

The Board recognizes the considerable amount of work, discussed above, that both DOE and the NRC have sponsored to study topics related to extended storage (60–80 years) and subsequent transportation of SNF. For the different SNF types, cladding types, and operating histories (including burnups) analyzed, these studies indicate that any degradation of either SNF or dry-storage canisters during extended periods of storage (60–80 years) will be limited. Although these studies address extended storage, rather than indefinite storage (more than 80−120 years), they provide data relevant to an assessment of indefinite storage of SNF.

Regarding indefinite storage, the Board notes that in NRC's "Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel" (NRC 2014), the NRC concluded:

> "…that there is no technical reason that spent fuel cannot be safely stored in dry casks beyond the short-term storage timeframe."[37]

However, NRC (2014) also stated:

> "Storage of spent fuel beyond the short-term storage timeframe would continue under an approved aging management program to ensure that monitoring and maintenance are adequately performed."

In reference to the need for repackaging, NRC (2014) noted:

> "…actual replacement times will depend on actual degradation observed during…continued storage. Studies and experience to date do not preclude a dry cask service life longer than 100 years."

Nevertheless, as the basis for analyzing the environmental impact of continued storage of SNF, NRC's generic environmental impact statement (NRC 2014) assumed:

> "…the replacement of dry casks after 100 years of service life…"

In a Board report (NWTRB 2021) evaluating the DOE R&D program on HBF, the Board concluded:

> "Nothing has been found to date in the DOE R&D program that indicates that safe long-term storage and subsequent transportation of commercial HBF cannot be accomplished while meeting all regulations."

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[37] "Short-term storage timeframe" refers to a period of 60 years following the end of the licensed operating lifetime of a nuclear power plant and is one of three timeframes considered in NRC's "Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel" (NRC 2014). As SNF will be loaded into dry-storage canisters during the operating lifetime of a nuclear power plant, some SNF will have been stored for significantly longer than 60 years by the end of the "short-term storage timeframe."

However, in the same report (NWTRB 2021), the Board noted that "many of the tests and models used to determine the performance of HBF have been completed for a relatively narrow range of fuel and cladding types, burnup levels, temperatures, storage and transportation system designs, etc." and recommended that DOE "indicate how its tests and models do or do not apply to the broad range of HBF types and storage and transportation system designs for which information is still needed and take steps to meet those remaining technical information needs."

The Board notes that DOE and the private nuclear industry are both working independently to develop consolidated interim storage facilities for SNF. NRC granted licenses to Interim Storage Partners LLC and Holtec International for consolidated interim storage facilities in Andrews County, Texas and Lea County, New Mexico, respectively, for an initial operational period of 40 years (NRC 2021b; NRC 2023b).[38] However, if unforeseen circumstances arise that require SNF to be stored at a consolidated interim storage facility longer than 80–120 years, then the implications of indefinite storage and repackaging discussed in this report would need to be considered.

The Board's findings and recommendations related to the indefinite storage alternative and the other two principal alternative approaches to managing commercial SNF are documented below in Section 3.4.

3.2 Repackaging Spent Nuclear Fuel into Smaller Canisters for Transportation and/or Disposal

A second approach to managing commercial SNF involves repackaging the SNF from existing dry-storage casks into new, smaller SNF canisters. The term repackaging is used in this report specifically to refer to an operation in which individual SNF assemblies are unloaded from a dry-storage cask and loaded into a new, typically smaller, canister. Repackaging is distinct from the operation to transfer a dry-storage canister loaded with SNF from one storage or transport cask (or overpack) to another—such transfer operations do not involve the handling of individual SNF assemblies, which entails the risk of the SNF being damaged. Depending on the design of the SNF cask or canister, the repackaging operation may be performed in a spent fuel pool or a dry transfer facility at a nuclear power plant site, an interim storage facility, or a repository site.

There are two main reasons it may be necessary to repackage SNF. First, some dry-storage casks were not designed for transportation and none were designed for disposal. Consequently, unless the casks can be demonstrated to meet the appropriate regulatory requirements and not impose inordinate physical constraints on disposal systems, the SNF must be repackaged before transportation away from the ISFSI for further storage at a consolidated interim storage facility or for disposal in a repository. Second, while there is a high level of confidence that any degradation of dry-storage casks, or the SNF they contain, will be limited during extended storage periods, it is necessary to anticipate that degradation

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[38] The operational period for DOE's consolidated interim storage facility will depend on "negotiated agreements with host communities and the timeline for permanent disposal capability" (DOE 2023, page 20).

of SNF or dry-storage casks will eventually occur to the extent that repackaging becomes necessary in order to meet the safety requirements for transportation or additional periods of storage, and then disposal. A more detailed description of the repackaging alternative is provided in Appendix C.

3.2.1 DOE Research

Past DOE R&D, conducted in the 1990s to 2010s, led to preliminary designs of standardized canisters that could be introduced as part of an effort to repackage at least some portion of the commercial SNF inventory from large DPCs into smaller canisters. DOE also considered conceptual designs for repackaging facilities. These efforts are well-documented:

Standardized canisters:

- Multi-purpose Canister (MPC) (DOE 1994).
- Transportation, Aging, and Disposal Canister (DOE 2006).
- Storage, Transportation, and Disposal Canister (Areva 2013; Energy Solutions et al. 2013, 2015a, 2015b)

Repackaging facilities:

- Yucca Mountain license application (DOE 2009, Section 1.2.5).
- Dry packaging facility design concept (Adeniyi et al. 2017; Bader 2018).
- Mobile examination and remediation facility (Chatzidakis et al. 2018).

In 2019, DOE sponsored a comparative cost analysis of different alternatives for managing commercial SNF, including the repackaging alternative (Freeze et al. 2019). Freeze et al. (2019) analyzed a reference scenario consistent with a 2008 “Total System Life Cycle Cost” analysis; the analysis reflects what might have been had the Yucca Mountain project proceeded as planned. Freeze et al. (2019) also conducted a cost analysis for three future alternative scenarios and variants, including three representative dates for the first receipt of SNF at a repository: 2031, 2041, and 2117. The Board reviewed and provided feedback on the DOE cost analysis (Bahr 2021), which is discussed further in Section 3.2.2.

More recently, in 2021, DOE sponsored an evaluation of options for managing the back end of the nuclear fuel cycle (Freeze et al. 2021). This evaluation included a discussion about repackaging. The stated reasons that repackaging may be needed were (Freeze et al. 2021):

- Reduce canister size, and thus thermal output, for disposal concepts that use clay-based backfill or buffer materials contacting the waste package.[39]

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[39] Title 10 of the Code of Federal Regulations, Part 63.2 defines “waste package” as the waste form and any containers, shielding, packing, and other absorbent materials immediately surrounding an individual waste container.

- Reduce reactivity[40] by limiting the amount of commercial SNF or by installing fillers for moderator exclusion.[41]
- Limit the size and weight of waste packages for easier disposal handling and emplacement operations.
- Provide for continued storage (e.g., after 100 years) and subsequent transportation and disposal for cases where there are concerns about canister integrity during extended storage.
- Enable transportation, and disposal of commercial SNF currently stored in storage-only systems.

Freeze et al. (2021) also discussed the drawbacks of repackaging:

- Potential for additional occupational radiation doses to workers from repackaging operations.
- Need for a wet or dry handling facility at locations that have no spent fuel pools.
- Need for added transfer capabilities and reactor spent fuel pool facilities.
- Generation of low-level radioactive waste from used DPCs.
- Added cost of canisters and handling facilities.

The DOE-sponsored evaluation concluded the discussion of repackaging with the following assessment: "There is no realistic prospect for implementing a standardized canister system in the U.S. before roughly 2030 at the earliest, by which time at least 60,000 metric tons of heavy metal of spent fuel will already be in dry storage in DPCs. Furthermore, there is currently no financial incentive for utilities to switch from their current dry storage canisters to a standardized canister" (Freeze et al. 2021).

As of June 2023, there is no active DOE R&D activity related to commercial SNF repackaging.[42]

3.2.2 Board Evaluation

In recent years, DOE has conducted some limited evaluations of SNF management alternatives, including the repackaging alternative discussed in Freeze et al. (2019, 2021). In its letter to DOE dated January 11, 2021 (Bahr 2021), the Board reported observations and recommendations following a Board review of the DOE-sponsored comparative cost analysis

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[40] "Reactivity" is a term expressing the relation of a system containing fissionable material, like a nuclear reactor, to a critical condition (i.e., sustaining a nuclear "chain reaction"). For a system that is subcritical, an increase in reactivity indicates a move from subcriticality toward a critical condition. For a critical or subcritical system, a decrease in reactivity indicates a move toward subcriticality or a move further from critical, respectively.

[41] "Moderator exclusion" means limiting the entry of water (a moderator) if the DPC is breached, thereby mitigating the potential for nuclear criticality.

[42] The Board notes that DOE's Office of Nuclear Energy and Office of Environmental Management was directed by Congress, in the Explanatory Statement for the Consolidated Appropriations Act, 2023, to "establish a road-ready, dry storage packaging configuration capability for Department-owned spent fuel." This activity includes some SNF of commercial origin that are stored and managed by DOE.

presented in Freeze et al. (2019). As documented in its letter (Bahr 2021), "… the Board concludes that, for several reasons, there are opportunities to improve future cost analyses." Examples of potential areas of improvement include addressing a potential underestimation of taxpayer liabilities associated with extended storage of commercial SNF, the need for an improved assessment of the recycling and reuse of used DPCs after repackaging, and an assessment of the impacts of disposal canister sizes on repository designs in host rock types (e.g., crystalline rock) that are not similar to Yucca Mountain rocks. Specific details of these issues can be found in Bahr (2021).

Addressing a broader perspective, Bahr (2021) concluded, "[t]he Board recognizes that these opportunities for improving future cost analyses could allow a better accounting of the costs, but will not change the finding in the rough-order-of-magnitude cost analysis that the single largest cost driver is the extent of future delays in DOE receiving SNF for centralized interim storage or disposal." The Board also offered this recommendation:

> "… the Board recommends that DOE provide information to decision-makers that clearly indicates that decisions on the disposal of SNF in DPCs versus SNF repackaging have implications for the development of potential disposal systems, which are related to host rock types, the timing and rate of DPC disposal, and total system life cycle costs." (Bahr 2021)

The Board observes that DOE cannot legally dictate the packaging or storage approach for commercial SNF while nuclear utilities hold title to the SNF (beyond what is included in the Standard Contracts between DOE and each utility storing SNF). When DOE takes title to the commercial SNF, it will then be able to control the means of packaging, storing, and transporting commercial SNF. In the meantime, there has been little to no interest by the nuclear utilities in repackaging SNF from DPCs into smaller standardized SNF canisters. For example, during the Summer 2016 Board public meeting in Washington, D.C. (NWTRB 2016, pp. 132–133), Kris Cummings of the Nuclear Energy Institute summarized the nuclear industry's position:

> "… we should recognize that the repository should be designed for the waste form, the canisters, not the other way around. Any repackaging, if needed, should not be performed at the nuclear power plant sites. Going back to what I said earlier. We're not repackaging facilities. We generate electricity. We safely store our waste. But we're not in the business of repackaging…"

The Board also notes that another significant complicating factor regarding the repackaging alternative is that of the 3,962 dry-storage canisters and casks loaded with commercial SNF as of June 1, 2023, approximately 18 percent are not approved by the NRC for transportation (Freeze et al. 2021; UxC 2023a). Unless NRC can approve these canisters for transportation, they cannot be shipped to another location for repackaging and would have to be repackaged at their current locations. However, at many of the older nuclear power plant sites, the reactor facilities have been shut down, and no spent fuel pool is available to support SNF repackaging. At these sites, a dry repackaging facility would have to be made available to enable the repackaging of SNF in dry-storage casks that are not approved for transportation.

This could be done by constructing a repackaging facility at each site or by building a mobile/modular repackaging facility that could be moved from one site to another.[43]

Alternatively, a new approval approach may alleviate the need for repackaging. In this approach, the existing transportation Certificates of Compliance[44] could be amended, or new transportation packages would need to be developed and certified to gain NRC approval for transportation of the non-transportable SNF canisters. Such an approach may include design changes to the SNF casks or canisters, or other compensatory measures (e.g., using an overpack container that precludes full flooding of the transportation package) to support NRC approval. If successful, and if NRC approves, the SNF canisters could then be transported, thus making repackaging unnecessary. Conceivably, however, repackaging could still be necessary before disposal, depending on the selected repository design.

Given the many variations and complexities that need to be considered for this approach to managing commercial SNF, the Board observes that more detailed, integrated systems analyses of this approach (and other alternatives) are needed to better inform decision-makers. In order to facilitate an evaluation of the pros and cons in a meaningful way, the integrated systems analyses would need to take account of the variations and complexities of repackaging the SNF into smaller canisters, which include, among others:

- Costs and logistics of developing and licensing one or more standardized SNF canister sizes.
- Pros and cons of adding standardized SNF canisters at different points in the back end of the nuclear fuel cycle.
- Costs and logistics of developing and licensing one or more repackaging facilities.
- Additional radiation dose to workers associated with the repackaging operations.
- Pros and cons of reusing SNF canisters emptied during repackaging and decontaminated or disposing of the canisters as low-level radioactive waste.
- The timing of each step in the repackaging scenario and how it may delay DOE taking title to commercial SNF, increasing DOE’s liability cost related to commercial SNF storage.

The Board has not attempted to quantify the impacts of these many variations in the repackaging alternative, but notes that DOE has developed and continues to refine integrated systems analysis tools that are well suited for these types of evaluations. For example, DOE

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[43] In a 2010 report (NWTRB 2010), the Board recommended several R&D programs related to the extended storage and transportation of SNF, including the design and demonstration of dry-transfer systems for removing fuel from casks and canisters following extended dry storage.

[44] Certificate of Compliance means the certificate issued by NRC that approves the design of a package for the transportation of radioactive material in accordance with the provisions of Title 10 of the Code of Federal Regulations, Part 71, Subpart D—Application for Package Approval, or the certificate issued by NRC that approves the design of a spent fuel storage cask in accordance with the provisions of Title 10 of the Code of Federal Regulations, Part 72, Subpart L—Approval of Spent Fuel Storage Casks.

sponsored the development of the Next Generation System Analysis Model (NGSAM)[45] and the Performance Assessment of Strategy Options Model (PASO),[46] which can be applied to evaluate many of the variations and complexities noted above. The Board's findings and recommendations related to this and the other two principal alternative approaches to managing commercial SNF are documented below in Section 3.4.

3.3 Direct Disposal of Spent Nuclear Fuel in Dual-Purpose Canisters in a Geologic Repository

A third approach to managing commercial SNF is direct disposal in a geologic repository of the SNF in DPCs. In this alternative, DOE would transport SNF in welded DPCs (and possibly SNF in bolted lid casks) directly from SNF storage locations to a repository site for disposal without repackaging the SNF into smaller standardized canisters or disposal canisters.[47] Intermediate storage of the DPCs at a consolidated interim storage facility may also be considered as part of this alternative.

There are several reasons for considering this alternative (see SNL 2020a, Freeze et al. 2021). First, it would lower the collective worker dose associated with the management of SNF compared to repackaging the SNF into smaller canisters. In the latter case, the DPC would be cut open and the SNF would be transferred into another canister. These operations that would require more hands-on worker activities, resulting in higher worker radiation doses. Second, direct disposal of SNF in DPCs would simplify the overall SNF management program, including minimizing the number of SNF shipments for transportation, possible interim storage, and disposal; reducing the number of facilities to license, construct, and operate; and reducing the risks of SNF damage because less SNF assembly handling would be needed. Third, it would significantly reduce the cost associated with SNF management. Alsaed and Hardin (2019) estimated that the cost avoidance associated with direct disposal of SNF in DPCs is approximately $20 billion.[48]

However, if SNF is to be disposed of in large DPCs, the size and weight of the casks in which the canisters are stored and transported and the overpacks into which they will be loaded for disposal, together with the fissile content, radiation level, and heat output of the SNF, may present problems for transportation or emplacement in a geologic repository. For example, because of the tendency for SNF with higher burnup to be placed in more recent

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[45] NGSAM is a simulation software tool that provides system analysts with a tool that can accurately and flexibly model the Integrated Waste Management System for SNF, such as alternative disposition pathways for commercial SNF being stored dry in at-reactor ISFSIs or wet in spent-fuel pools (Joseph et al. 2019).

[46] The PASO Model is a dynamic, probabilistic simulation model that can be used to address key questions for various DOE Integrated Waste Management SNF/HLW disposition and/or consolidated interim storage scenarios DOE might consider as part of its nuclear waste management strategies.

[47] The Board notes that this alternative would require changes to the standard contracts that have been put in place between DOE and the nuclear utilities who hold title to and are storing commercial SNF, pursuant to 10 CFR Part 961 (Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste).

[48] The estimated $20 billion cost avoidance (in 2019 dollars) is for disposing, without repackaging, of SNF totaling 109,300 metric tons of uranium. The cost avoidance would be higher if more SNF is produced and more DPCs are loaded than assumed in the analyses reported by Alsaed and Hardin (2019).

and larger DPCs, these DPCs will take longer to cool, if needed, before emplacement in a repository. There may also be additional implications for repository performance during the postclosure period due, for example, to the higher heat loads of individual canisters, the potential for criticality events, and the larger source term (inventory of radionuclides) in each large DPC. Further, direct disposal of SNF in DPCs may introduce other technical as well as financial and regulatory issues that must be resolved during repository licensing (SNL 2020a).

3.3.1 DOE Research

DOE has broadly addressed the direct disposal alternative in several past evaluations (Hardin et al. 2015; SNL 2020a; Freeze et al. 2021). In planning and prioritizing its future R&D activities, DOE has continued to emphasize efforts to study and understand the feasibility and implications of the direct disposal of commercial SNF in DPCs. DOE periodically updates its disposal R&D priorities in its disposal R&D 5-year plan, most recently published in 2021 (Sassani et al. 2021).

In line with its stated priorities, DOE supports several specific R&D activities related to the direct disposal of SNF in DPCs, including research on (1) the consequences of potential criticality events on the long-term performance of a geologic repository after closure; (2) potential filler materials that could be injected as liquids into existing DPCs, where they solidify and prevent groundwater ingress into breached DPCs and, thereby, reduce the probability for nuclear criticality; and (3) modifications to future DPCs so they will remain subcritical in any repository setting. Section 4.2 provides more detailed descriptions of the ongoing R&D work related to the direct disposal of SNF in DPCs.

3.3.2 Board Evaluation

Because DOE has concentrated much of its recent disposal R&D on specific aspects of the viability of direct disposal of SNF in DPCs, this report includes a section (Section 4) focused on those specific R&D efforts. The Board's evaluation of DOE's R&D activities related to direct disposal of SNF in DPCs, as well as the Board's findings and recommendations are provided in that section.

