**UNITED STATES**
**NUCLEAR WASTE TECHNICAL REVIEW BOARD**
2300 Clarendon Boulevard, Suite 1300
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January 11, 2021

The Honorable Rita Baranwal
Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Dr. Baranwal:

On behalf of the U.S. Nuclear Waste Technical Review Board (Board), I want to thank you and your staff, as well as the staff from the national laboratories, for supporting the Board's 2020 Summer Meeting, which was held virtually on July 27–28, 2020. The purpose of the meeting was to review information on U.S. Department of Energy, Office of Nuclear Energy (DOE-NE) research and development (R&D) activities related to disposal of commercial spent nuclear fuel (SNF) contained in dual-purpose canisters (DPCs) in a geologic repository. This letter presents the Board's observations and recommendations resulting from the meeting. The agenda and presentation materials for the meeting are posted on the Board's website at https://www.nwtrb.gov/meetings/past-meetings/summer-2020-board-meeting. The meeting transcript and an archived recording of the webcast also are posted on the same web page.

The Board also thanks the staff from DOE and the national laboratories for supporting a technical fact-finding meeting that was held on March 6, 2020, at the Oak Ridge National Laboratory (ORNL). This fact-finding meeting enabled the Board to prepare for the July 2020 public meeting.

*Background*

In the United States, commercial SNF is stored at over 70 sites, including operating and decommissioned power plants, and is continuing to be generated at a rate of more than 2,000 metric tons of uranium per year (see appendix for details). Much of the SNF is inside canisters known as DPCs, which are in dry storage. These DPCs have been designed for interim storage and transportation, but not for their potential use for direct geologic disposal. Currently, there are more than 3,000 DPCs in the U.S. and this number will increase with time as more SNF discharged from reactors is transferred from spent fuel pools into DPCs. A Board recommendation after its January 2012 public meeting[1] for DOE was to look into the disposability of SNF in DPCs.

[1] Ewing, R.C. 2013. Board letter to Dr. Peter Lyons following the January 9, 2012, Board meeting on DOE integration issues (March 28, 2012). https://www.nwtrb.gov/docs/default-source/correspondence/bjg166.pdf?sfvrsn=11.

Disposing of SNF in DPCs in a geologic repository, after loading the canisters into suitable disposal overpacks, has the potential to avoid the difficulties that could occur (e.g., fuel damage) when cutting the DPCs open and repackaging the fuel into smaller canisters, the need to dispose of the empty canisters, and the additional worker dose that would be incurred during repackaging. Thus, over the past several years, DOE has been investigating the technical feasibility of direct disposal of DPCs in a repository. This technical work could support future decision making by DOE on commercial SNF management alternatives.

At a Board public meeting held on October 2018 in Albuquerque, New Mexico,[2] representatives from DOE and the national laboratories described the results of DOE's preliminary studies on the technical feasibility of disposal of SNF in DPCs. Since that meeting, DOE has made progress in its R&D efforts on this topic and, at the July 2020 public meeting, the Board heard presentations from DOE and national laboratory staff on recent results.

On Day 1 of the July 2020 meeting, the first technical presentation was by Timothy Gunter (DOE-NE), who reviewed past DOE studies on the technical feasibility of disposal of SNF in DPCs and provided an update on current DOE R&D activities on the subject. In a following presentation, Ernest Hardin [Sandia National Laboratories (SNL)] described past DOE studies that evaluated the engineering feasibility and thermal management of disposing of SNF in DPCs. The last presentation of the day was by Kaushik Banerjee (ORNL) on analyses of the potential for nuclear criticality of DPCs, which is one of DOE's ongoing R&D activities.