From a broad perspective, the direct disposal alternative, like the repackaging alternative (Section 3.2), introduces several additional variables and complexities. The Board notes that additional detailed systems analyses, like those discussed in Section 3.2.2, would better inform decision-makers about the pros and cons of direct disposal of SNF in DPCs, compared to other alternatives. Some examples of the complexities introduced by the direct disposal alternative are:

- Contents (and condition of the contents) of some DPCs approved for dry storage do not meet the requirements for transportation in the associated transportation cask's Certificates of Compliance.
- Cooling time requirements for large DPCs and the impacts of those cooling times on integrated system planning.
- Impacts of large DPC sizes on a nationwide, integrated transportation system for commercial SNF.

- Impacts of large DPC sizes on each of the possible repository designs, considering disposal package handling and engineering challenges.
- Impacts of large DPC sizes on each of the possible repository designs, considering thermal management (disposal package spacing, disposal drift spacing, extent of the use of backfill or buffer materials, etc.).
- Impacts of large DPC sizes on each of the possible repository designs, considering radionuclide inventory as it affects criticality safety, radionuclide release, and migration.

The Board's findings and recommendations related to this and the other two principal alternative approaches to managing commercial SNF are documented in Section 3.4.

3.4 Board Observations, Findings, and Recommendations

The Board observes that DOE has examined, in a variety of past evaluations, the pros and cons of the three principal alternatives for managing commercial SNF. The Board also notes that, given the variety of SNF types, SNF operating histories and burnups, dry-storage cask system designs, and site-specific conditions, a "one-size-fits-all" approach to managing commercial SNF may not be feasible—rather, some combination of the three alternatives may need to be implemented. Nonetheless, evaluating the pros and cons of the alternatives can provide valuable information to decision-makers as they consider the best approach for managing and disposing of the nation's nuclear waste. DOE has developed a number of useful analysis tools, particularly NGSAM and PASO, that are well-suited for these types of evaluations.

While DOE's past evaluations have been informative, none have been fully comprehensive in considering all the advantages and disadvantages of each alternative. For example, some loaded DPCs currently in storage are known to include contents that do not meet the requirements of the associated Certificate of Compliance for transportation (Clarity et al. 2017; NWTRB 2019). To be considered for the direct disposal alternative, these DPCs will need additional analyses and their Certificates of Compliance for transportation will need to be amended before they can be transported away from their storage sites. The additional analyses will need to incorporate updated data and appropriate best estimate plus uncertainty evaluations in order to determine key issues including criticality. The number of loaded DPCs that will need additional analyses is not known; considerable time and effort may be required to determine this, which will be important in order to make a meaningful comparison of the principal alternatives for SNF management.

As another example, the potential impacts of direct disposal of SNF in large DPCs on the repository environment have yet to be fully examined and compared to the case of disposing of smaller standardized SNF canisters that would be expected in a repackaging scenario. Examples of the impacts of direct disposal that could be important to repository performance are the higher heat loads of individual canisters and the larger source term (inventory of radionuclides) in each large DPC, which can affect the potential for criticality and the concentrations of radionuclides released when the DPC eventually fails (likely thousands of years after repository closure).

The Board recognizes that DOE is aware of these issues and commends DOE for its work to address the issues in its integrated waste management and disposal R&D programs. For example, in its disposal 5-year R&D plan, DOE "…identified a number of 'gap' activities that represent future R&D necessary to adequately advance the state of the art of [disposal research]…These gaps tended to be focused in the areas related to the engineered barriers, for example cladding and waste package degradation…" (Sassani et al. 2021). The Board agrees that the development of a technically sound degradation model for the waste package (SNF DPC and its disposal overpack) is needed and will be important in the assessment of disposal alternatives.

The Board observes that DOE has in place the proper tools to evaluate the alternative approaches for implementing an integrated waste management system (e.g., tools like NGSAM and PASO) and to evaluate different and non-site-specific repository concepts (e.g., the Geologic Disposal Safety Assessment [GDSA] Framework).

The Board commends DOE for supporting these efforts and encourages DOE to continue the refinement and application of its systems analysis tools. However, the Board observes that more work is necessary to focus the DOE-sponsored systems analysis tools on several key issues as identified below in order to advance meaningful comparative analyses.

Finding 1: The Board finds that DOE has not fully analyzed, in an integrated manner, all the key aspects of the alternative approaches for managing commercial SNF such that a meaningful comparison of the alternatives can be made. Particular issues that need to be addressed include:

(1) The implications (time, effort, and cost) of identifying and finding a resolution for commercial SNF canisters approved by the NRC for storage, but which include contents not currently approved by the NRC for transportation.

(2) The implications for the design, construction, and operation of a geological repository of disposing of SNF in large DPCs versus disposing of SNF repackaged into smaller canisters, with a particular focus on waste package degradation, thermal management, postclosure criticality, and the engineering aspects of waste package emplacement in various rock types.

Recommendation 1: *The Board recommends that DOE give higher priority to refining its systems analysis tools and completing comprehensive analyses that address issues (1) and (2) in Finding 1, as well as the other variables and complexities noted in this report. By doing so, decision-makers would be better informed of the pros and cons of the alternative approaches for implementing an integrated waste management system and better prepared to adopt one or a combination of alternative approaches that would be the most effective and efficient for the nationwide program.*

4. DOE RESEARCH ON DIRECT DISPOSAL OF SPENT NUCLEAR FUEL IN DUAL-PURPOSE CANISTERS

4.1 Technical Feasibility

As indicated in Section 1, DOE began evaluating the technical feasibility of disposing of SNF in DPCs in a geologic repository in 2013. The initial multiyear study, conducted from 2013 to 2015, focused on four factors: (1) safety (preclosure operational safety and postclosure waste isolation), (2) engineering feasibility, (3) thermal management, and (4) postclosure criticality control (Hardin 2015; Hardin et al. 2015). Several different disposal concepts were evaluated that included consideration of different host rock types (i.e., hard rock [e.g., granite, tuff], sedimentary [e.g., claystone, shale], and salt), whether the waste was to be in direct contact with the host rock or engineered barrier system (EBS) materials, and whether repository drifts were backfilled. From the technical feasibility study, DOE concluded there are no major implementation barriers to the geologic disposal of SNF in DPCs, although additional R&D is required to address the technical information needs that were identified (Gunter 2020).

The DOE-sponsored study concluded there are no significant implications for operational safety during the pre-closure period (Hardin 2015; Hardin et al. 2015). The operations involved in the handling and packaging of large DPCs into disposal overpacks are within the state of available technology and practice in the U.S. nuclear industry.

With respect to postclosure safety, the study concluded that there are no significant non-site-specific technical concerns for waste isolation (Hardin 2015; Hardin et al. 2015). The safety case, regardless of host rock geology, would rely on both engineered and natural barriers, although the degree of reliance on the different barriers would depend on the host rock geology. For example, in the case of disposal in a salt repository, isolation of the waste from the biosphere would rely heavily on the characteristics of the host salt formation, with less reliance on the performance of the waste package. By comparison, the design of a repository in a crystalline host rock would not be able to rely to the same extent on the host rock properties for waste isolation, so there would necessarily be more reliance on engineered barrier and waste package performance.[49]

Further, the technical feasibility study found no significant technical issues concerning the engineering feasibility of direct disposal of SNF in DPCs (Hardin 2015; Hardin et al. 2015). The operations involved in transporting DPC-based waste packages underground and emplacing them in disposal tunnels are technically feasible, although some engineering R&D would likely be needed and some of the possible conveyance systems could be the largest of their kind. For example, one option for transporting DPC-based waste packages underground

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[49] In a later report, Freeze et al. (2021) concluded that preliminary results from performance assessment models of non-site-specific repositories in argillite, salt, crystalline, and unsaturated host rocks, supplemented by performance assessment model results from other countries, suggest that repository designs capable of sufficient postclosure isolation are feasible in all geologic media; however, thermal and criticality constraints vary among the different geologic media and repository designs.

would be to use a vertical shaft hoisting system. German engineers have developed and conducted a full-scale demonstration testing of a shaft hoist design with payload capacities up to approximately 85 metric tons (Hardin et al. 2013; SNL 2021a). However, the payloads of DPCs in overpacks may be as high as 175 metric tons, depending on the DPC size and the design of the disposal overpack (Hardin et al. 2013). German engineers (BGE Technology) have also completed conceptual designs for upscaling the hoist capacity to 175 metric tons in support of the potential direct disposal of waste transportation and storage canisters in a repository (Hardin et al. 2013; SNL 2021a). According to the DOE-sponsored study, it is possible to overcome the engineering challenges of handling payloads weighing up to 175 metric tons in a hoist system repository (Hardin 2015; Hardin et al. 2015).

Related to the need for maintenance of the access portals and underground workings, the DOE-sponsored study concluded that developments in excavation and construction techniques over the past two decades suggest that repository construction costs would be manageable and that repository openings could be stable for 50 years or more with little or no maintenance in many rock types (Hardin et al. 2015).

Further, the study concluded that thermal management is not an overarching technical issue and would likely not present any problem in salt and crystalline rocks, which have high thermal conductivity and high temperature tolerance (up to 200°C). The study also noted that disposal concepts that call for clay-based buffer or backfill, which have a lower temperature tolerance, could require much longer decay storage/aging times for SNF and larger repository layouts to allow more spacing between waste packages. The study authors recognized a need to understand better and develop models for predicting the behavior of clay materials when exposed to temperatures of 200°C or greater or identify alternative materials suitable for those temperatures.[50]

The technical feasibility study acknowledged that the potential for nuclear criticality over repository time frames (10,000 years or more) could be a challenge for most geologic environments[51] because the neutron absorber materials used in existing DPC designs are aluminum-based and will degrade readily with long-term exposure to groundwater (Hardin et al. 2015). The study concluded that groundwater flooding and the consequent neutron absorber degradation can be mitigated by improving the performance of disposal overpacks (e.g., by using multiple, dissimilar corrosion-resistant materials, such as layers of nickel-based alloy and titanium) or by filling the void spaces inside the DPC before disposal, to prevent water ingress into DPCs. The study also concluded that an increase in reactivity from groundwater flooding can be offset by the available uncredited reactivity margin in

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[50] DOE has ongoing experimental and modeling activities designed to understand better the behavior of clay materials when exposed to elevated temperatures (Jové Colón et al. 2021; Birkholzer and Faybishenko 2021).

[51] In a salt repository, however, the water will have a sufficiently high concentration of chlorine (as chloride ions) to ensure the SNF in the DPC does not reach criticality because the chlorine acts as a neutron absorber.

some of the as-loaded DPCs.[52] Further, the study pointed out that if criticality events can be excluded based on low consequence (e.g., low radiation dose to the public), then virtually all DPCs could be disposed of using any of the repository concepts considered in the study.

Price (2015) summarized 26 recommended R&D activities derived from the technical feasibility study that could provide the information needed to consider SNF disposal in DPCs repository siting decisions. To help guide and prioritize R&D activities related to direct disposal of SNF in DPCs, DOE sponsored a study to develop options for DPC disposition R&D (SNL 2020a). The options developed from the study were:

1. Criticality consequence analysis: Evaluating the consequences of potential criticality events on overall repository performance to determine if the consequences are acceptably low.

2. Injectable fillers: Developing and demonstrating fillers that could be injected as liquids into existing DPCs, where they solidify and prevent groundwater ingress into breached DPCs in a repository.

3. Modification of DPCs to be loaded in the future: Developing technical solutions for modifying DPCs to be loaded in the future so they will remain subcritical in any repository setting. These technical solutions include (1) insertion of disposal control rods (pressurized water reactor [PWR] fuel); (2) insertion of disposal control rods or blades (boiling water reactor [BWR] fuel); (3) replacement neutron absorber plates; and (4) zone loading of fuel assemblies in each DPC to limit reactivity in the event of waste package breach, flooding, and internal degradation.

4. Repackaging: Repackaging the SNF in DPCs into disposal-ready, repository-specific SNF canisters.

The SNL (2020a) report recommended that R&D start "with a significant effort directed toward consequence screening (option 1) to determine if engineered solutions that are presently developmental (options 2 and 3) can be avoided." The report also stated that option 4 is relatively well understood and would be the costliest to implement[53] and that there is no DOE R&D planned for that option.

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[52] DPCs certified by the NRC are loaded with SNF assemblies using well-defined fuel assembly loading criteria, such as specifications for approved contents in the DPC's Certificate of Compliance for Radioactive Material Packages. These specifications define limiting (bounding) loading conditions and SNF characteristics (i.e., fuel type, initial enrichment, and discharge burnup) for which the DPC's safety analysis report has demonstrated compliance with the applicable NRC safety standards set forth in Title 10 of the Code of Federal Regulations, Part 71, "Packaging and Transportation of Radioactive Material" (referred to as the "design-basis" analysis). DPCs are loaded with SNF assemblies that provide some margin to the limiting licensing conditions that is unquantified and uncredited. A more realistic reactivity analysis can be performed by using the characteristics of the SNF actually loaded into a DPC, referred to as the "as-loaded" analysis, and this provides a more realistic calculation of the reactivity margin to reach criticality.

[53] Cost analysis reported by Alsaed and Hardin (2019) indicates the cost avoidance associated with no repackaging of SNF in DPCs is approximately $20 billion (in 2019 dollars).

Currently, DOE R&D is underway for option 1 (criticality consequence analysis) and option 2 (injectable fillers). Some preliminary R&D is also underway on option 3 (modification of DPCs to be loaded in the future). These R&D activities, identified as key near- and longer-term research topics in DOE's disposal R&D 5-year plan (Sassani et al. 2021), are described in the next section and are the focus of the Board's review.

4.2 Current DOE Research and Development Activities on Direct Disposal of Spent Nuclear Fuel in Dual-Purpose Canisters

4.2.1 Criticality Consequence Analysis

DOE is currently conducting studies to examine the potential consequences of hypothesized criticality events on the long-term performance of a geologic repository after closure (e.g., Price et al. 2021, 2022). The studies focus solely on the consequences of criticality during the postclosure period, not the probability of occurrence of criticality.[54] Only criticality events inside DPCs are considered, i.e., criticality events external to the waste package, in the near field or in the far field, are not examined.[55]

Price et al. (2021) examined the postclosure consequences of two types of criticality events: steady-state criticality events (low power and long duration) and transient criticality events (high power and short duration). The authors considered that the primary consequence of a steady-state criticality event is a change in the radionuclide inventory.[56, 57] For transient criticality events, Price et al. (2021) considered that the primary consequence is a sudden power pulse that might damage fuel, neighboring waste packages, or the engineered barrier system in the vicinity of the critical waste package.[58]

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[54] The Board has noted (Bahr 2022) that an alternative approach to assessing the risks from postclosure criticality may be to determine that the probability for criticality to occur is sufficiently small so that a detailed consequence assessment is not needed.

[55] A scenario of a criticality event external to the waste package would involve the migration of fissile material from inside of a breached waste package and the accumulation of such material in the repository near field or far field in a sufficiently large and dense mass to start a nuclear chain reaction.

[56] The changes in radionuclide inventory include the generation of fission products (both long-lived and short-lived) and higher actinides, which leads to the depletion and generation of fissile material and neutron absorbers (Price et al. 2021). Previous analyses (Price et al. 2019) examined the change in the inventory of 58 nuclides: 46 radionuclides and 12 stable fission products. Price et al. (2021) stated that modeling the transport and dose of all 58 nuclides is unnecessary and impractical because of computational requirements. They identified 12 fission and activation product radionuclides (^{137m}Ba, ^{14}C, ^{36}Cl, ^{135}Cs, ^{137}Cs, ^{129}I, ^{126m}Sb, ^{79}Se, ^{126}Sn, ^{90}Sr, ^{99}Tc, and ^{90}Y) that need to be considered in the radionuclide transport and/or dose calculations.

[57] Price et al. (2021) included a model of the clay buffer in their postclosure performance simulations. Using this illitization model enables simulating the transformation of smectite into illite, which results in an increase in buffer permeability. Price et al. (2021) also implemented a model of anisotropic temperature-dependent thermal conductivity in all their simulations.

[58] The mechanical consequences can result from the pressure pulse generated by rapid volatilization of water with power production and from rapid heating or thermal cycling of the waste package internals, including water (Price et al. 2021).

Price et al. (2021) described the information, modeling tools,[59] and techniques needed to incorporate the effects of postclosure criticality in repository-scale performance assessments, as well as the results of their initial analysis that examined the potential consequences of postclosure criticality. Several assumptions were made in their study, including:

- All the DPCs in the repository have the same as-loaded radionuclide inventory and configuration.
- All the waste packages fail simultaneously, water enters the waste packages, and criticality occurs.[60] The probability that these conditions occur is not calculated. In the steady-state criticality case, the criticality event is concurrent with the breaching of the waste package, assumed to be at 9,000 years after repository closure, and continues for 10,000 years (i.e., until 19,000 years after closure).
- Fuel assembly configurations remain intact (assumed to be the most reactive credible fuel configuration under disposal conditions), but cladding has failed, which permits radionuclides to be released into the water in a breached waste package and to be transported into the engineered barrier system and beyond.
- Basket neutron absorbers have degraded and been transported out of the fuel basket prior to the initiation of a criticality, slowly over time for the steady-state criticality event and nearly instantly for the transient criticality event.
- Steady-state criticality events do not oscillate between being supercritical and subcritical.

Price et al. (2021) initially evaluated DPCs containing PWR assemblies emplaced in two different hypothetical repositories as geologic reference cases: a saturated repository in shale and an unsaturated repository in alluvium. The hypothetical repository in saturated shale is located at a depth of 500 m. The model domain contains 4,200 waste packages, each containing 37 PWR assemblies with the same radionuclide inventory, which are emplaced in long tunnels backfilled with bentonite.[61] Bentonite, a low-permeability material, is designed to delay water movement and radionuclide transport. A well that provides 2 liters per day of drinking water to a member of the public is placed 5 km downstream from the repository where consequences are calculated. The hypothetical repository in unsaturated alluvium is at a depth of 250 m. The model domain is simpler compared to the hypothetical shale

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[59] The modeling tools include the PFLOTRAN code, a multiphase, subsurface flow, and reactive transport code designed for simulating flow and reactive transport in porous media (Lichtner et al. 2020).

[60] These conservative and unrealistic assumptions are made to allow criticality to occur during the first 10,000 years after repository closure. For example, the assumed bathtub model for water accumulation is inconsistent with past modeling of waste package degradation, wherein patches on any part, not just the top, of the waste package can degrade. Price et al. (2021) noted that future studies will examine the effects of varying the onset of postclosure criticality spatially and temporally.