Presentations on ongoing DOE R&D activities continued on Day 2 of the July 2020 meeting, starting with a presentation by Laura Price (SNL) on consequence analyses of criticality events in DPCs during the period after the repository closes. The next two presentations, one by Kaushik Banerjee (ORNL) and another by Mark Rigali (SNL), described the development and testing of materials that can be used to fill the void spaces inside a DPC prior to disposal to prevent a criticality event. Dr. Banerjee's presentation described the development of testing and simulation methods, whereas Mr. Rigali covered work that is focused on the development and testing of phosphate-cement-based filler materials. If a canister is breached, the filler materials are envisioned to mitigate water entry into the canister and thereby prevent criticality, depending of the efficacy of the void filling. The last presentation of Day 2 of the meeting was by Geoff Freeze (SNL) and Rob Howard (ORNL), who described DOE R&D activities on cross-cutting issues relevant to disposal of SNF in DPCs.

After discussing and evaluating the information presented at the meeting and supporting DOE reports, the Board has several specific comments and recommendations related to the individual presentations that are recorded in the body of this letter. In addition, the Board offers the following broader observations based on issues that cut across the presentations.

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[2] "DOE R&D Activities Related to Managing and Disposing of Commercial Spent Nuclear Fuel," Fall 2018 Board Meeting, October 24, 2018, Albuquerque, New Mexico. https://www.nwtrb.gov/meetings/past-meetings/fall-2018-board-meeting---october-24-2018.

## General Observations

- Disposal of SNF in DPCs is a very important R&D topic and DOE is addressing key questions related to safety, engineering feasibility, thermal management, and postclosure criticality. The Board commends DOE as the R&D activities appear to be well managed and focused on the key points. However, the Board also notes that the scope of what can be accomplished is limited to non-site-specific assessments because no decision has been made whether to proceed with a repository at Yucca Mountain, Nevada or to search for potential sites elsewhere.

- Decisions in the near term on the disposability of SNF in DPCs and on the direction of the nation's geologic disposal program are needed because their interdependence will shape waste management and disposal activities over many years. A decision on disposability of SNF in DPCs would substantially impact how SNF is stored, transported, and disposed of, and may require interim storage of SNF for hundreds of years, depending on the repository concept that is selected.

- DOE considers that its Standard Contract with the nuclear utilities requires taking delivery of individual SNF assemblies from the utilities, which would mean opening the welded DPCs and repackaging the SNF into other containers. At the July 2020 Board meeting, William Boyle (DOE-NE) acknowledged that the practical implications of doing so—increased cost and occupational radiation exposure—have been known for a long time. However, none of the parties to the contract have moved to revise the contract, either through litigation or renegotiation, despite the increasing cost of the current course. The Board observes that such clarification could impact the need for and focus of DOE R&D activities on direct disposal of SNF in DPCs.

- An evaluation of the potential impact of future use of accident tolerant fuels (ATFs), high-assay low-enriched uranium (HALEU) fuels, and other advanced fuels [e.g., tri-structural isotropic (TRISO) fuel, molten fuel salt, etc.] on the back-end of the fuel cycle is needed. Given the effort underway now within DOE-NE to produce a report, "Initial ATF Storage and Transportation Gap Analysis," with the stated purpose to "document data needs for ATF and higher burnup fuels for storage and transportation," the Board observes that the natural extension of this work is to include disposal of ATF and other advanced fuels in the next iteration of the Gap Analysis report.

## DOE-NE Presentations

### Past Studies on the Technical Feasibility of Disposal of Spent Nuclear Fuel in Dual-Purpose Canisters

Timothy Gunter (DOE-NE) and Ernest Hardin (SNL) described the feasibility studies DOE conducted during the period 2013–2017. These studies evaluated the technical feasibility of disposing of SNF in DPCs in a geologic repository based on four factors: (i) safety (preclosure operational safety and postclosure waste isolation), (ii) engineering feasibility, (iii) thermal management, and (iv) postclosure criticality. The main conclusion of the studies was that there are no implementation barriers to geologic disposal of SNF in DPCs, although additional R&D is required to address the technical information needs that were identified.

In his presentation, Mr. Gunter stated that disposal of SNF in DPCs could result in a cost savings of up to $20 billion compared to repackaging the SNF into other canisters, based on an analysis presented in a 2019 SNL report.[3] According to Mr. Gunter, the significant contributors to the reduction in cost are (i) elimination of disposal canister procurement costs, (ii) reduction in the number of disposal overpacks, (iii) elimination of repackaging operations, i.e., the removal and transfer of commercial SNF from DPCs into transportation, aging, and disposal (TAD) canisters, and (iv) elimination of disposal of DPC hulls and baskets as low-level waste (LLW). The cost analysis of SNF management alternatives presented in the SNL report included three scenarios, and variants, for disposal of SNF in DPCs, in Yucca Mountain, Nevada, in 2031 and 2041, and in a Yucca Mountain equivalent repository in 2117.

The Board reviewed the technical basis for SNL's cost analysis of disposal of SNF in DPCs. Based on the Board analysis, which is presented in an appendix to this letter, the Board concludes that, for several reasons, there are opportunities to improve future cost analyses. First, the cost savings of $20 billion reported in the 2019 SNL report is based on a comparison with disposal of SNF in TAD canisters, starting in 2031, at Yucca Mountain. The Board notes that DOE appears to have underestimated taxpayer liabilities for each scenario and variant. Second, DOE's technical basis for the LLW disposal cost estimates is incomplete because potential recycle and reuse of DPCs was not considered and disposal costs were based on outdated information that do not reflect current LLW disposal options. Third, the SNL rough-order-of-magnitude cost analysis did not consider repository environments that are different from Yucca Mountain for any scenario, which means there is an incomplete basis for assessing disposal costs relative to repackaging costs. For instance, if the SNF in DPCs were to be disposed of in a repository with crystalline or argillite host rock, the SNF may require thermal aging, for a period of 100 years or more, at a surface facility before it can be emplaced in the repository. The costs of extended interim storage for direct disposal of the SNF in DPCs in all potential repository host rocks needs to be considered. Also, the disposal of SNF in DPCs in a crystalline or argillite repository will require a larger footprint (i.e., more excavation) for a given inventory because of the lower thermal conductivity of those host rock types, which will affect the repository construction cost. The 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 recommends that DOE provide information to decision-makers that clearly indicates that decisions on the direct disposal of DPCs versus SNF repackaging have implications for the development of potential disposal systems, which are related to current design concepts for various host rock types, the timing and rate of DPC disposal, and total system life cycle costs.*

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[3] Freeze, G., E. Bonano, E. Kalinina, J. Meacham, L. Price, P. Swift, A. Alsaed, D. Beckman, and P. Meacham. 2019. *Comparative Cost Analysis of Spent Nuclear Fuel Cost Alternatives*. SAND2019-6999, Revision 1. Albuquerque, New Mexico: Sandia National Laboratories. June. The report provided rough-order-of-magnitude cost estimates for a variety of waste management options.

For future DOE cost analyses of waste management alternatives, the Board observes that a better accounting of relevant costs and related uncertainties could:

- Consider a larger range of costs associated with extended storage of SNF—the duration of which would depend on the repository host rock type—and with the expected backlog of SNF in dry storage at the time repository or centralized interim facility operations begin when estimating the increase in taxpayer liability, which will continue to accrue as long as the SNF is not removed from nuclear power plant sites;
- Include alternative scenarios that have repository SNF acceptance rates greater than 3,000 metric tons of heavy metal (MTHM);[4] and
- Take account of current LLW disposal costs and the potential for DPC recycling or reuse.