[61] Modeling activities for a hypothetical shale repository conducted in FY2022, reported by Price et al. (2022), focused more on incorporating additional features, events, and processes into the PFLOTRAN model. The model domain for the FY2022 simulations represented a quarter of a waste package in the repository system near-field region.

repository; it includes only one waste package with 37 PWR assemblies emplaced in a tunnel with a 4 m × 4 m square cross-section and a backfill of crushed alluvium.[62]

Price et al. (2021) estimated the consequences of steady-state criticality events on the performance of each hypothetical repository by calculating and comparing the doses to a member of the public in scenarios where steady-state criticality events occur versus scenarios where a criticality event does not occur.[63] They planned to estimate the consequences of transient criticality events on the performance of each hypothetical repository by calculating the range of predicted power over time produced by the transient criticality event and determining whether the pulse of energy could cause mechanical damage to the engineered or natural barrier.[64]

The modeling results reported by Price et al. (2021) for the hypothetical saturated shale repository showed that, over the 1,000,000-year simulation time, ^{129}I was the only radionuclide that reached the well that is used by a member of the public. There was very little difference (less than 1 percent) in the doses from ^{129}I received by a member of the public in the scenario where the repository remained subcritical versus the scenario where the repository experienced a steady-state criticality event. Thus, in this hypothetical repository system, a 10,000-year long steady-state criticality event for all waste packages at the assumed steady-state power does not affect repository performance. The modeling results also showed that ^{237}Np is not transported beyond the vicinity of the repository and, therefore, does not result in a dose to a member of the public. Further, the short-lived fission products produced by the steady-state criticality event, ^{90}Sr and ^{137}Cs, decay before reaching the sand aquifer that is the water source for the member of the public and, therefore, also does not result in a dose to a member of the public.

For the hypothetical unsaturated alluvial repository, Price et al. (2021) were unable to calculate the dose for a member of the public resulting from a steady-state criticality event because the improvements needed to enable the PFLOTRAN software to run the simulations were not yet completed. Nevertheless, Price et al. (2021) were able to determine that the power that can be generated by a steady-state criticality event is limited by the infiltration rate: higher infiltration rates allow the criticality event to generate more power. At the reference infiltration rate assumed in the simulations (2 mm/yr), the power that can be

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[62] The model domain of the simulations conducted in FY2022 for a hypothetical unsaturated alluvial repository was 3,915 m × 1,065 m × 1,005 m in size and contained 1,350 waste packages (Price et al. 2022).

[63] Doses were not calculated in the steady-state criticality simulations conducted in FY2022 (Price et al. 2022).

[64] Price et al. (2021) only reported a range of predicted power that might be generated by a transient postclosure criticality event and noted that the approach to determining the extent of mechanical damage to barriers is still being developed.

generated in a single waste package is between 50 W and 200 W, whereas it is between 300 W and 400 W at an infiltration rate of 10 mm/yr.[65, 66]

Price et al. (2021) described their progress on modeling transient criticality events and the subsequent effects on repository performance, work which is continuing as this report is being written.[67] For the hypothetical unsaturated repository, they created a model of the canister containing 37 PWR fuel assemblies under repository-relevant conditions and ran a series of steady-state criticality calculations using the Monte-Carlo N-Particle (MCNP) computer code to characterize multiple reactivity feedback mechanisms and derive feedback coefficients. The feedback coefficients were then used in kinetics analysis using RAZORBACK, a transient analysis computer code designed to simulate the operation of a research reactor (Talley 2017), to characterize the expected transient pulse. Price et al. (2021) ran multiple simulations using different reactivities and insertion times and calculated peak power, total integrated energy, maximum fuel temperature, average fuel temperature, maximum coolant temperature, average coolant temperature, time of peak power, and actual reactivity insertion. The results indicate that, assuming there is catastrophic failure of the boron carbide poison plates in the SNF basket, rapid releases of energy on the order of 10^8 – 10^9 J per canister are possible. Price et al. (2021) stated it is not yet clear whether these energies would be consequential in-situ, and they plan to examine the mechanical consequences of rapid energy releases of this magnitude with a future solid mechanics study.

For the hypothetical shale saturated repository, Price et al. (2021) assumed that a reactor-based rod ejection accident could be used as a surrogate for a transient criticality event. For this analysis, Price et al. (2021) used the SIMULATE-3K code, a proprietary code developed to perform transient analysis of the core of commercial PWRs and BWRs (Studsvik 2023). The simulations were completed for PWR and BWR canisters containing 37 and 89 fuel assemblies, respectively. Price et al. (2021) ran multiple simulations with different reactivities and insertion times and calculated peak power, total energy, maximum fuel temperature, maximum average fuel temperature, maximum water temperature, maximum average water temperature, transient time, radial peaking factor, and axial peaking factor. For the canister containing PWR fuel assemblies, simulations for both single and multiple rod ejections were completed simultaneously. An attempt was also made to simulate a boron dilution event to assess transient behavior when more spatially uniform reactivity insertion occurs, but this simulation proved to be impossible under the imposed stagnant flow conditions. For the BWR fuel assembly loaded canister, only the simultaneous multiple rod ejection simulation was completed. The results indicate that rapid releases of energy on the

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[65] As indicated in the preceding footnote, further DOE work is planned to determine if the calculated rapid energy production can result in damage to SNF, engineered barriers, and natural barriers.

[66] For the simulations conducted in FY2022 for a hypothetical unsaturated alluvial repository, Price et al. (2022) reported values of temperature, gas pressure, gas saturation, and liquid saturation at an observation point within the center-most waste package in the repository, calculated for an infiltration rate of 10 mm/yr and at different criticality power levels (0, 50, 200, and 400 W).

[67] The Board notes that in contrast to Price et al.'s (2021) modeling of steady-state criticality events where the postulated scenarios causing criticality are reasonable, their postulated scenarios for modeling transient criticality events that involve sudden removal of neutron absorbers are speculative.

order of 10^8 to 10^{11} J per PWR canister and 10^8 to 10^{10} J per BWR canister are possible and that water could boil, but that temperatures remain well below the melting temperature of UO_2. Price et al. (2021) indicated further work is needed (1) to improve the neutronic calculations; (2) to identify additional features, events, and processes that need to be included in the model of postclosure criticality and incorporate their effects into appropriate codes; and (3) to examine repository-wide sensitivities and variabilities (e.g., spatial and temporal variability in criticality occurrence).

Price et al. (2021) used a number of different models in the simulations. Originally, the SHIFT Monte Carlo code employing continuous energy treatment was used to model a canister containing 32 PWR fuel assemblies in a saturated shale repository. SHIFT was loosely coupled to the RELAP-3D system thermal-hydraulic code, which was used to model the canister, in order to determine achievable power as a function of canister' outside-wall temperature. Isotopic depletion was completed using SCALE. Based on the predicted isotopic inventories at 19,000 years after repository closure, PFLOTRAN was used to predict radionuclide transport with and without criticality assumed over 10,000 years. A similar analysis was also completed using the MCNP Monte Carlo code for a canister loaded with 37 PWR fuel assemblies in an unsaturated alluvial repository. In both cases, the initial isotopic compositions at 10,000 years were based on Used Nuclear Fuel Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) predictions.[68]

For the transient analysis of criticality in a saturated shale repository, CASMO and SIMULATE were used to complete isotopic depletion and establish initial conditions for the transient simulation, which was completed using SIMULATE-3K (S3K). CASMO solves the transport equation and completes depletion for a lattice to generate neutronic parameters (e.g., energy collapse, spatially homogenized cross-sections, discontinuity factors, yields, and kinetic parameters) as a function of instantaneous and history effects (e.g., coolant density, fuel temperature, and reactivity control material). SIMULATE uses the neutronic parameters in solving the three dimensional, few-group neutron diffusion equation employing a nodal spatial treatment. The thermal-hydraulic simulations use the internal models of SIMULATE and S3K to predict fuel and coolant temperatures and coolant densities needed to address feedback on cross-sections.

For the unsaturated alluvial repository, both MCNP and RAZORBACK were used, with MCNP evaluating the reactivity coefficients and RAZORBACK completing the transient simulations. RAZORBACK uses the Point Kinetics Equations (PKE), a zero-dimensional model, to predict canister power versus time based on the MCNP-generated reactivity coefficients and specified reactivity insertion. An internal thermal-hydraulic model solves for fuel and coolant temperatures and coolant quality, along with other properties, for either the peak power fuel pin or an average fuel pin based upon an input description of the spatial power distribution. Various weightings are used to translate predicted property values to core canister average values to be used with the reactivity coefficients.

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[68] DOE recently presented some details on UNF-ST&DARDS to the Board; they made some initial observations on the tool (Siu 2023).

4.2.1.1 Board Observations, Findings, and Recommendations

The Board observes that the work DOE has completed to date can be characterized as preliminary with the objective of gathering sufficient information so that the scope of future consequence analyses can be defined with increased confidence. DOE examined two hypothetical repositories—a saturated repository in shale and an unsaturated repository in alluvium—with regard to changes in isotopic composition, dose consequence, and material property alterations resulting from a steady-state criticality event. For prompt critical transient events, the total energy released, fuel and coolant temperatures, and coolant quality in the two repositories were evaluated.

Finding 2a: The Board finds that sufficient work has been completed to define the path forward regarding analyzing hypothesized postclosure criticality events. There is now sufficient information to determine, going forward, what simulation codes to be used in the analyses, events to be analyzed, and the parameters of interest to evaluate.

Finding 2b: However, the Board finds that some of the DOE-sponsored evaluations of postclosure criticality may be based on assumptions that are not fully supportable, and some of the codes used in the criticality consequence analyses[69] may not be appropriate. Specific comments and considerations regarding the modeling of postclosure criticality are listed below.

1) For steady-state criticality events:
    a) The usage of Monte Carlo neutronic codes is appropriate.
    b) Down-selection to a single Monte Carlo code to complete the bulk of the analysis will produce a more consistent comparison of results and reduce the necessary verification and validation effort.
    c) Validation of computer modeling codes is needed, although there would be challenges in doing so given the lack of relevant data concerning time of radioactive decay and SNF canister geometry.
    d) Selection of a waste package thermal-hydraulic code is needed, taking into account modifications that may be necessary within the code to enable modeling the waste package and whether or not the code needs to be incorporated into PFLOTRAN. This effort can build upon the work already completed utilizing STAR-CCM+ for verification. COBRA-SFS can be included in the assessment of possible codes given that it has been tailored to SNF canister applications and the applicability of its parent code, COBRA, to water-cooled reactor cores.
    e) The assumption of constant power for 10,000 years needs to be examined for conservatism, and if found to be overly conservative, it can be replaced with a

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[69] The Board did not evaluate the capabilities of the PFLOTRAN code, so the Board's findings do not apply to it.

more realistic, time-dependent power level determined by criticality that decreases over time, until negligible power is achieved.

2) For transient criticality events, including hypothetical prompt critical events, neither the MCNP-RAZORBACK nor CASMO-SIMULATE codes appear appropriate. Both codes assume a vertical orientation of the SNF canister, which will impact hydraulic analysis relevant to certain transients. RAZORBACK employs the PKE code and a single rod thermal-hydraulic analysis, which will have limited spatial information and reactivity coefficients obtained from an MCNP analysis based upon non-transient thermal-hydraulic conditions. CASMO-SIMULATE isotopic depletion and reactor simulation capabilities are geared toward reactor core applications. Due to the lack of access to and knowledge of the source codes, they are not as modifiable as needed to represent repository applications.

   Additional considerations for transient criticality events are:

   a) There is a need for a single code or package of codes (e.g., radiation code + thermal-hydraulic code) that would be applicable to all repository types and require minimum development effort. A panel of experienced reactor physics experts with knowledge of light water reactor analysis would be able to recommend such a code (or package of codes).

   b) An assessment is needed to determine whether a Monte Carlo stochastic (versus deterministic) modeling approach can be employed to complete the transient simulations. A Monte Carlo modeling approach would be preferable unless it is judged to be impractical due to required computer resource and execution time.

   c) Regarding a and b above, the code that is selected preferably would either be configurable without source code modifications to represent the systems to be simulated or have an open-access source file so modifications can be made more readily, as needed. Compatibility of the thermal-hydraulic model with canister conditions, whether linked to an external thermal-hydraulic code or to an internal model, needs to be factored into the selection decision, recognizing that thermal-hydraulic predictions will not only be used to assess feedback effects on neutronics, but possibly also to support canister damage assessments.

   d) If group cross-sections and spatially homogenized neutronic parameters are required, consideration needs to be given to generating these parameters utilizing a continuous energy Monte Carlo-based model of each loaded canister (i.e., with the SNF loaded in the fuel basket). If this generation approach is to be pursued, the Monte Carlo code needs to be the same as that used to complete the steady-state criticality analysis.

   e) If a deterministic modeling approach is selected, it can be verified by comparison with Monte Carlo predictions of reactivity and power distribution at steady-state conditions for a range of thermal-hydraulic and reactivity control conditions representative of transient conditions.

    f) An assessment is needed of whether fuel failure during the transient criticality event is a relevant concern. If fuel failure is relevant, modes of fuel failure other than fuel melt, which has already been identified for reactivity-induced accidents, can be examined for relevance in a repository setting.

    g) There is a need to define the sequence of possible events leading to prompt criticality[70] such that they are both realistic and possible to simulate.

3) For both steady-state and transient criticality events, the initial isotopic inventory of the canister at the start of the criticality event needs to be based on UNF-ST&DARDS predictions.[71]

4) There is a need to pursue uncertainty quantification to ensure that what are believed to be conservative assumptions are truly conservative when considering uncertainty.

Recommendation 2: *The Board recommends that DOE address the points noted in Finding 2b of this report regarding the ongoing consequence analysis of postclosure criticality.*

4.2.2 Development and Testing of Dual-Purpose Canister Fillers

To evaluate the feasibility and effectiveness of DPC fillers to mitigate or prevent criticality in a repository setting, DOE's R&D is focused on fillers that can be injected into a DPC as liquids using existing drain/vent ports or using a custom-built port. The fillers subsequently solidify upon cooling or after chemical reactions have occurred. The fillers are intended to limit the ingress of water if the DPC is breached and thereby reduce the probability for nuclear criticality. DOE could potentially implement injectable fillers on existing loaded DPCs, once it has assumed responsibility for the DPCs (i.e., has taken title to the SNF), and with DPCs to be loaded in the future, provided NRC regulatory approval could be obtained.

To be effective in mitigating criticality, the filler will need to exhibit several attributes (SNL 2021b), including:

- Injectability: The filler material must be injectable through small-diameter ports, with inner diameters of 0.75 in. to 1.25 in. (~20 to 30 mm) and possibly as small as ~0.4 in. (~10 mm) in some DPC designs (SNL 2017). Fillers must adequately flow and penetrate DPC interstices with apertures as small as ~1 mm before setting as a monolithic pour.

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[70] Prompt nuclear criticality refers to the condition in which a nuclear chain reaction increases rapidly with time in an exponential manner, resulting in a sustained and self-sustaining release of nuclear energy. This condition typically involves the rapid multiplication of nuclear fission events, leading to a significant increase in the number of nuclear reactions and the release of a large amount of energy in a very short period.

[71] The Board did not evaluate the codes within UNF-ST&DARDS, so the Board's findings do not apply to those codes. The UNF-ST&DARDS codes are being used (1) to determine the initial isotopic inventory within the context of postclosure criticality analysis and (2) to identify actual fuel loadings in canisters that have the greatest potential for postclosure criticality and, thus, deserve additional analysis of steady-state and transient criticality events.

- Minimal volume change: There should be minimal shrinkage or expansion during initial set and subsequent cooling to limit stress on DPC internal components and to maintain the low permeability of the solidified material.
- Material compatibility: Fillers need to be chemically inert or react minimally with DPC internal components, including Zircaloy cladding, aluminum-based neutron absorbers, and other structural materials.
- Chemical stability: The filler must not chemically degrade significantly over the timeframe of concern for criticality, either before the canister breach, or after breach when the canister's interior is exposed to groundwater. Gas generation by chemical reactions or due to radiolysis should be limited or controlled while the DPC is intact in the repository before the breach to mitigate potential canister rupture.

Additional desirable physical, chemical, and operational attributes of filler materials are summarized in other reports (SNL 2017, 2020a, 2021b).

The work plan for DOE's DPC filler R&D activities, described in SNL (2021b), includes developing and optimizing filler compositions with the appropriate chemical and physical properties (e.g., viscosity, density, porosity/permeability, and chemical and radiation durability). Filler materials that exhibit appropriate properties will be used in tests and demonstrations of DPC filling, initially at a sub-scale (unit cell) level but eventually at full scale. Because it is not possible to perform tests and demonstrations for all types of DPC designs and filler materials, modeling and simulation capabilities are also being developed that can be used to down-select filler materials and assess the DPC filling process (SNL 2021b). Materials being considered as potential DPC fillers are phosphate-based cements and low-melting-point metals and metal alloys.

4.2.2.1 Development and Testing of Chemically Bonded Phosphate Cement Fillers

Chemically bonded phosphate cements are different from Portland cements in that they have ionic or covalent bonds instead of the hydrogen bonding and van der Waals bonds present in the latter. But like Portland cements, chemically bonded phosphate cements are mixed and set at ambient temperature. Chemically bonded phosphate cements are formed by acid-base reactions between a soluble source of metal cations (such as calcium oxide, magnesium oxide, or zinc metal) and an acidic phosphate salt (such as that of potassium, ammonium, or aluminum). Chemically bonded phosphate cements have potential applications in nuclear shielding, as well as in novel architectural products, improved oil-field cements, corrosion and fire protection coatings, and advanced bone and dental cements (Jeong and Wagh 2003; Wagh 2013).

In FY2021 and FY2022, DOE conducted research on the following chemically bonded phosphate cements:[72]

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[72] DOE discontinued evaluating calcium phosphate cements, magnesium potassium phosphate cements, and fly ash phosphate cements due to the less promising results from its initial studies (SNL 2021c).

- Aluminum phosphate cements, specifically aluminum oxide/aluminum phosphate (Al_2O_3/$AlPO_4$) cements in which Al_2O_3 serves as the filler material bound by an $AlPO_4$ binder formed by the reaction of Al_2O_3 with various phosphate sources.

- Wollastonite phosphate cements, specifically wollastonite and aluminum or calcium aluminum phosphates in which $CaSiO_3$ serves as the filler material bound by a calcium phosphate that serves as the binder.

- Calcium aluminate phosphate cements, specifically grossite ($CaAl_4O_7$) and hibonite ($CaAl_{11}O_{18}$) fillers bound by an $AlPO_4$ that serves as the binder.

The DOE research efforts in FY2021 and FY2022 focused on the optimization of compositions and subsequent processing of these three materials to achieve dense and well-consolidated monolithic samples (SNL 2021c, 2022). Advanced testing also was conducted to evaluate cement performance when exposed to radiation doses expected within a DPC and to representative postclosure geochemical environments. The FY2022 results indicated that calcium aluminate phosphate cements appear to show the most promise as a DPC filler material and warrant further testing under gamma radiation and hydrothermal conditions (SNL 2022). The aluminum phosphate cements performed poorly during hydrothermal testing in water at 250°C suggesting they may slowly decompose as water enters breached canisters in the postclosure repository environment. The wollastonite phosphate cements showed that the short “working times”[73] of these materials are a challenge to overcome, so less research effort is planned on these cements in the future (SNL 2022).