Ernest Hardin (SNL), in his presentation, concluded that engineering challenges can be met, including a first-of-a-kind heavy shaft hoist, if needed, to take the loaded DPCs from the surface to an underground disposal facility. The conclusion about the heavy shaft hoist is based on a "DIREGT" conceptual hoist design developed by BGE Technology (Germany) to accommodate a 175-MT payload, the estimated weight of a DPC package with shielding. Dr. Hardin acknowledged that the heaviest payload that an actual operating hoist system can accommodate today is 50 MT, which is a system used for a potash mine in Canada. He mentioned that an 85-MT payload hoist system concept was developed for the Belgian program that can accommodate Pollux[5] casks. He also stated that BGE Technology provided DOE a rough-order-of-magnitude cost estimate of the 175-MT hoist system, which was in the tens of millions of dollars. This is regarded as a manageable cost according to Dr. Hardin.

The Board notes that a hoist system that can handle the anticipated weight of DPCs plus shielding overpack remains to be demonstrated with actual prototypes of equipment. If filler is added to a large canister, the 145 MT package Dr. Hardin referred to would become 195 MT, i.e., 20 MT over the current maximum capacity of the BGE Technology concept. The Board considers that more development/demonstration work is needed to support the DOE assumption regarding the handling of waste packages in a repository.

*The Board recommends that DOE (i) update the conceptual hoist design to take account of the additional weight of DPC fillers, (ii) determine the qualification that would be required for the system, (iii) update the cost estimate for such a system, and (iv) determine the time required to develop an operational system.*

## Dual-Purpose Canister Nuclear Reactivity Analysis

Kaushik Banerjee (ORNL) described the reactivity analyses of loaded DPCs DOE conducted to determine which of the DPCs have the potential to reach criticality if breached and flooded with

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

[5] Pollux casks are designed and manufactured by the German company Gesellschaft für Nuklear Service (GNS) for the shipping, interim storage, and geologic disposal of SNF.

water. Dr. Banerjee explained that DPCs licensed by the U.S. Nuclear Regulatory Commission (NRC) are loaded using well-defined fuel assembly loading criteria, such as specifications for approved contents in the DPC's certificate of compliance. 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 regulatory requirement (referred to as the "design-basis" analysis).
Dr. Banerjee explained that DPC's are loaded with SNF assemblies that provide some margin to the limiting licensing conditions that is unquantified and uncredited. He stated that 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 reaching criticality. The results of the as-loaded criticality analysis Dr. Banerjee presented indicate that the majority of the 708 canisters that were analyzed would remain subcritical during the geologic disposal period, even if there is a loss of neutron absorber material and the carbon steel in the internal components of the canister.

DOE is to be commended for moving away from design-basis analysis to using as-loaded SNF data. The Board notes that many of the DPCs that have calculated reactivities higher than the subcritical limit ($k_{eff}$ >0.98) contain damaged fuel assemblies, which have been modeled conservatively. *The Board encourages DOE to use data on the as-loaded damaged fuel assemblies (e.g., fuel burnup and extent of assembly damage). By doing so, it may be possible to show that the DPCs with damaged fuel have a $k_{eff}$ below the subcritical limit. The Board also encourages DOE to extend the reactivity analysis to include loaded "bare-fuel" casks.*

The Board notes that degradation of the fuel baskets might significantly change the reactivity of the DPCs. *Thus, the Board recommends that DOE focus more effort on characterizing basket degradation, which is perhaps going on under a different program.*

**Consequences of Nuclear Criticality in Dual-Purpose Canisters After Disposal**

Laura Price (SNL) described a DOE study that was initiated to examine the potential consequences, with respect to long-term repository performance, of criticality events that might occur in DPCs during the postclosure period of a hypothetical repository. Ms. Price indicated that to model the consequences of postclosure criticality, an approach was developed to couple neutronics and thermal-hydraulic calculations, and a PFLOTRAN[6] submodule was built to take account of the effects of postclosure criticality events. Ms. Price explained these effects can be complex as there are many processes involved in modeling criticality events in DPCs, many of which are coupled. These processes include changes in temperature, pressure, and radionuclide inventory; fuel/basket/neutron absorber degradation; changes in in-package chemistry; container corrosion; and evolution in near-field conditions.