4.2.2.2 Development and Testing of Low-Melting-Point Metal and Metal Alloy Fillers

DOE is investigating low-melting-point metals and metal alloys as DPC filler materials for several reasons (Fortner 2022a):

- Metals have long-term durability and strength that are well-understood.
- Casting of metals/metal alloys is expected to result in low porosity (<10 percent), which would limit groundwater ingress into a breached DPC during the postclosure period.
- Molten metals, such as tin and associated alloys, have low viscosities, which likely would enable them to be pumpable through small orifices, such as the DPC drainpipe, and to penetrate small apertures associated with fuel assemblies.

Low-melting-point metals that can be used as fillers include tin, lead, bismuth, cadmium, and zinc. The melting points of tin, lead, bismuth, and cadmium are below 350°C and zinc has a melting point of 419 °C. However, lead and cadmium are regulated materials; lead, in particular, is toxic, very heavy, and can cause embrittlement of other metal components.

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[73] The cement mixture does not remain plastic for a very long time. It stiffens and sets as chemical reactions continue, and eventually becomes rigid at the time of final setting. The “working” or “setting” time is the period during which it is still possible to disturb, remix, and/or pour the cement mixture.

Zinc has the potential to interact with fuel cladding, although, for the intended filler application, the potential cladding interaction may not be important.

Low-melting-point eutectics can be formed by combining the metals identified in the preceding paragraph in proper ratios. For example, the $Sn_{63}Pb_{37}$ alloy, a solder used in electronics, has a melting point of 183°C. A lead-free or cadmium-free eutectic, e.g., $Sn_{95.6}Ag_{3.5}Cu_{0.9}$ with a melting point of 217°C or $Sn_{91}Zn_{9}$ with a melting point of 199 °C, could be investigated also as DPC filler materials. Other low-melting-point metal alloys are listed in Table 1.

Table 1. Low-melting-point metal alloys (Fortner et al. 2022b)

Eutectic material (atom %)	Specific gravity	Viscosity (mPa·s)	Melting point (°C)
11.3% Al, 88.7% Zn	6	1.4	381
3.8% Ag, 96.2% Sn	7	1.4	221
43% Bi, 57% Sn	8.6	-	139
1.8% Cu, 98.2% Sn	8.8	1.8	227
84.7% Sn, 15.2 % Zn	6.98	1.8	200

Ongoing DOE R&D activities include evaluating metal/metal alloy filler candidates; optimizing casting parameters (e.g., melt temperature, pour flow rate, and mold temperature); and designing and conducting scaled-up casting experiments that capture the effects of complex fuel assembly features (e.g., mixing grids) (Fortner et al. 2022a). Modeling and simulation tools that can be used to understand various elements of the DPC filling process and to test various filling parameters (e.g., melt temperature, pour flow rate, and mold temperature) are also being developed (Brickner et al. 2021, Appendices C and D).

Fortner et al. (2022b) reported on experimental work conducted in FY2022 to determine (1) whether a DPC can be filled with molten metal in a practical manner using the DPC drainpipe, (2) realistic filling rates, and (3) the volume fraction that is filled. A filling test examined the viability of using molten metal in a pour casting process to encapsulate the spent fuel in a DPC by observing the filling and solidification behavior in a scaled section of a DPC internal fuel rod bundle and support structure. The test used a eutectic Sn-Bi alloy that has a low melting point temperature of 135°C and a test setup shown in Figure 2. The metal was poured from a pot furnace at ~175°C into an insulated mock-up mold that was heated at temperatures between 200°C to 240°C. The mold was successfully filled with the Sn-Bi alloy.

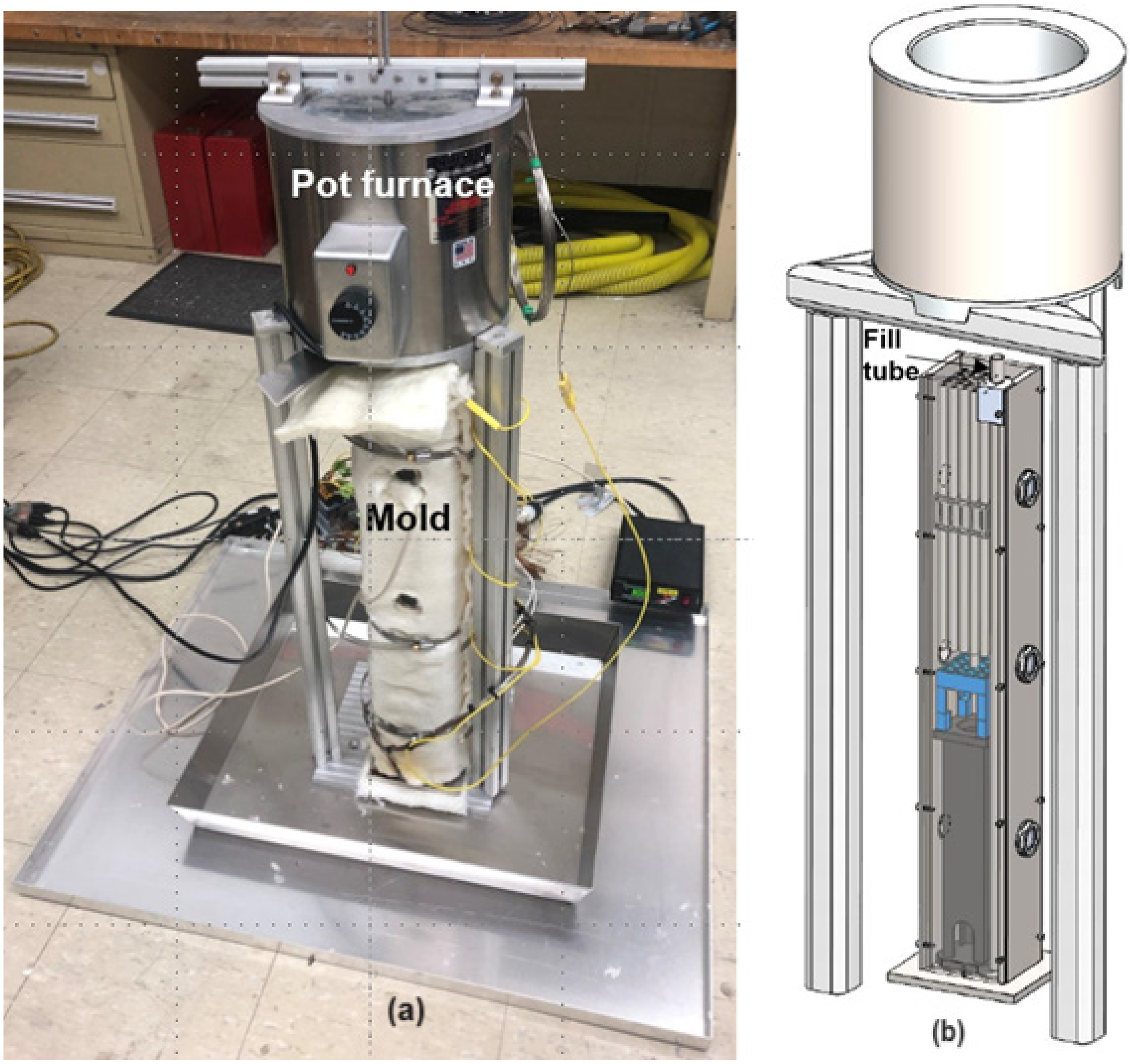

Figure 2. As assembled filling test apparatus and drawing showing pour test internals. (a) Test setup with pot furnace above the insulated mock-up mold. (b) Drawing of pot furnace on a stand and mold with 5 × 5 array of simulated fuel rods atop a stand representing a bottom spacer. The mold has internal dimensions of 68.6 cm × 7 cm × 8.6 cm. The simulated fuel rods are 30.5 cm long, and the stand is 57.8 cm tall. The fill tube runs along the front corner of the mold and is 1.42 cm in inner diameter. (Source: Fortner et al. 2022b)

Once fully cooled, the mold was taken apart, and the casting, freed from the mold, is shown in Figure 3. Visual inspections indicated that the casting surface had a smooth, uniform surface with no evidence of bubbles, voids, or cracks (Figure 3a); the wetting between the simulated fuel rods and the Sn-Bi alloy was excellent (Figure 3b).

Destructive and non-destructive analyses on the pour casting are planned to evaluate the success of DPC drainpipe filling fully. Other future work includes down-selecting promising metal filler candidates, materials testing on selected filler materials (e.g., corrosion, materials interaction, radiation hardening, radiolysis), and assembly-scale and, eventually, full-scale DPC filling experiments and simulations (Fortner et al. 2022b).

4.2.2.3 Board Observations, Findings, and Recommendations

DOE has been carrying out several R&D activities to determine the feasibility of using filler materials in DPCs to control reactivity and reduce the probability of criticality during the postclosure period. The focus has been on several filler attributes including injectability, volume change, material compatibility, and radiation and chemical stability. The experimental work is complemented by development and validation of computational capabilities to model thermal-hydraulic behavior. The Board encourages DOE to conduct these R&D activities in a timely manner such that the information obtained can be used to further down-select filler materials for larger-scale filler experiments.

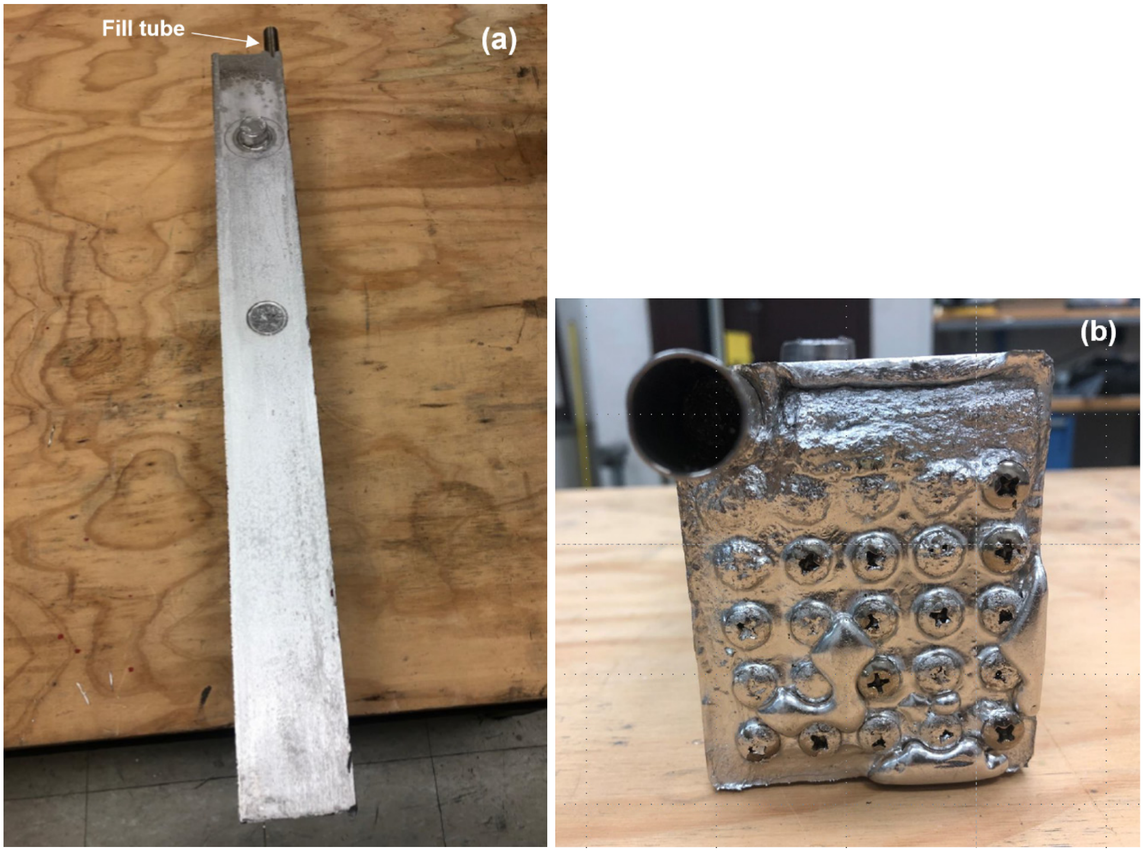

Figure 3. Casting from fill test.
(a) Side view of pour casting with mold removed (circular marks show viewport positions); (b) Top of pour casting, showing fill tube and tops of simulated fuel rods. (Source: Fortner et al. 2022b)

The Board notes that DPCs currently in use come in a variety of designs[74] and have different fuel loadings, affecting the ability to adequately fill the canister to mitigate criticality events.

The Board observes that DPC filling experiments cannot be done on all possible canister designs and fuel loadings. Thus, computational simulations are required to enable predicting canister filling and filler material solidification. The Board encourages DOE to continue with the development and validation of computational capabilities that can be used for predicting solidification of DPC fillers (both metal alloys and phosphate-based cements) and canister filling for the range of canister designs and fuel loadings.

The Board observes that filler materials, especially metal/metal alloy fillers, can add significant weight to DPCs.[75] With filling completed at the repository site, the added weight to the DPCs will only impact repository handling of the DPCs, which could be significant. For example, in a letter to DOE following the Board's 2020 Summer Meeting (Bahr 2021), the Board noted that the total weight of a waste package containing a DPC with filler material would exceed the maximum capacity of a conceptual repository shaft hoist system developed by BGE Technology and recommended that DOE update the conceptual hoist design to take account of the additional weight of DPC fillers. The Board acknowledges that DOE intends to seek solutions to issues that may arise, if any, due to the added weight from DPC fillers [e.g., redesign of handling features like skirts or trunnions (SNL 2020a)].

Further, the Board observes that using fillers for DPCs and the facilities that would implement the technology would require approval by the NRC. The Board acknowledges that DOE has taken steps to identify the regulatory considerations for using fillers to facilitate direct disposal of SNF in DPCs, including developing a high-level concept of operations report that could be used in future interactions with NRC (e.g., Alsaed 2018).

The Board remains interested in DOE's R&D on DPC fillers and looks forward to reviewing DOE's progress in the future.

4.2.3 Modification of Dual-Purpose Canisters to be Loaded in the Future

DOE is evaluating different options for modifying fuel assemblies and baskets for DPCs to be loaded in the future; this would substantially reduce the probability of postclosure criticality after waste package breach and flooding with groundwater (SNL 2020b). The evaluation is focused on fuel assembly or basket modifications that do not require potentially significant changes to existing DPC basket designs. The evaluation acknowledged that every option being considered would likely require regulatory certification, including amendments to existing Certificates of Compliance for storage and transportation and acceptance by the nuclear industry.

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[74] There are 37 unique canister types used in canister-based dry-storage systems (Freeze et al. 2021).

[75] As indicated in footnote 18, DPCs typically weigh between 38 and 58 tons [between 34 and 53 metric tons] when loaded with SNF. Cement-based fillers, with a typical density of 2 g/cm^3, could add about 13 tons [12 metric tons] to a large DPC, whereas molten metal fillers, with a density of 9 g/cm^3 could add about 59 tons [54 metric tons] (Hardin 2020, pp. 125-126).

The DOE study (SNL 2020b) explored several different options for adding disposal criticality control features to SNF assemblies:

- PWR disposal control rods.
- BWR control rods.
- BWR fuel re-channeling.
- Zone loading to limit reactivity addition.
- Rod consolidation.

The DOE study also described two modifications to DPC baskets that could be made external to fuel assemblies for control of disposal criticality:

- Absorber plate replacement (basket redesign).
- Chevron insert absorber plates.[76]

The DOE study (SNL 2020b) concluded:

- Disposal control rods for PWR fuel could be closest to being realized among the alternatives considered in the study. However, Certificate of Compliance restrictions on control component placement in DPCs will need to be studied to determine the availability of basket locations for disposal control rods.

- Re-channeling of BWR fuel is technically feasible for any BWR fuel assembly. The added weight change from installing re-channels may be small or zero, depending on the characteristics of advanced neutron absorber channels, but corrosion testing and prototype demonstration of fabrication properties of the absorber materials are needed.

- Chevron inserts for BWR or PWR fuel are potentially useful for baskets made of aluminum-based materials and could also be used to retrofit any DPC of an existing design that used aluminum-based absorber plates. However, the implementation of chevron inserts would depend on the amount of available space in DPC basket cells. Corrosion testing of inserts in representative geologic disposal environments, as well as prototype demonstration, are also needed.

- Replacing absorber plates made of aluminum-based materials (e.g., Boral®) in DPC baskets of existing designs is a potentially feasible change. It would add cost and weight similar to chevron inserts, but such baskets could become available once corrosion testing of advanced neutron absorber and other materials is complete.

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[76] Chevron-shaped inserts, which are longitudinal bi-fold plates, are used to supplement neutron absorption in spent fuel pool racks after degradation of polymeric boron-containing absorber material (SNL 2020b). Chevron inserts made with advanced neutron-absorbing material can potentially be used in DPCs with PWR or BWR fuel. These inserts could be inserted in every cell of a DPC basket without changing the basket design and require only sufficient clearance in the basket fuel cell (SNL 2020b, 2020c).

- Zone loading by strategic placement of fuel assemblies in the DPC basket could expand the applicability of the reactivity margin strategy, although this may be limited due to the preferential usage of and, therefore, depletion of low-reactivity fuel assemblies in the spent fuel pool required to complete zone loading. Also, implementation of zone loading would require re-licensing of loading protocols to meet DPC surface dose and temperature limits.

- The other solutions considered in the study (BWR control rods or blades, rod consolidation) are impractical because they would require disassembly of fuel assemblies, and/or significant redesign of existing DPC baskets.

4.2.3.1 Board Observations, Findings, and Recommendations

The Board observes that DOE is examining several options for modifying fuel assemblies and baskets for DPCs to be loaded in the future in ways that would reduce the probability of criticality after the closure of a repository when waste packages may have been breached and flooding with groundwater may have occurred. These options include specialized control rods in PWR assemblies going to disposal, control rods and fuel rechanneling in BWR assemblies, absorber plate replacements, chevron absorber inserts, zone loading of canisters, and rod consolidation.

Finding 3: The Board finds that a set of criteria needs to be developed for use in assessing the various options for modifying fuel assemblies and baskets for DPCs to be loaded in the future and in prioritizing R&D activities. The criteria could include (1) how rapidly each option could be implemented in practice, (2) how many DPCs to be loaded in the future potentially could benefit, (3) the associated cost of implementation of each option per DPC, and (4) the criticality prevention effectiveness of each option.

Recommendation 3: *The Board recommends that DOE establish a set of criteria to evaluate the various options for modifying fuel assemblies and baskets for DPCs to be loaded in the future. Using these criteria, DOE should assess the various options to determine R&D priorities. In developing the criteria and in evaluating the various options, the Board recommends DOE consultation with fuel owners and cask vendors to gain industry insights on and acceptance of potential DPC modifications.*

5. OBSERVATIONS, FINDINGS, AND RECOMMENDATIONS

The inventory of commercial SNF in the United States will continue to increase with time as more SNF is discharged from reactors at commercial nuclear power plants. Much of this inventory is in dry storage inside dry-storage casks, most of which are large, welded canisters referred to as DPCs that have been designed for interim storage and transportation but not for their potential use for geologic disposal.