Ms. Price described the analysis of two hypothetical repositories: (i) a saturated repository in shale at 500-m depth and backfilled with bentonite, and (ii) an unsaturated repository in alluvium at 250-m depth and backfilled with crushed alluvium. The analysis calculated radionuclide concentrations in the host rock with and without the occurrence of a critical event, which can be

[6] PFLOTRAN is an open source code for thermal hydrology and reactive chemical transport in variably saturated porous geologic media.

either a steady-state or a transient event. Ms. Price indicated that research efforts thus far have concentrated on building the capability to analyze steady-state criticality events, although an approach for addressing transient criticality events is being developed. She acknowledged that, because the work she described represents a starting point, the analyses used simplifying or bounding assumptions. These assumptions include (i) the top side of the DPC is breached at 9,000 years after repository closure allowing water to enter and the criticality event is initiated when the DPC is filled with water, (ii) the fuel assembly spacer grids remain intact and the cladding maintains its configuration but has small holes, (iii) the aluminum-based neutron absorbers are no longer present, (iv) the criticality event reaches a steady-state and is not cyclic, and (v) the bentonite backfill does not act as a barrier to radionuclide transport during the criticality event because of the high temperatures. Also, the analyses Ms. Price described modeled the effects of a criticality event in a single DPC that contains 37 pressurized water reactor assemblies. However, Ms. Price indicated the assumptions used in the analyses she presented will be reviewed and may be revised as the work progresses.

The Board recognizes that evaluating the consequences of criticality in DPCs after disposal is technically very challenging and observes that DOE has made significant progress in its work in this area. The Board understands that the initial analyses must make simplifying and, at times, conservative assumptions. *The Board suggests that, as DOE continues this work, it should consider the following:*

- *Examine more realistic degradation rates of engineered barriers (i.e., DPCs and bentonite buffers).*
- *Evaluate scenarios in which more than one DPC experiences a criticality event, including the potential for neutron coupling between adjacent waste packages.*
- *Evaluate the effect of an extended criticality event on the behavior of the repository system.*
- *Propagate the consequence results through a full performance assessment (i.e., to releases to the accessible environment and doses to the public).*
- *Extend the analysis to evaluations of risk by also calculating the probability of waste package failure, such as taking into account the corrosion resistance of different waste package materials and their corrosion rates in different geochemical environments.*
- *Consider more realistic host rocks, such as fractured crystalline rock, instead of unsaturated alluvium.*
- *Consider scenarios with environmental conditions that may arise due to climate change, which may affect subsurface conditions for the different host rocks.*
- *Start to develop and document an approach that can be used to validate the coupled models used in consequence analysis.*

**Dual-Purpose Canister Filler Testing and Analysis**

Kaushik Banerjee and Mark Rigali gave presentations on DOE studies designed to evaluate materials that could be used to fill the void spaces inside a DPC prior to disposal. The current focus of the studies is on fillers that can be injected into a DPC as liquids using existing drain/vent ports or using a custom-built port.  These fillers, which may include cement slurries and low-melting point metals or alloys, subsequently would solidify upon cooling or after chemical reactions have occurred. The fillers would be intended to limit the entry of water if the DPC is breached and, thereby, mitigate the potential for nuclear criticality. Dr. Banerjee explained that, because it is not possible to perform experiments for all types of DPC designs and filler materials, DOE is developing numerical simulation capabilities that can be used to downselect filler materials and to assess the DPC filling process. Dr. Banerjee also described the bench-scale laboratory testing that is being used to validate the numerical simulations.

Mr. Rigali's presentation focused on the development and testing of cementitious DPC fillers, particularly phosphate-based cements that include aluminum phosphate cements, calcium phosphate cements, and wollastonite aluminum phosphate cements. The research involves optimizing the filler material compositions and the subsequent processing of the materials to achieve dense and well-consolidated monolithic samples with relatively low porosity. According to Mr. Rigali, the phosphate-based cements have several properties that make them attractive as potential DPC fillers, including nontoxicity, neutral pH, and low solubility (at near-neutral pH). He acknowledged, however, that a disadvantage of phosphate-based cements is the filler material needs to be mixed with water to facilitate the chemical reactions, and some of the reactions generate additional water. Because water retained in the DPC may increase the SNF reactivity and accelerate corrosion, some of this water may need to be driven out of the DPC by heating, which will require the filler to have sufficient intrinsic porosity and permeability to allow the water to escape from the DPC.