The three principal alternative approaches for managing commercial SNF in an integrated waste management system are (1) indefinite storage (for more than 80–120 years) at ISFSIs, (2) repackaging the SNF into smaller canisters before disposal, and (3) direct disposal of SNF in DPCs in a geologic repository. Each of these alternative approaches has implications for the SNF management and disposal system. DOE has examined, in a variety of past evaluations, the pros and cons of each alternative approach and has developed a number of useful analysis tools well-suited for these types of evaluations.

DOE R&D activities related to direct disposal of SNF in DPCs currently focus on three areas: (1) the consequences of potential criticality events on the long-term performance of a geologic repository after closure; (2) potential filler materials that could be injected as liquids into existing DPCs, where they solidify and prevent groundwater ingress into breached DPCs and, thereby, reduce the probability for nuclear criticality; and (3) modifications to future DPCs so they will remain subcritical in any repository setting.

Based on reviews of DOE documents, fact-finding meetings with national laboratory and DOE personnel, and the presentations and discussions at Board public meetings, the Board makes the following observations, findings, and recommendations.

5.1 Alternative Approaches for the Management of Commercial Spent Nuclear Fuel

The Board observes that while DOE's past evaluations have been informative, none has been fully comprehensive in considering all of the advantages and disadvantages of each alternative. The Board recognizes that DOE is aware of the issues that need to be addressed and commends DOE for addressing those issues in its integrated waste management and disposal R&D programs.

The Board observes that DOE has the proper tools in place to evaluate the alternative approaches for implementing an integrated waste management system (e.g., tools such as NGSAM and PASO) and to evaluate different and non-site-specific repository concepts (e.g., the GDSA Framework).

The Board commends DOE for supporting the development of systems analysis tools and encourages their continued refinement and application. The Board observes that more work is necessary to focus the systems analysis tools on several key issues, as identified below, in order to advance meaningful comparative analyses.

Finding 1: The Board finds that DOE has not fully analyzed, in an integrated manner, all the key aspects of the alternative approaches for managing commercial SNF such that a meaningful comparison of the alternatives can be made. Particular issues that need to be addressed include:

(1) The implications (time, effort, and cost) of identifying and finding a resolution for commercial SNF canisters approved by the NRC for storage, but which include contents not currently approved by the NRC for transportation.

(2) The implications for the design, construction, and operation of a geological repository of disposing of SNF in large DPCs versus disposing of SNF repackaged into smaller canisters, with a particular focus on waste package degradation, thermal management, postclosure criticality, and the engineering aspects of waste package emplacement in various rock types.

Recommendation 1: *The Board recommends that DOE give higher priority to refining its systems analysis tools and completing comprehensive analyses that address issues (1) and (2) in Finding 1, as well as the other variables and complexities noted in this report. By doing so, decision-makers would be better informed of the pros and cons of the alternative approaches for implementing an integrated waste management system and better prepared to adopt one or a combination of alternative approaches that would be the most effective and efficient for the nationwide program.*

5.2 DOE Research on Direct Disposal of Spent Nuclear Fuel in Dual-Purpose Canisters

5.2.1 Criticality Consequence Analysis

The Board observes that the work DOE has completed to date can be characterized as preliminary with the objective of gathering sufficient information so that the scope of future consequence analyses can be defined with increased confidence. DOE examined two hypothetical repositories—a saturated repository in shale and an unsaturated repository in alluvium— regarding changes in isotopic composition, dose consequence, and material property alterations resulting from a steady-state criticality event. For prompt critical transient events, the total energy released, fuel and coolant temperatures, and coolant quality in the two repositories were evaluated.

Finding 2a: The Board finds that sufficient work has been completed to define the path forward regarding analyzing hypothesized postclosure criticality events. There is now sufficient information to determine going forward what simulation codes to be used in the analyses, events to be analyzed, and the quantities of interest to evaluate.

Finding 2b: However, the Board finds that some of the DOE-sponsored evaluations of postclosure criticality may be based on assumptions that are not fully supportable, and some of the codes used in the criticality consequence analyses[77] may not be appropriate. Specific comments and considerations regarding the modeling of postclosure criticality are listed below.

1) For steady-state criticality events:
   a) The usage of Monte Carlo neutronic codes is appropriate.
   b) Down-selection to a single Monte Carlo code to complete the bulk of the analysis will produce a more consistent comparison of results and reduce the necessary verification and validation effort.
   c) Validation of computer modeling codes is needed, although there would be challenges in doing so given the lack of relevant data concerning time of decay and SNF canister geometry.
   d) Selection of a waste package thermal-hydraulic code is needed, taking into account modifications that may be necessary within the code to enable modeling the waste package and whether or not the code needs to be incorporated into PFLOTRAN. This effort can build upon the work already completed utilizing STAR-CCM+ for verification. COBRA-SFS can be included in the assessment of possible codes given that it has been tailored to SNF canister applications and the applicability of its parent code, COBRA, to water-cooled reactor cores.
   e) The assumption of constant power for 10,000 years needs to be examined for conservatism, and if found to be overly conservative, it can be replaced with a more realistic, time-dependent power level determined by criticality that decreases over time.
2) For transient criticality events, including hypothetical prompt critical events, neither the MCNP-RAZORBACK nor CASMO-SIMULATE codes appear appropriate. Both codes assume a vertical orientation of the SNF canister, which will impact hydraulic analysis relevant to certain transients. RAZORBACK employs the PKE code and a single rod thermal-hydraulic analysis, which will have limited spatial information and reactivity coefficients obtained from an MCNP analysis based upon non-transient thermal-hydraulic conditions. CASMO-SIMULATE isotopic depletion and reactor simulation capabilities are geared toward reactor core applications. Due to the lack of access to and knowledge of the source codes, they are not as modifiable as needed to represent repository applications.

   Additional considerations for transient criticality events are:

   a) There is a need for a single code or package of codes (e.g., radiation code + thermal-hydraulic code) that would be applicable to all repository types and

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[77] The Board did not evaluate the capabilities of the PFLOTRAN code, so the Board's findings do not apply to it.

require minimum development effort. A panel of experienced reactor physics experts with knowledge of light water reactor analysis would be able to recommend such a code (or package of codes).

    b) An assessment is needed to determine whether a Monte Carlo stochastic (versus deterministic) modeling approach can be employed to complete the transient simulations.

    c) Regarding a and b above, the code that is selected preferably would either be configurable without source code modifications to represent the systems to be simulated or have an open-access source file so modifications can be made, as needed. Compatibility of the thermal-hydraulic model with canister conditions, whether linked to an external thermal-hydraulic code or to an internal model, needs to be factored into the selection decision, recognizing that thermal-hydraulic predictions will not only be used to assess feedback effects on neutronics, but possibly also to support canister damage assessments.

    d) If group cross-sections and spatially homogenized neutronic parameters are required, consideration needs to be given to generating these parameters utilizing a continuous energy Monte Carlo-based model of each loaded canister (i.e., with the SNF loaded in the fuel basket). If this generation approach is to be pursued, the Monte Carlo code needs to be the same as that used to complete the steady-state criticality analysis.

    e) If a deterministic modeling approach is selected, it can be verified by comparison with Monte Carlo predictions of reactivity and power distribution at steady-state conditions for a range of thermal-hydraulic and reactivity control conditions representative of transient conditions.

    f) An assessment is needed to determine whether fuel failure during the transient is a relevant concern. If fuel failure is relevant, modes of fuel failure other than fuel melt, which has already been identified for reactivity-induced accidents, can be examined for relevance to a repository setting.

    g) There is a need to determine the sequence of possible events leading to prompt criticality such that they are both realistic and possible to simulate.

3) For both steady-state and transient criticality events, the initial isotopic inventory of the canister at the start of the criticality event needs to be based on UNF-ST&DARDS code predictions.

4) There is a need to pursue uncertainty quantification to ensure that what are believed to be conservative assumptions are truly conservative when considering uncertainty.

Recommendation 2: *The Board recommends that DOE address the points noted in Finding 2b of this report regarding the ongoing consequence analysis of postclosure criticality.*

5.2.2 Development and Testing of Dual-Purpose Canister Fillers

DOE has been carrying out R&D activities to determine the feasibility of using DPC filler materials intended to limit the ingress of water if the DPC is breached and, thereby, reduce the probability for nuclear criticality during the postclosure period. Materials being evaluated as potential DPC fillers are phosphate-based cements and low-melting-point metal alloys. The experimental work is complemented by development and validation of computational capabilities to model thermal-hydraulic behavior. The Board encourages DOE to conduct these R&D activities in a timely manner such that the information obtained can be used to further down-select filler materials for larger-scale filler experiments.

The Board notes that DPCs currently in use come in a variety of designs and have different fuel loadings, which will affect the ability to adequately fill the canister to mitigate criticality events. The Board observes that DPC filling experiments cannot be done on all possible canister designs and fuel loadings. Thus, computational simulations are required to enable predicting canister filling and filler material solidification. The Board encourages DOE to continue with the development and validation of computational capabilities that can be used for predicting canister filling and solidification of DPC fillers (both metal alloys and phosphate-based cements) for the range of canister designs and fuel loadings.

The Board observes that filler materials, especially metal/metal alloy fillers, can add significant weight to DPCs. With filling completed at the repository site, the added weight to the DPCs will only impact repository handling of the DPCs, which could be significant. The Board acknowledges that DOE intends to seek solutions to issues that may arise, if any, due to the added weight from DPC fillers. The Board remains interested in this topic and looks forward to reviewing DOE's progress in the future.

Further, the Board observes that the use of fillers for DPCs and the facilities that would implement the technology would require approval by the NRC. The Board acknowledges that DOE has taken steps to identify the regulatory considerations for the use of fillers to facilitate direct disposal of SNF in DPCs, including developing a high-level concept of operations report that could be used in future interactions with NRC.

5.2.3 Modification of Dual-Purpose Canisters to be Loaded in the Future

The Board observes that DOE is examining several options for modifying fuel assemblies and baskets for DPCs to be loaded in the future in ways that would reduce the probability of criticality after the closure of a repository when waste packages may have been breached and flooding with groundwater may have occurred. These options include specialized control rods in PWR assemblies going to disposal, control rods and fuel rechanneling in BWR assemblies, absorber plate replacements, chevron absorber inserts, zone loading of canisters, and rod consolidation.

Finding 3: The Board finds that a set of criteria needs to be developed for use in assessing the various options for modifying fuel assemblies and baskets for DPCs to be loaded in the future and in prioritizing R&D activities. The criteria could include (1) how rapidly each option could be implemented in practice, (2) how many DPCs to be loaded in the future potentially could benefit, (3) the associated cost of implementation of each option per DPC, and (4) the criticality prevention effectiveness of each option.

Recommendation 3: *The Board recommends that DOE establish a set of criteria to evaluate the various options for modifying fuel assemblies and baskets for DPCs to be loaded in the future. Using these criteria, DOE should assess the various options to determine R&D priorities. In developing the criteria and in evaluating the various options, the Board recommends DOE consultation with fuel owners and cask vendors to gain industry insights on and acceptance of potential DPC modifications.*

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APPENDICES

APPENDIX A — MANAGEMENT OF COMMERCIAL SPENT NUCLEAR FUEL

A.1 Spent Nuclear Fuel

Fuel used in most operating commercial nuclear reactors, including both pressurized water reactors (PWRs) and boiling water reactors (BWRs),[78] is in the form of cylindrical pellets made of uranium dioxide (UO_2) that are typically 0.3 to 0.4 in [8 to 10 mm] in diameter and 0.35 to 0.6 in [9 to 15 mm] in length (Bruno and Ewing 2006). The pellets are sealed inside long metal tubes, referred to as cladding, to form fuel rods. Typically, the cladding material is zirconium alloy. Fuel rods are held in a square array by spacer grids and other components to form a "fuel assembly." Figure A-1 shows examples of PWR and BWR fuel assemblies.

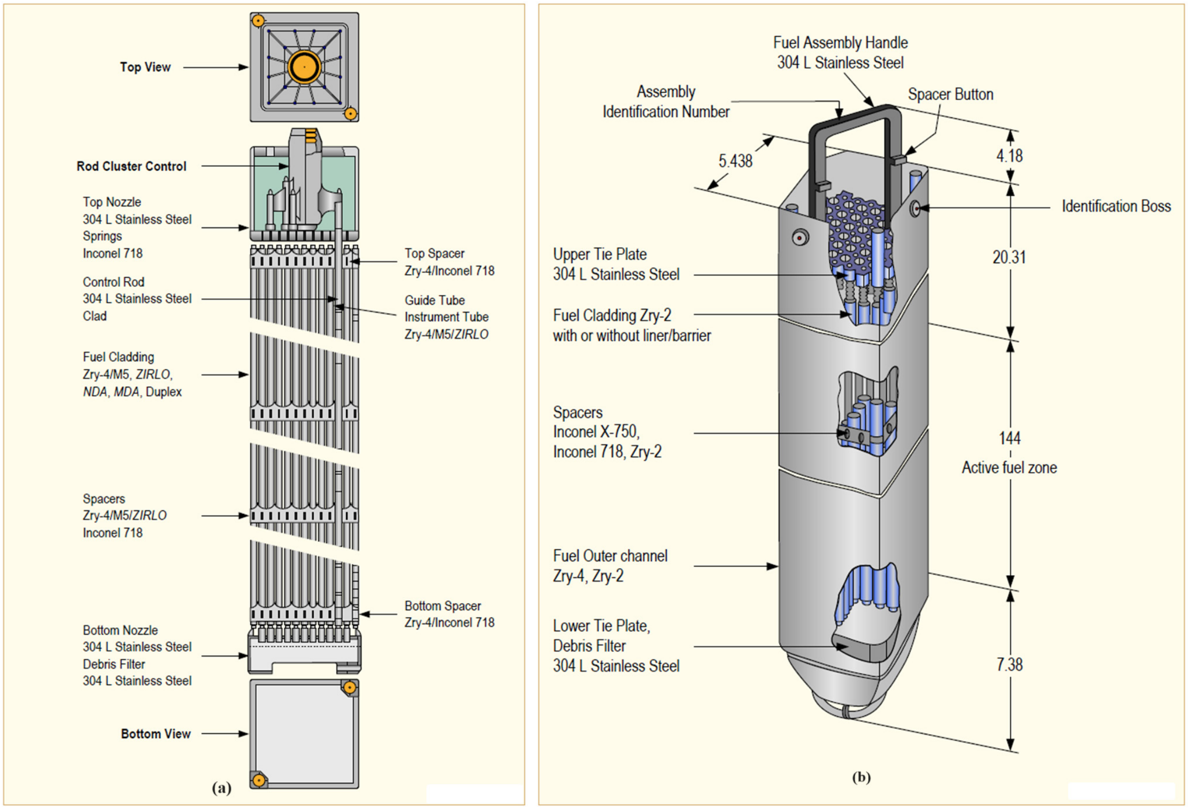

Figure A - 1. Typical (a) pressurized water reactor fuel assembly and (b) boiling water reactor fuel assembly (Strasser et al. 2014). Dimensions in inches.

PWR fuel assemblies have lengths most commonly ranging from 137.1 to 165.7 in [3.5 to 4.2 m] and widths most commonly ranging from 7.76 to 8.54 in [0.20 to 0.22 m] (Peters et al. 2022, Table A-1). BWR assemblies have lengths most commonly ranging from 134.4 to

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[78] In the United States, 93 nuclear power reactors — 31 BWRs and 62 PWRs — were in operation as of July 2023 (NRC 2023).

176.2 in [3.4 to 4.5 m] and widths most commonly ranging from 4.28 to 5.44 in [0.11 to 0.14 m] (Peters et al. 2022, Table A-2).

When nuclear fuel in a reactor can no longer efficiently sustain a nuclear fission reaction, the fuel assembly is removed from the reactor and replaced. The discharged fuel is referred to as "spent nuclear fuel" (SNF) or used nuclear fuel.

A.2 Management of Spent Nuclear Fuel

A.2.1 Wet Storage of Spent Nuclear Fuel

When SNF is first removed from a nuclear reactor, it is intensely radioactive and thermally hot due to radioactive decay (the heat generated is called decay heat), which decreases over time. Until the radioactivity has subsided sufficiently, the SNF must be stored underwater in a spent fuel pool (Figure A-2) adjacent to the reactor to dissipate the decay heat. The water in the spent fuel pool also provides shielding to protect plant operators and equipment from SNF radiation.

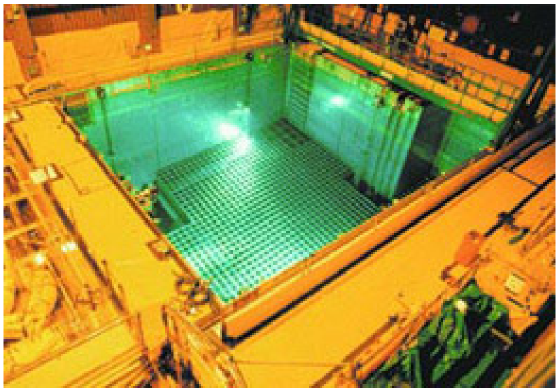

Figure A - 2 An example of a spent fuel pool at a reactor (NRC 2021).

A.2.2 Dry Storage of Spent Nuclear Fuel

Following a period of pool storage, SNF is typically transferred to dry-storage casks[79] to make space in the pool for SNF that will be discharged from continued reactor operation. Dry-storage casks fall into two main groups: (1) non-canistered dry-storage casks and (2) canister-based dry-storage casks. Figure A-3 explains the terminology used in this report for SNF containers.

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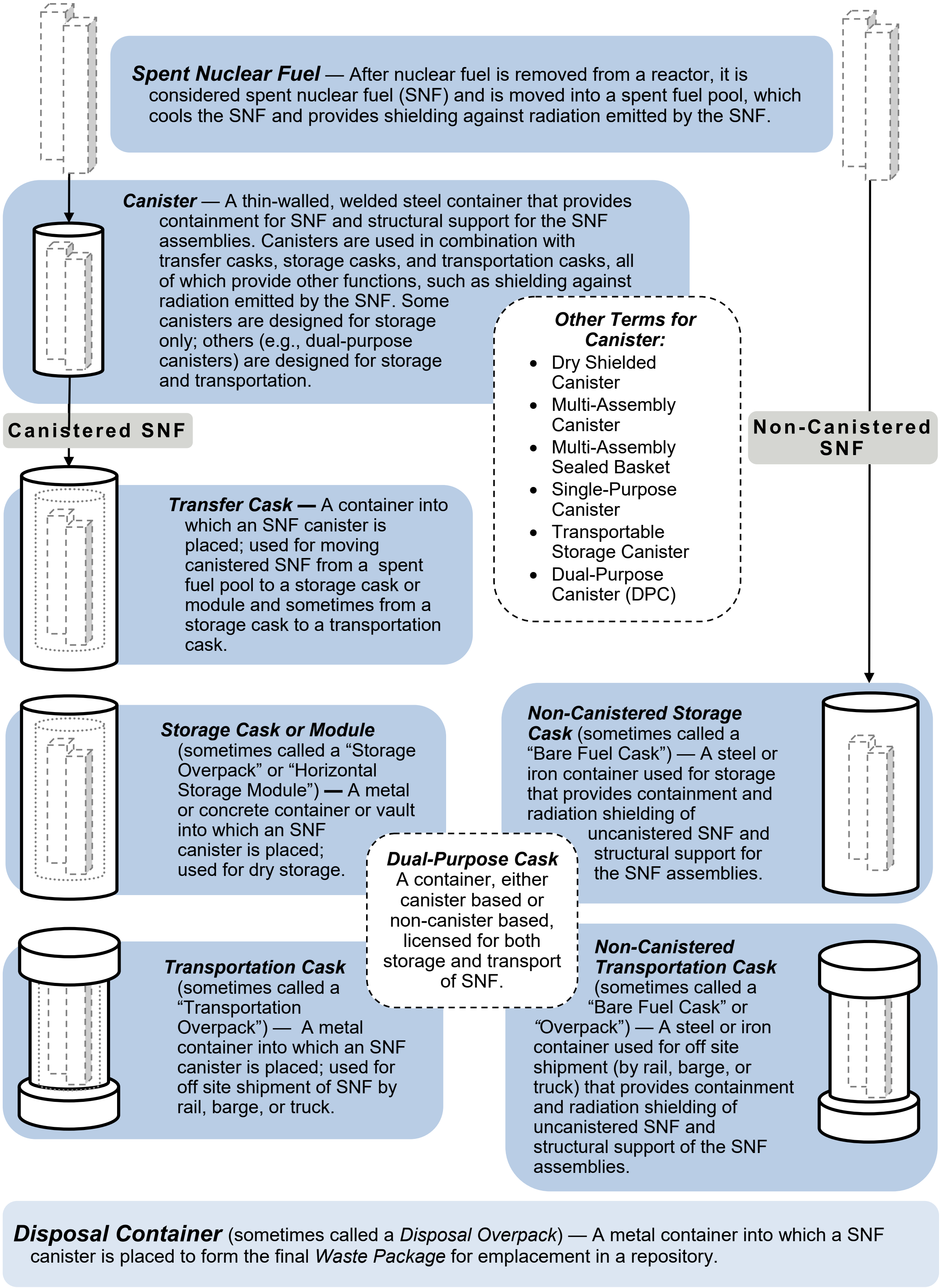
[79] A number of different terms are used in the commercial nuclear industry and by DOE to refer to the large engineered systems used for dry storage of SNF. Apart from when differences in the designs of these systems make it necessary to distinguish between them, or it is necessary to refer to specific system components, this report uses the term "dry-storage cask" generically to refer to any of these systems and the term "canister" to refer to the welded internal system component that contains the SNF in many of these systems.



Spent Nuclear Fuel — After nuclear fuel is removed from a reactor, it is considered spent nuclear fuel (SNF) and is moved into a spent fuel pool, which cools the SNF and provides shielding against radiation emitted by the SNF.

Canister — A thin-walled, welded steel container that provides containment for SNF and structural support for the SNF assemblies. Canisters are used in combination with transfer casks, storage casks, and transportation casks, all of which provide other functions, such as shielding against radiation emitted by the SNF. Some canisters are designed for storage only; others (e.g., dual-purpose canisters) are designed for storage and transportation.

Other Terms for Canister:

- Dry Shielded Canister
- Multi-Assembly Canister
- Multi-Assembly Sealed Basket
- Single-Purpose Canister
- Transportable Storage Canister
- Dual-Purpose Canister (DPC)

Transfer Cask **—** A container into which an SNF canister is placed; used for moving canistered SNF from a spent fuel pool to a storage cask or module and sometimes from a storage cask to a transportation cask.

Storage Cask or Module (sometimes called a "Storage Overpack" or "Horizontal Storage Module") **—** A metal or concrete container or vault into which an SNF canister is placed; used for dry storage.

Non-Canistered Storage Cask (sometimes called a "Bare Fuel Cask") — A steel or iron container used for storage that provides containment and radiation shielding of uncanistered SNF and structural support for the SNF assemblies.

Dual-Purpose Cask A container, either canister based or non-canister based, licensed for both storage and transport of SNF.

Transportation Cask (sometimes called a "Transportation Overpack") — A metal container into which an SNF canister is placed; used for off site shipment of SNF by rail, barge, or truck.

Non-Canistered Transportation Cask (sometimes called a "Bare Fuel Cask" or "Overpack") — A steel or iron container used for off site shipment (by rail, barge, or truck) that provides containment and radiation shielding of uncanistered SNF and structural support of the SNF assemblies.

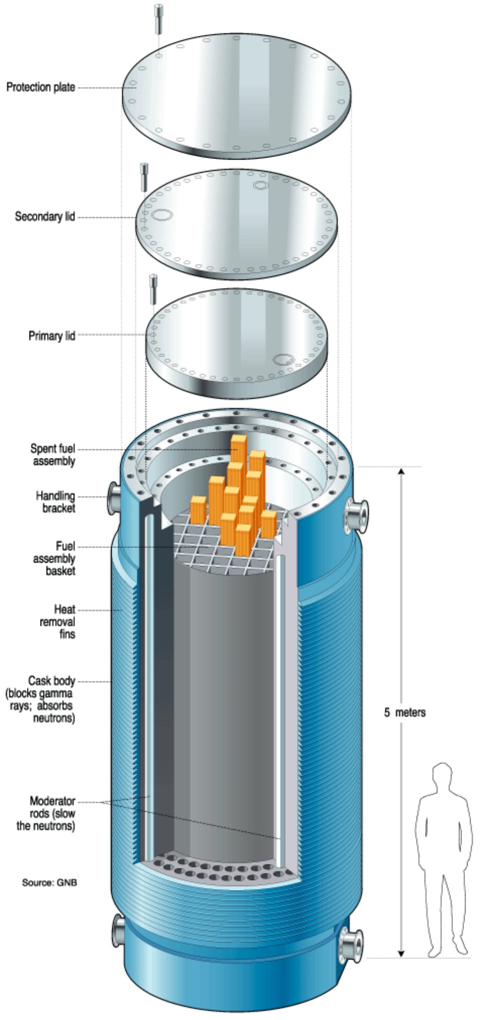
Disposal Container (sometimes called a *Disposal Overpack*) — A metal container into which a SNF canister is placed to form the final *Waste Package* for emplacement in a repository.

Figure A - 3. Terminology used in the nuclear industry for containers holding commercial spent nuclear fuel.

Non-Canistered Dry-Storage Casks

Non-canistered dry-storage casks are cylindrical vessels made of steel or iron, with walls up to 16 in [41 cm] thick, and have internal baskets to support the SNF assemblies (Raddatz and Waters 1996). Figure A-4 shows a typical non-canistered dry-storage cask design. SNF is loaded directly into non-canistered dry-storage casks underwater in a spent fuel pool. The closure lids of non-canistered casks are bolted, which facilitates reopening the cask to allow the SNF to be repackaged, if needed, for transportation or disposal. These casks provide sealed containment for the SNF, to prevent any release of radioactive material and control the storage environment for the SNF, fuel heat removal, and radiation shielding. Some non-canistered casks are certified for both storage and transportation and are referred to as dual-purpose casks.

Non-canistered dry-storage casks are up to 8 ft 11 in [2.7 m] in diameter, up to 16 ft 5 in [5.0 m] in length, and, when loaded with SNF, weigh up to 121 tons [110 metric tons] (Carter 2016). These casks are stored vertically on concrete pads at the dry storage facility. Figure A-5 shows non-canistered casks of different designs[80] stored at the Idaho National Laboratory site.



Source: GNB

Figure A - 4. A non-canistered dry-storage cask (Zorpette 2001).

Canister-Based Dry-Storage Casks

Dry-storage canisters are cylindrical steel vessels, with walls that range in thickness from 0.5 to 1.0 in [1.3 to 2.5 cm], and have internal baskets to support the SNF assemblies. Dry-storage canisters are typically between 5 and 6 ft [between 1.5 and 1.8 m] in diameter, between 15 and 16 ft [between 4.6 and 5.0 m] in length, and, when loaded with SNF, weigh between 38 and 58 tons [between 34 and 53 metric tons] (Carter 2016).

Canisters provide containment for the SNF, to prevent release of radioactive materials and control the storage environment for the SNF, and fuel heat removal, but offer only limited radiation shielding capability. Canisters are loaded with SNF underwater in a spent fuel pool and then moved to a location in the spent fuel pool area for the water to be removed and the lids to be welded on. Following filling with helium, to assist in cooling the SNF during

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[80] The VSC-17 dry-storage cask shown in Figure A-5 has a unique design—it has 17 "canisters" that have the same external dimensions as a PWR assembly (14 ft [4.3 m] × 8.5 in. [21.6 cm] square) (Carlson et al. 2006).

storage, canisters are moved to a dry-storage facility in a transfer cask, which provides the necessary shielding for the SNF during transfer operations.

Figure A - 5. Dry-storage casks at the Idaho Nuclear Technology and Engineering Center, Idaho National Laboratory (Hanson et al. 2012).

At the dry-storage facility, canisters are placed in concrete (or concrete and steel) dry-storage casks (Figure A-6). The dry-storage casks are stored vertically above ground on concrete pads (Figure A-6a) or below ground (Figure A-6b). The canisters may also be emplaced horizontally in concrete storage units called "modules" or "vaults" (Figure A-6c). The dry-storage cask or concrete module provides the necessary radiation shielding, heat removal via natural convection, and physical protection for the SNF during storage.

Figure A - 6. Spent nuclear fuel canisters stored in (a) vertical, above ground dry-storage casks, (b) vertical, below ground dry-storage casks, and (c) horizontal storage modules (Rechard et al. 2015).

Although some of the earlier-design canisters are NRC-approved for storage only, ~84 percent of the canisters loaded with SNF as of June 1, 2023, are NRC-approved for both the storage of (inside a dry-storage cask) and transportation (inside a transport cask or overpack) of SNF (Freeze et al. 2021; UxC 2023a) and are referred to as dual-purpose canisters (DPCs). Most of the SNF currently in dry storage at nuclear power plant sites is in DPCs (Greene et al. 2013).

DPCs are typically loaded into different casks for storage and transportation. However, cask vendors are now building and obtaining certifications for canister-based casks that can be used for storage and transport.

A.2.3 Transportation of Spent Nuclear Fuel

Transportation of SNF requires the use of a transport cask, or overpack, a robust iron or steel container that includes shielding to reduce the radiation levels outside the cask and is sealed to prevent the release of radioactive materials. Transport casks are cylindrical vessels with shielding materials ranging from 5 to 15 in [13 to 38 cm] in thickness. The cask closure system consists of one or two steel lids that have elastomer or metal seals to provide containment during transportation. Transport casks may be up to 9 ft 2 in [2.8 m] in diameter, up to 19 ft 8 in [6.0 m] in length, and, when loaded with SNF, may weigh up to 218 tons [197 metric tons] (Carter 2016). Figure A-7 is a schematic illustration of a SNF transport cask.

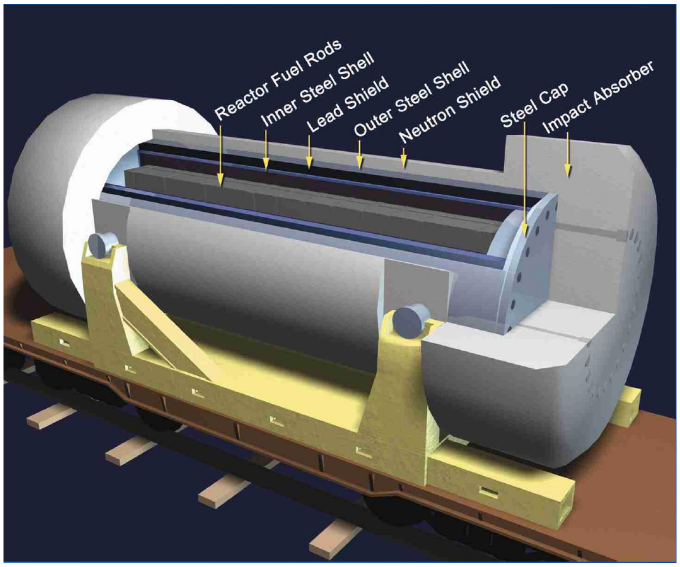

Figure A - 7. A schematic illustration of a spent nuclear fuel transport cask (McCullum 2012).

Transport casks can be designed to hold DPCs containing the SNF or bare SNF assemblies in a fuel basket inside the transport cask. The lid of the transport cask is closed using bolted fasteners. Before transport, impact limiters, typically made of wood, rigid foam, or honeycombed metal, are attached to both ends of the cask to absorb impact loads in accident conditions. Because of the size and weight of the casks used for dry storage of SNF at nuclear power plant sites, rail or barge would be the preferred modes of transport for these loads, rather than by truck over roads. DOE indicated in its Record of Decision, published in 2004, that transportation of SNF and HLW to the proposed Yucca Mountain geologic repository would be mostly by rail (DOE 2004). Figure A-8 is a photo of two transport casks used to ship commercial SNF by rail from the West Valley Demonstration Project in New York to the Idaho National Laboratory in 2003. These two casks, the TN-REG (holding SNF from the R.E. Ginna nuclear power plant) and the TN-BRP (holding SNF from the Big Rock Point nuclear power plant) were designed as dual-purpose casks (storage and transportation) by Transnuclear, Inc. (now Orano TN). The casks, still loaded with SNF, are in storage at the Idaho National Laboratory.

Figure A - 8. Rail transport casks (with impact limiters installed) used to transport spent nuclear fuel from the West Valley Demonstration Project Site (West Valley, New York) to the Idaho National Laboratory (Bickford 2022).

Small transport casks, typically containing one PWR or two BWR SNF assemblies, may be transported over roads by legal weight truck without a special weight permit. One such example is the NAC International NAC-LWT transport cask shown in Figure A-9. Small transport casks like the NAC-LWT are not intended for transporting large quantities of commercial SNF. Shipments of larger transport casks by road, including casks carrying large DPCs, would exceed the 80,000 lb. [36,000 kg] federal limit for legal weight trucks and would require special permits from the state transportation authorities. If large transport casks are to be transported by road, they require an overweight load permit, a superload permit or a "heavy haul" permit. Figure A-10 shows a transport cask in Spain being moved by road under a heavy haul permit. [81]

Figure A - 9. NAC International NAC-LWT transport cask (Power Technology 2024).

Figure A - 10. Multimodal Transportation Test; ENRESA [Empresa Nacional de Residuos Radiactivos Sociedad Anónima] ENUN-32P cask on a heavy haul truck (McConnell et al. 2018) (see footnote 81).

A.2.4 Geologic Disposal of Spent Nuclear Fuel

Disposal Containers

Whether SNF is disposed of in a geologic repository in DPCs or in different canisters following repackaging, the implementer (DOE) will need to develop containers or overpacks suitable for disposal in a repository. Various disposal container designs may need to be developed if SNF is to be disposed of without repackaging because of the variety of DPC designs used at nuclear power plant sites.

If SNF is repackaged before disposal, but this would allow the use of a single or a limited number of designs of disposal containers. While this would simplify the subsequent handling

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[81] Although Figure A-10 demonstrates a heavy-haul truck transport of an SNF cask, the Board notes that this particular cask was holding surrogate SNF for a test shipment in Spain, and the cask is not currently licensed in the U.S. Furthermore, the configuration shown in Figure A-10 does not include the cask impact limiters, which would be installed on both ends of the cask, in the case of an irradiated SNF shipment.

and emplacement operations at the repository, it requires repackaging of the SNF that will have been loaded into DPCs up to that time.

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APPENDIX B — INDEFINITE STORAGE OF SPENT NUCLEAR FUEL AT INDEPENDENT SPENT FUEL STORAGE INSTALLATIONS

This Appendix considers the implications of a scenario in which spent nuclear fuel (SNF) discharged from nuclear power plants would continue to be stored indefinitely at independent spent fuel storage installations (ISFSIs),[82] with none transported to a repository site or a consolidated interim storage facility[83] for the foreseeable future.[84]

B.1 Number of Dry-Storage Casks Required for Storage of Spent Nuclear Fuel at Nuclear Power Plant Sites

From 2008 through 2022, an average of more than 190 dry-storage casks (both canistered and non-canistered casks) per year were loaded at nuclear power plant sites (Freeze et al. 2021; UxC 2022, 2023a). As of June 1, 2023, almost 4,000 dry-storage casks are in service at ISFSIs (UxC 2023b).

Figure B-1 illustrates the projected inventory of SNF (in metric tons of heavy metal [MTHM])[85] from 1985 through 2080 that will be discharged from the nuclear power plants and stored in dry-storage casks or in spent fuel pools (Freeze et al. 2021).[86] The projected inventory totals 135,809 MTHM in 2080, when all SNF from the final shutdown reactor will have been transferred to storage. Freeze et al. (2021) estimated that the number of dry-storage casks required to store this projected inventory is about 10,000. However, as can be

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[82] An ISFSI is a facility designed and constructed for the interim storage of spent nuclear fuel that is solid, reactor-related, and greater-than-Class-C waste and other associated radioactive materials. An ISFSI may be considered independent even if it is located on the site of another NRC-licensed facility (NRC 2021). As of January 2022, ISFSIs are in operation at all nuclear power plant sites except for the Shearon Harris site in New Hill, North Carolina (UxC 2022). The Shearon Harris Nuclear Power Plant will not require dry storage of SNF through the expiration of its renewed operating license in 2046 (Peters et al. 2022; UxC 2022).

[83] Under the NWPA, a monitored retrievable storage facility is to be designed, constructed, and operated by DOE. However, NRC also licenses consolidated interim storage facilities, which can be designed, constructed, and operated by a private commercial entity. For the purposes of this report, the term “consolidated interim storage facility” means a DOE monitored retrievable storage facility, a commercial storage facility, or both.

[84] For the purposes of this report, this means storage for more than 80–120 years.

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

[86] The projected inventory illustrated in Figure B-1 is for a “no replacement nuclear power generation” scenario that makes several assumptions, including (1) no new reactors are constructed and operated (i.e., no replacement); (2) 60 or 80 years of operation (depending on renewal status) for existing reactors (as of the end of 2020), when early shutdowns have not been announced; and (3) no SNF is reprocessed and all remain in storage (Freeze et al. 2021). Under the second assumption, all currently operating reactors will be shut down by 2055, except for Watts Bar 2, which will be shut down in 2075 and have all its SNF transferred to dry storage by 2080.

seen from Figure B-1, the projected rate of discharge of SNF is much higher in the first half of the century than in the second half; with the result that by 2050, approximately 95 percent of the total, or about 9,500 dry-storage casks, will have been loaded and stored at ISFSIs.

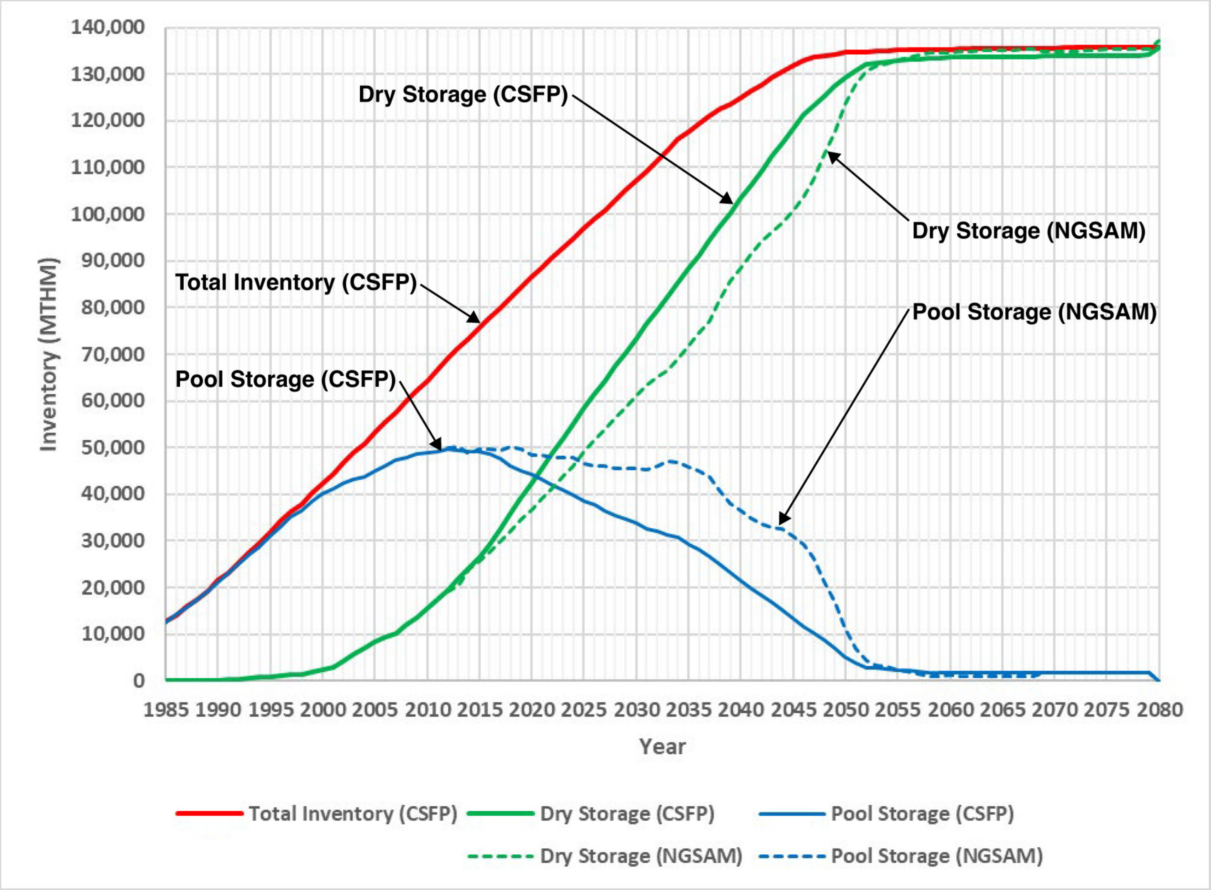

Figure B - 1. Projected inventory of U.S. commercial spent nuclear fuel in storage (Freeze et al. 2021).

Notes: The projected inventories were calculated using the U.S. Commercial Spent Fuel Projection (CSFP) tool (solid curves) (Vinson 2015) or the Next-Generation System Analysis Model (NGSAM) (dashed curves) (Joseph et al. 2019).

B.2 Requirement for Independent Spent Fuel Storage Installation Capacity

To accommodate the increase in the number of dry-storage casks with time, the capacity of ISFSIs at nuclear power plant sites may need to be increased. Some utilities have already licensed ISFSIs with sufficient capacity for dry storage of all the SNF discharged from their reactors through the end of their operating lifetimes. Other utilities would need to increase the capacity of their ISFSIs, which may require renewing the license of those facilities.

B.3 Replacement of Dry-Storage Casks and Independent Spent Fuel Storage Installations

As discussed in Section 2, the absence of a clearly defined path or timeframe for disposal of SNF has led the nuclear utilities to view long-term, on-site storage as the de facto SNF management program in the United States for the foreseeable future. In line with this, the utilities have been seeking ISFSI license renewals to increase the duration of dry storage of SNF. Furthermore, in 2014, the NRC generically analyzed the environmental impact of continued storage of SNF for periods of up to 160 years, and possibly even longer (NRC 2014).[87]

Given the trend in extending the duration of certifications for dry-storage casks, it is necessary to anticipate the eventual need to repackage SNF if it remains at ISFSIs indefinitely. Depending on the timing of the need for repackaging and whether standardized cask designs are developed as part of the waste management program, repackaging may be into dry-storage canisters like those in service today, into more advanced designs of dry-storage canisters or standardized canisters. To support its analysis of future repackaging, the NRC's "Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel" (NRC 2014) assumed construction of a dry-transfer facility at each site. Alternatively, it may be possible to avoid the construction of a dry-transfer facility at each site if a transportable repackaging facility design is licensed and enough units are made available to allow use at each site on the schedule necessary to meet the terms of the license for the ISFSI.

For the scenario in which SNF would continue to be stored indefinitely at ISFSIs, it is assumed that SNF stored in non-canistered storage casks would be repackaged into dry-storage canisters the first time the SNF needed to be repackaged. It is also necessary to assume the need to replace the ISFSI structures and equipment periodically. This would not require handling individual SNF assemblies, as is the case for repackaging, but would require relocation of dry-storage casks within the site as part of the operations required for periodic replacement of ISFSI structures and equipment.

B.4 Release of Nuclear Power Plant Sites for Other Uses

Sites used for industrial purposes may be released for other purposes following the decommissioning of the facilities located on them and the removal of the waste materials generated during the operation and decommissioning of those facilities. Depending on the subsequent use planned for a nuclear power plant site following decommissioning, it may be appropriate to leave some facilities for continued use. For example, if the utility plans to

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[87] NUREG-2157, "Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel" (NRC 2014) analyzes three timeframes that represent potential storage periods: (1) a short-term timeframe, which includes 60 years of continued storage after the end of a reactor's licensed life for operation before SNF is sent to a repository; (2) an additional 100-year timeframe (i.e., 60 years plus 100 years) to address the potential for delay in repository availability; and (3) an indefinite timeframe to address the possibility that a repository never becomes available.

construct another power plant at the site, it may be appropriate to avoid decommissioning the transmission lines or electrical switchgear.

While decommissioning the reactor and other major facilities at a nuclear power plant site may allow the reuse of some of the sites, continued dry storage of SNF at an ISFSI would prevent the release of the complete site for subsequent use. Indefinite storage of SNF would also require the utility to maintain security and systems at the site, as well as maintaining the site license and capabilities for responding to emergencies. Given the assumption in the NRC generic environmental impact statement (NRC 2014) that a dry-transfer facility would eventually be needed at each ISFSI, the utility would also need to maintain the capability for locating such a facility in the vicinity of the ISFSI, and this may further limit the extent to which the utility could make the site available for other uses.

Thus, indefinite storage of SNF at ISFSIs could have significant implications for utilities, both in requiring a continuing commitment to the operation and maintenance of the ISFSI and in limiting the potential release of the site for other uses.

B.5 Other Implications for a National Waste Management System

A scenario in which SNF discharged from nuclear power plants is stored indefinitely at ISFSIs avoids the need for near-term transportation, consolidated interim storage, and a repository, saving money in the near term. However, if the SNF is eventually disposed of in a repository, the overall lifetime system costs of SNF management would be significantly higher due to the costs of maintaining the ISFSIs.

Continued storage of SNF at ISFSIs will also allow more time for the SNF decay heat and radiation levels to decrease, which could make future operations much easier. Further, although the NRC has found, through its licensing process for ISFSIs, that dry storage of SNF is safe, additional analyses may be required to demonstrate the safety of dry storage for periods much longer than the term of the licenses and renewals the NRC has approved for ISFSIs.

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APPENDIX C — REPACKAGING SPENT NUCLEAR FUEL FROM DRY-STORAGE CASKS

In this report, the term repackaging is used to refer to the operation in which individual spent nuclear fuel (SNF) assemblies are unloaded from a dry-storage cask[88] and loaded into a new, typically smaller, canister for transport, possible further storage, and eventual disposal. Repackaging is distinct from the operation to transfer a dry-storage canister loaded with SNF from one storage or transport cask (or overpack) to another. Such transfer operations do not involve the handling of individual SNF assemblies, which entails the risk of the SNF being damaged.

Depending on the approach taken for a national nuclear waste management program, the repackaging operation may be performed at the nuclear power plant site, at an interim storage facility, or at a repository site and may be performed in a spent fuel pool or in a dry transfer facility. This Appendix considers why repackaging SNF may be required and discusses the implications of repackaging.

C.1 Factors Determining the Need to Repackage Spent Nuclear Fuel

There are two main reasons it may be necessary to repackage SNF. First, some dry-storage casks were not designed for transportation, and none were designed for disposal. Consequently, unless the casks can be demonstrated to meet the appropriate regulatory requirements and to not impose physical constraints on disposal systems, the SNF will need to be repackaged before emplacement in a repository or, possibly, before transportation away from the nuclear power plant site or an interim storage facility. Second, while there is a high level of confidence that any degradation of dry-storage casks, or the SNF they contain, during extended storage periods will be limited, it is necessary to anticipate that degradation of SNF or dry-storage casks will eventually occur to the extent that repackaging becomes necessary in order to meet safety requirements for transportation or for additional periods of storage and then disposal.

Several factors must be considered when determining whether, and when, it is necessary to repackage SNF from dry-storage casks into different containers prior to transportation, further periods of interim storage, or disposal in a geologic repository. Among these factors are size and weight limitations, criticality safety requirements, temperature limits, radiation limits, and potential degradation of dry-storage casks or SNF over time. The trend toward higher fuel burnups in U.S. commercial reactors (see Box C-1) will have an impact on the last four of these factors. From the utilities' perspective, other factors will also be important

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[88] A number of different terms are used in the commercial nuclear industry and by the U.S. Department of Energy (DOE), to refer to the large engineered systems used for dry storage of SNF. Apart from when differences in the designs of these systems make it necessary to distinguish between them, or it is necessary to refer to specific system components, this report uses the term "dry-storage cask" generically to refer to any of these systems and the term "canister" to refer to the welded internal system component that contains the SNF in many of these systems. Appendix A explains the terminology used in this report for SNF containers.

if repackaging is required at nuclear power plant sites, such as the time required for the introduction of new dry-storage cask designs, the impacts of repackaging on utility operations, worker exposure to ionizing radiation, the generation of additional quantities of low-level radioactive waste, and cost.

Box C - 1. Burnup of Spent Nuclear Fuel

"Burnup" is a measure of the amount of energy produced by nuclear fuel in a reactor. It is expressed in gigawatt-days per metric ton of initial uranium (GWd/MTU). Over time, utilities have increased fuel burnup levels to get more energy out of their fuel before replacing it. The average burnup two decades ago was approximately 35 GWd/MTU but is over 45 GWd/MTU today. In the United States, SNF assemblies with burnups greater than 45 GWd/MTU are considered "high burnup" assemblies.

Burnup level is an important factor in SNF storage, transportation, and disposal due to the impact it has on the decay heat and radioactivity of the fuel. At higher burnups, the fuel discharged from the reactor is more radioactive and generates more heat due to the radioactive decay of fission products. Thus, dry-storage casks, transport casks, and waste packages loaded with high burnup SNF would be hotter and have higher radiation levels than similar containers loaded with the same quantity of lower burnup fuel after the same cooling time. Increasing burnup levels also affects the physical properties of fuel pellets and cladding, which may make the cladding more susceptible to cracking, particularly during handling and transportation. However, the cladding materials used in the fabrication of fuel intended to be used to higher burnups are designed to mitigate these effects.

C.1.1 Size and Weight Limitations

Since the introduction of the first dry-storage casks, utilities and cask vendors have sought to increase cask capacities, driven by the economy of scale. Table C-1 shows how cask capacities and weights have increased since the first dry-storage casks were loaded in 1986.

As noted in Appendix A, canisters used in dry-storage canister systems are up to 6 ft [1.8 m] in diameter, up to 16 ft [4.9 m] in length, and weigh up to 58 tons [52.8 metric tons] when loaded with SNF. If these canisters were to be used for direct disposal of SNF,[89] it would require that all of the facilities in which they would be handled be equipped to accommodate their size and weight, plus the size and weight of the casks in which the canisters are stored and transported and the overpacks into which they will be loaded for disposal. Conversely, if their size and weight could not be accommodated for transportation and/or emplacement in a repository, the SNF in the canisters would need to be repackaged.

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[89] It is assumed in this report that only SNF in welded, dry-storage canisters will be considered for the option of direct disposal (i.e., without repackaging the SNF) in a repository. These canisters would be placed inside a cask for continued storage or transportation or inside a disposal container for emplacement in a repository. Appendix A explains the terminology used in this report for SNF containers.

Table C - 1. Increase in dry-storage cask capacities and weights with time

Vendor	Cask/Canister (Associated Dry-Storage System)	Year First Licensed	Maximum Number of Assemblies	Loaded Weight
NAC International	NAC I28 S/T Metal Storage/Transport Cask	1986	28 PWR	103 tons (94 metric tons)
Holtec International	MPC-32 Multi-Purpose Canister (HI-STORM storage overpack)	2000	32 PWR	122 tons (111 metric tons)
Holtec International	MPC-37 Multi-Purpose Canister (HI-STORM FW storage overpack)	2011	37 PWR	218 tons (198 metric tons)

The transportation infrastructure close to some nuclear power plants currently would not be able to support transportation of loads of these weights and dimensions. However, some of the components delivered to nuclear power plant sites during initial construction (or refurbishment or removed during decommissioning) are of at least the same size and weight as loaded canisters and overpacks. Consequently, refurbishment or reinstatement of the infrastructure near those plants would allow transportation of canisters and casks away from the nuclear power plant sites. Also, the cask vendors and the utilities are aware of the limits that apply to moving large and heavy loads by road, by rail, and by barge, and have ensured that the canisters and casks loaded at the nuclear power plant sites can be transported to other facilities when necessary.

Limitations on the size and weight of waste packages that can be handled at a repository site may be more restricting. The maximum load that can be lowered down a shaft at a mine or a disposal facility to depths of 300–500 meters, using currently available technology, is approximately 85 metric tons (SNL 2021). This may not be sufficient to allow payloads of dual-purpose canisters (DPCs) in overpacks, which may weigh as much as 175 metric tons depending on the DPC size and disposal overpack design (Hardin et al. 2013). However, as discussed in Section 4.1, German engineers (BGE Technology) have completed conceptual designs for upscaling hoist capacities to 175 metric tons, and a U.S. Department of Energy (DOE) study concluded that the engineering challenges that would be faced in handling such a payload using a hoist system in a repository can be met (Hardin 2015; Hardin et al. 2015). An alternative method of moving waste packages into a repository would be to use a vehicle ramp, although the construction and maintenance of a ramp for this purpose may also face challenges.

C.1.2 Criticality Safety

Nuclear fuel is designed to attain criticality to generate power when loaded into a reactor (see Box C-2). After being discharged from the reactor and until disposal, however, it is extremely important to prevent criticality from occurring. Consequently, dry-storage casks and transport casks are designed to prevent criticality when loaded with SNF.

The potential for criticality to occur in a cask or disposal container is dependent on the number and type of SNF assemblies in the cask, the isotopic composition of the SNF as influenced by the burnup of the SNF assemblies,[90] the cask design, the neutron absorber materials used in the construction of the cask or container,[91] and whether the cask could become flooded with water.[92]

Box C - 2. Criticality Safety

Inside a nuclear reactor, the fuel assemblies are arranged in a carefully designed, closely packed array such that the reactor can reach "criticality" in order to generate power. When the reactor is just at the point of criticality, the nuclear fission process in the fuel produces enough neutrons to sustain a steady-state fission process in what is referred to as a self-sustaining "chain reaction." Control rods or chemicals containing boron dissolved in the coolant in the reactor contain materials that absorb neutrons and are moved into and out of the reactor to control the reactor power. The control rods are fully inserted or the concentration of boron chemicals is increased to shut the reactor down for maintenance or refueling.

When SNF is stored, transported, or disposed of in a repository, the canister or cask in which the SNF is contained needs to satisfy the criticality safety requirements in the appropriate NRC regulations. These requirements are defined to prevent the fuel reaching criticality after being discharged from the reactor and prior to disposal.

The U.S. Nuclear Regulatory Commission (NRC) specifies the requirements for criticality safety during SNF storage in Title 10 of the Code of Federal Regulations, Part 72 (10 CFR 72), *Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater Than Class C Waste*. 10 CFR 72 stipulates that the "storage cask must be designed and fabricated so that the spent fuel is maintained in a subcritical condition under credible conditions." There is no specific requirement to demonstrate that a dry-storage cask cannot reach criticality when flooded, as flooding of a storage facility is not considered a credible condition, even in the event of a severe accident at the independent spent fuel storage installation (ISFSI).

The NRC regulation relating to the transportation of SNF and SNF containers is Title 10 of the Code of Federal Regulations, Part 71 (10 CFR 71), *Packaging and Transportation of Radioactive Material.* 10 CFR 71 stipulates that "…a package used for the shipment of fissile material must be so designed and constructed and its contents so limited that it would be subcritical if water were to leak into the containment system [during an accident]" (10 CFR 71.55). These requirements for criticality safety are more restrictive than those for storage. During transportation, the fuel must remain subcritical in severe accident

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[90] The potential for criticality decreases with increasing SNF burnup.

[91] These are materials included in the design of a cask or disposal canister to prevent criticality from occurring (see Box C-2)

[92] Water reduces the energy of neutrons released by fission in the uranium fuel, increasing the potential for criticality to occur. In having this effect, water is said to act as a "neutron moderator."

conditions, including a breach of the transport cask, a breach of the SNF canister, and full flooding of the canister, unless the design of the cask and the canister (if one is used) can be demonstrated to prevent flooding with water in the event of all credible accident conditions. Given the difference in criticality safety requirements for storage and transportation, nuclear utilities may have to repackage some SNF from large dry-storage casks into different, possibly smaller capacity, casks prior to transportation to ensure the SNF remains subcritical.

C.1.3 Surface Temperature Limits

The surface temperature of a cask during storage and while being transported is important to limit risk to members of the public. Also, some geologic repository concepts include a maximum surface temperature limit for waste packages to be emplaced in the repository. The surface temperature is dependent on the cask/waste package design, the number and type of SNF assemblies in the cask/waste package, the isotopic composition of the SNF as influenced by its burnup, the spacing of casks/waste packages in the repository, and the time since the SNF was discharged from the reactor. As the time after discharge from the reactor increases, the decay heat produced by the SNF decreases, and so does the surface temperature of the cask/waste package.

Dry-Storage Cask Surface Temperature Limit During Storage

During cask handling operations and storage on a nuclear power plant site, access to a dry-storage cask is under the control of the utility and is limited to utility staff. Consequently, there is no requirement for a regulatory limit on the cask surface temperature prior to the transportation of the SNF away from the site.[93]

Transport Cask Surface Temperature Limit During Transportation

10 CFR 71 defines limits for transport cask surface temperatures during transportation. 10 CFR 71.43(g) stipulates that "A package must be designed, constructed, and prepared for transport so that in still air at 38°C [100°F] and in the shade, no accessible surface of a package would have a temperature exceeding 50°C [122°F] in a non-exclusive use shipment, or 85°C [185°F] in an exclusive use shipment."[94] Thus, if transportation is required prior to the surface temperature of a transport cask meeting the requirement of 10 CFR 71, it may be necessary to repackage the SNF from large dry-storage casks into different, likely smaller-

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[93] Temperature limits may be specified for some cask components during this time and the maximum temperature the fuel cladding is allowed to reach is specified. However, these are to avoid degradation of the materials concerned, not to prevent injury to personnel.

[94] Title 10 of the Code of Federal Regulations, Part 71.4 defines "exclusive use" as "the sole use by a single consignor of a conveyance for which all initial, intermediate, and final loading and unloading are carried out in accordance with the direction of the consignor or consignee. The consignor and the carrier must ensure that any loading or unloading is performed by personnel having radiological training and resources appropriate for safe handling of the consignment." Transportation of SNF is generally intended to be in the form of exclusive-use shipments (NRC 2020b).

capacity canisters[95] in order to meet the temperature limit for the surface of the transport cask.

Waste Package Surface Temperature Limit for Disposal

Repository concepts being considered in the U.S. and other countries include a maximum surface temperature limit for waste packages to be emplaced in the repository, because elevated temperatures could degrade the performance of engineered and natural barriers designed to prevent water intrusion and isolate the wastes for long periods of time. In order to meet the specified temperature limit in the repository, it may be necessary to repackage the SNF from large dry-storage casks into smaller canisters (hence lower heat load) prior to disposal. If SNF in dry-storage canisters were to be directly disposed of in a repository (i.e., without repackaging the SNF), another option is to provide a longer cooling time for the SNF in dry storage, although it may take decades or even more than 100 years for SNF in some large canisters to cool sufficiently to allow direct disposal in a repository. The potential thermal effects could also be reduced by increasing the waste package spacing in the disposal drifts or by increasing the spacing between the repository drifts, both of which would decrease the temperatures within the repository.

C.1.4 Cask Radiation Limits

In a manner similar to temperature limits, the NRC sets limits on radiation levels from SNF casks to protect people from radiation. As noted in the above discussion of cask temperatures, the radiation level from a cask is dependent on the number and type of SNF assemblies in the cask, the isotopic composition of the SNF as influenced by its burnup, the time since the SNF was discharged from the reactor, and the cask design. The longer the SNF has been out of the reactor, the lower the radioactivity of the fuel and the lower the radiation level from the cask.

The radiation limits applicable to the storage and transportation of SNF are specified in 10 CFR 72 and 10 CFR 71, respectively. For SNF storage, 10 CFR 72.104(a) states that "During normal operations and anticipated occurrences, the annual dose equivalent to any real individual who is located beyond the controlled area[96] must not exceed 0.25 mSv [25 mrem] to the whole body, 0.75 mSv [75 mrem] to the thyroid and 0.25 mSv [25 mrem] to any other critical organ as a result of exposure to direct radiation from ISFSI…operations." For SNF transportation, 10 CFR 71.47 states that the radiation level at any point on the outer surface of the transport cask must not exceed 2 mSv/hr [200 mrem/hr] and that the radiation level at any point 2 m [6.6 ft] from the outer surface must not exceed 0.1 mSv/hr [10 mrem/hr].

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[95] It is assumed in this report that if SNF were to be repackaged, it would be loaded into canisters similar to those in service today, into more advanced designs of dry-storage canisters or standardized canisters. These canisters would be placed inside a cask for continued storage or for transportation, or inside a disposal container for disposal in a repository.

[96] A controlled area is a nuclear power plant site or storage facility where casks are stored, and access is controlled by the utility or storage facility operator.

Because the radiation limits during storage are different from those during transportation, it is possible for a cask to meet the requirements for storage but not for transport. Thus, some SNF may need to be repackaged before it can be transported away from the nuclear power plant site, unless it can be stored long enough for the radiation levels to decrease sufficiently to meet limits for transportation.

No regulatory limits have been specified for the radiation levels from waste packages to be emplaced in a repository.

C.1.5 Degradation of Spent Nuclear Fuel and Dry-Storage Casks

Degradation of dry-storage casks (and internal canister components) over long periods of storage (assuming delayed disposal) may eventually lead to the need for repackaging of the SNF they contain, while degradation of SNF may eventually impact the ability to retrieve SNF assemblies from casks for repackaging. Consequently, the potential for degradation during storage of SNF and the canisters used in canistered dry-storage casks has been the subject of research programs undertaken by several organizations, including DOE (e.g., Bryan et al. 2021; Duncan et al. 2021), NRC (e.g., Oberson et al. 2013; He et al. 2014) and EPRI (e.g., EPRI 2013, 2014). However, none of the research completed to date indicates that there will be significant degradation of either SNF or dry-storage canisters during prolonged periods of storage.

The NRC has concluded (NRC 2014):

> "…that there is no technical reason that spent fuel cannot be stored in dry casks beyond the short-term storage timeframe."[97]

and, in reference to the need for repackaging (NRC 2014), that:

> "…actual replacement times will depend on actual degradation observed during … continued storage. Studies and experience to date do not preclude a dry cask service life longer than 100 years."

Nevertheless, as the basis for analyzing the environmental impact of continued storage of SNF, the NRC assumed (NRC 2014):

> "…the replacement of dry casks after 100 years of service life…"

Accordingly, in preparing its generic analysis of the environmental impact of continued storage of SNF, the NRC assumed (NRC 2014):

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[97] "Short-term storage timeframe" refers to a period of 60 years following the end of the licensed operating lifetime of a nuclear power plant and is one of three timeframes considered by the NRC in its Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel – Final Report (NRC 2014). As SNF will be loaded into dry-storage canisters during the operating lifetime of a nuclear power plant, some SNF will have been stored for significantly longer than 60 years by the end of the "short-term storage timeframe."

- Spent fuel canisters and casks would be replaced approximately once every 100 years
- A dry-transfer system would be built at each ISFSI location for fuel repackaging
- ISFSI and dry-transfer system facilities would be replaced approximately once every 100 years

NRC storage regulations (10 CFR 72) require that “storage systems must be designed to allow ready retrieval of spent fuel … for further processing or disposal.” If monitoring of the condition of a dry-storage system or projection of potential degradation using computer models indicates that the requirement for “ready retrieval” may not continue to be met, it may be necessary to repackage the SNF for continued dry-storage.

NRC guidance allows demonstrating “ready retrievability” of SNF in dry-storage casks for further processing or disposal using any one, or a combination, of three retrieval options (NRC 2020a):

- Remove individual or canned SNF assemblies from wet or dry storage.
- Remove a canister loaded with SNF assemblies from a storage cask/overpack.
- Remove a cask loaded with SNF assemblies from the storage location.

Based on this guidance, SNF repackaging would not be required for additional periods of storage due to changes in fuel cladding condition, unless the canister fails and requires replacement (NRC 2020a). However, if there is some technically supported reason to believe that cladding degradation has occurred to the extent that the ability of the fuel assemblies in a cask to maintain their structural integrity is in question, repackaging may be required prior to subsequent transportation.

For example, the NRC transportation regulations (10 CFR 71.55) require that:

> “A package used for the shipment of fissile material must be designed and constructed and its contents so limited that … under normal conditions of transport … the geometric form of the package contents would not be substantially altered.”

This requirement is intended to ensure that SNF assemblies will not be damaged by the vibrations and shocks normally experienced during transportation. If degradation of SNF during dry storage may have occurred to the extent that this regulatory requirement cannot be met, it may be necessary to repackage the SNF (e.g., load it into damaged fuel cans and then into a new canister) before transportation.

Given the assumptions made by the NRC in preparing its generic analysis of the environmental impact of continued storage of SNF, it is assumed for this report that repackaging due to degradation of SNF or dry-storage casks would only be required for the “Indefinite Storage” scenario considered in Appendix B.

C.2 Implications of Repackaging Spent Nuclear Fuel into Smaller Canisters

This section considers a scenario in which all SNF assemblies are repackaged from large dry-storage canisters and casks into different containers, in order to meet the regulatory requirements for transport or disposal. For this scenario, it is assumed that the SNF is repackaged into dry-storage canisters that are smaller than the canisters and casks currently used for dry-storage. The SNF may be repackaged at the nuclear power plant sites, the repository site, or a centralized interim storage facility.

Repackaging SNF would involve moving the dry-storage canister or cask to either a spent fuel pool or a dry repackaging facility, opening the canister or cask, transferring the SNF assemblies into a new dry-storage canister, and then sealing the canister. The canister would then be loaded into a storage cask, a transport cask, or a disposal container (also called disposal overpack [see Figure A-3]), depending on where the repackaging is performed. The implications of repackaging SNF into smaller canisters are discussed below.

C.2.1 Number of Canisters and Disposal Containers

Repackaging SNF from large dry-storage canisters and casks into smaller canisters would increase the number of canisters, as well as the number of disposal containers required for emplacement in a repository, compared to direct disposal of SNF already loaded in dry-storage canisters. The size of the increase would depend on the capacity of the new canisters into which the SNF assemblies were to be repackaged. Depending on where the repackaging takes place, it would also increase the number of storage casks and transport casks for earlier stages of the SNF management program.

C.2.2 Location of Repackaging Operations

Repackaging of the SNF from large dry-storage canisters and casks into smaller canisters could be performed at a nuclear power plant site, a consolidated interim storage facility,[98] or a geologic repository. Depending on where the repackaging is performed, the facility used may need to accommodate the full range of dry-storage canister and cask designs in use, or a more limited range of designs.

Repackaging at Nuclear Power Plant Sites

If SNF were to be repackaged at nuclear power plant sites, the downstream SNF management system (handling, transportation, offsite storage, and disposal) could be simplified because the equipment and operating procedures could be standardized. However, this would have a major impact on the normal operations of the nuclear power plants.

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[98] Under the NWPA, a monitored retrievable storage facility is to be designed, constructed, and operated by DOE. However, NRC also licenses consolidated interim storage facilities, which can be designed, constructed, and operated by a private commercial entity. For the purposes of this report, the term “consolidated interim storage facility” means a DOE monitored retrievable storage facility, a commercial storage facility, or both.

One option for repackaging at a nuclear power plant site would be to use the area in the spent fuel storage pool where SNF is loaded into dry-storage canisters and casks. However, the schedule for normal operations at nuclear power plant sites leaves essentially no time for additional operations. Also, the spent fuel pools were not designed for repackaging operations and would likely require engineering modifications to support this additional operation. As an alternative, it would be possible to construct a separate repackaging facility (e.g., a dry repackaging facility) at a nuclear power plant site and operate it separately. However, the utility may need to assume responsibility for the facility and its operation, and this would also have a significant impact on the other operations on the site and add more cost to the utility.

Repackaging at a Consolidated Interim Storage Facility

If the SNF in dry-storage canisters and casks at utility sites are transported to a consolidated interim storage facility and the SNF assemblies are repackaged into smaller canisters at that facility, the dry-storage system at the interim storage facility and the transport system for moving the smaller canisters to the geologic repository could be standardized. Note that this scenario assumes all SNF canisters and casks can be approved by the NRC for transportation away from the nuclear power plant sites.[99] The interim storage facility would have to include systems and equipment that could receive and unload the wide range of dry-storage canisters and casks from the utility sites. The interim storage facility would need to include a spent fuel pool or a dry repackaging facility to provide the proper shielding during repackaging operations. Later in the process, the surface facility operations at a geologic repository would be simplified because there would be no need to repackage the SNF into smaller canisters there. The loading of SNF canisters into disposal containers and the waste package emplacement operations could be standardized and simplified. Finally, the nuclear utilities would not face the challenges of additional operations and demands on personnel associated with repackaging SNF into smaller canisters at reactor sites.

Repackaging at the Repository Site

If the SNF in dry storage at utility sites are transported to a repository site before repackaging, the repository site would have to include surface facilities and equipment that could receive and unload the full range of dry-storage canisters and casks being used at nuclear power plant sites. Note that this scenario assumes all SNF canisters and casks can be approved by the NRC for transportation away from the nuclear power plant sites.[100] However, if the SNF is repackaged at the repository, then the final waste packages and emplacement processes could be standardized, which would make emplacement operations more efficient.

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[99] This assumption implies that some solution will be found for obtaining NRC approval for transporting SNF that has been loaded in canisters and casks not already approved by the NRC for transportation away from nuclear power plant sites.

[100] See previous footnote.

C.2.3 Time and Effort Required

Significant time and effort would be needed to repackage SNF from large dry-storage canisters and casks into smaller canisters. The time and effort required would depend on where the repackaging takes place, whether at nuclear power plant sites, at a centralized interim storage facility, or at the repository. It is possible that some repackaging may be required at nuclear power plant sites to meet transportation safety requirements while some repackaging also takes place at a centralized interim storage facility or at the repository site. In determining where to repackage the SNF, it would be necessary to consider how to minimize the time and effort required accounting for their impact on the different organizations (i.e., utility or government) that could be involved.

C.2.4 Radiation Dose to Operations Personnel

SNF repackaging would also potentially increase the radiation dose to workers. Although operations in a spent fuel pool or at a separate repackaging facility would be designed and managed to keep the radiation dose to operators within regulatory limits, any operation involving the handling of SNF may result in some radiation dose to workers. In determining where to repackage the SNF, it would be necessary to consider how to manage the radiation dose to workers.

C.2.5 Low-Level Radioactive Waste Generated

Repackaging SNF in dry storage into smaller canisters would result in empty dry-storage canisters and casks that would require disposal. Although decontamination of empty dry-storage canisters and casks would be required, with the possibility that some materials could be recycled or disposed of as commercial waste, some parts of the internal structure would probably need to be disposed of as low-level radioactive waste (Bahr 2022).

C.2.6 Transportation

Size/Weight of Transportation Vehicles

Repackaging SNF from large dry-storage casks into smaller canisters would provide more flexibility in how SNF is transported (e.g., via truck, rail, or barge). For example, the use of legal weight trucks for transportation avoids the need for permitting of overweight trucks and allows for the consideration of a greater number of alternative transportation routes (e.g., no need to avoid bridges with restrictive load limits).

Transport Cask Surface Temperature

Repackaging SNF into smaller canisters would allow operators to optimize the loading of canisters to meet the temperature limit specified in 10 CFR 71.43(g) for transportation. This flexibility would become more important as the nuclear utilities further shift to reactor operations that produce higher burnup SNF, which is characterized by higher radiation levels and higher decay heat when discharged from the reactor and while in storage.

Transport Cask Radiation Level

Repackaging SNF into smaller canisters would enable optimizing the loading of the transport cask to meet the radiation level limits specified in 10 CFR 71.47. Radiation levels of the

SNF, like the SNF decay heat, will increase as nuclear utilities further shift to reactor operations that produce higher burnup SNF.

Criticality Safety

Repackaging SNF into smaller canisters would assist in demonstrating that transport casks meet the criticality safety requirements of 10 CFR 71, as there would be less fissile material in the cask. Repackaging would also provide the opportunity to use more durable neutron absorbers that meet the regulatory compliance requirements for geologic disposal.

Maintaining Spent Nuclear Fuel Integrity

During repackaging, the operators would be able to assess the condition of the SNF before loading it into smaller canisters. If necessary, the SNF could be loaded into damaged fuel cans to meet the requirement for maintaining its geometric form for transportation.

C.2.7 Consolidated Interim Storage

The repackaging of SNF will have different implications, discussed below, on a consolidated interim storage facility depending on where the repackaging is done: at nuclear power plant sites, at a consolidated interim storage facility, or at the repository site.

Repackaging at the Utility Sites

If SNF is repackaged at the utility sites, the consolidated interim storage facility could use standardized equipment and designs for loading and unloading stations, on-site transport systems, and storage systems.

Repackaging at the Consolidated Interim Storage Facility

If SNF is repackaged at a consolidated interim storage facility, the facility would need to have a wide range of handling equipment to accommodate the various dry-storage canister and cask designs. The interim storage facility would need to include a spent fuel pool or a dry repackaging facility to provide the proper shielding during repackaging operations. If storage of SNF canisters and casks is needed before repackaging, the facility also would have to accommodate a wide range of storage configurations. After the repackaging of SNF is complete, the storage, loading, and off-site shipment could be standardized.

Repackaging at the Repository Site

If SNF is repackaged at the repository site, the consolidated interim storage facility will see few of the benefits of repackaging. The facility will have to receive, handle, and store the full range of dry-storage canister and cask sizes and shapes. However, it would not be necessary for the interim storage facility to include the capability to repackage the SNF.

C.2.8 Repository Emplacement

After repackaging, smaller SNF canisters would fit into smaller disposal containers, simplifying repository handling and emplacement of the waste packages. Moving smaller waste packages underground would present fewer challenges than large packages if using a shaft hoist. However, the emplacement time could be longer than for direct disposal of SNF in large dry-storage canisters because of the larger number of waste packages to be emplaced. Furthermore, the need to emplace a larger number of waste packages may require that the repository have a larger areal extent (footprint).

C.2.9 Repository Performance

Canister Size Effects

Repackaging SNF into smaller canisters could reduce the consequences of an individual waste package breach. In such an event, less radioactive material could be released into the repository environment, compared to the breach of a waste package containing a large dry-storage canister. Also, the consequences of drilling into a small container in a human intrusion scenario could be smaller than those of drilling into a large container.

Thermal Effects

Emplacing smaller disposal containers in a repository could result in a lower localized heat load compared to direct disposal of SNF in large dry-storage canisters. The lower heat load could reduce the degree, extent, and significance of chemical, electrochemical, and physical processes in the near field of a repository that may affect the performance of engineered and natural barriers.

Criticality Safety

Repackaging SNF into smaller canisters could assist in demonstrating that the criticality safety requirements for disposal are met in two ways. First, the smaller quantity of fissile material and increased surface-to-volume ratio could reduce the probability of a canister reaching criticality in the event that the canister becomes flooded with water, following corrosion of the disposal container. Second, repackaging would allow the design and use of smaller canisters with more durable neutron absorber materials to meet the regulatory requirement that the probability of a criticality event would be below a specified limit.[101]

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