The Board commends the DOE work on developing and testing DPC filler materials and supports continuing this work. *The Board understands the research is at an early stage, but as the work progresses, the Board suggests that DOE:*

- *Place priority on determining the minimum amount of void space that needs be filled in order to eliminate the potential for nuclear criticality. This includes determining the effect of the size, location, and relative distribution of void spaces in the DPC on the potential they could be filled with water and the subsequent impact on potential for criticality.*
- *Take account of the potential chemical interactions of the filler with the DPC and its internal components, as well as with the near-field environment for various potential host rocks, before going too far in the overall R&D work on a particular filler material.*
- *Take account of the effect of heating (either self-heating of the filler material due to exothermic reactions or an externally applied heat source), either to allow molten filler to flow or to drive out water from solidified cement-based fillers on the performance of the SNF, cladding, and DPC.*
- *Evaluate the long-term performance of the filler material, including the potential to form voids and to debond from DPC internal surfaces with time. For example, the process of debonding at the filler–cladding interface may damage the cladding.*
- *Take account of the connectivity (or lack thereof) of the pores in the filler that will be generated during the setting of cement-based fillers when determining whether the water can be driven out of the filler after it sets.*
- *Consider using data on the draining of an actual canister at a utility site to validate the filler flow models.*

**Cross-cutting R&D Activities**

Geoff Freeze and Rob Howard provided high-level summaries of how technical issues related to disposal of SNF in DPCs are integrated into other areas of the DOE R&D program, including the implications for the source term, interactions with engineered barriers, and thermal and shielding aspects during transportation. Dr. Freeze explained the potential effects of high temperatures that result from disposal of SNF in DPCs are being evaluated using DOE's Geologic Disposal Safety Assessment framework, which uses the PFLOTRAN code to model the effects. The high temperatures could affect the degradation rates of the waste form, the SNF cladding, and the DPC, as well as the chemistry inside the DPC and the interactions of engineered materials with the near-field environment. Mr. Howard explained that the tools and specific data that are used to evaluate criticality margin for the disposal of SNF in DPCs, which were described in one of Dr. Banerjee's presentations, can also be used to evaluate the thermal and shielding criteria to determine when the DPC is transportable. The Board appreciates the presentations by Dr. Freeze and Mr. Howard on cross-cutting R&D activities and plans to look more closely at these activities at future Board meetings.

The Board thanks DOE-NE for the efforts of its staff and those of the national laboratories to prepare detailed technical presentations, and we thank all for their participation in the meeting. We look forward to continuing our ongoing review of DOE's technical activities related to managing and disposing of SNF and high-level radioactive waste.

Sincerely,

{Signed by}

Jean M. Bahr
Chair

# Appendix

## Implications of the Delay in Developing a Repository Program for the Cost of the U.S. Program for Managing Spent Nuclear Fuel

The U.S. fleet of operating commercial reactors generate ~2,200 metric tons of heavy metal (MTHM)[7] of spent nuclear fuel (SNF) per year that need to be put into storage. Beginning in the mid-1980s when SNF storage pools at some nuclear power plants began to reach the limit of their storage capacity, SNF stored in those pools began being loaded into dry cask storage systems (DCSSs), dried, and placed into storage so that additional SNF discharged from the associated operating reactors could be stored in the pools. There are numerous types of DCSSs, but most are “dual-purpose canisters” (DPCs), designed and licensed for storage and transportation. The projected inventory of commercial SNF in pools, in dry storage, and in total, is depicted in Figure A-1.[8]

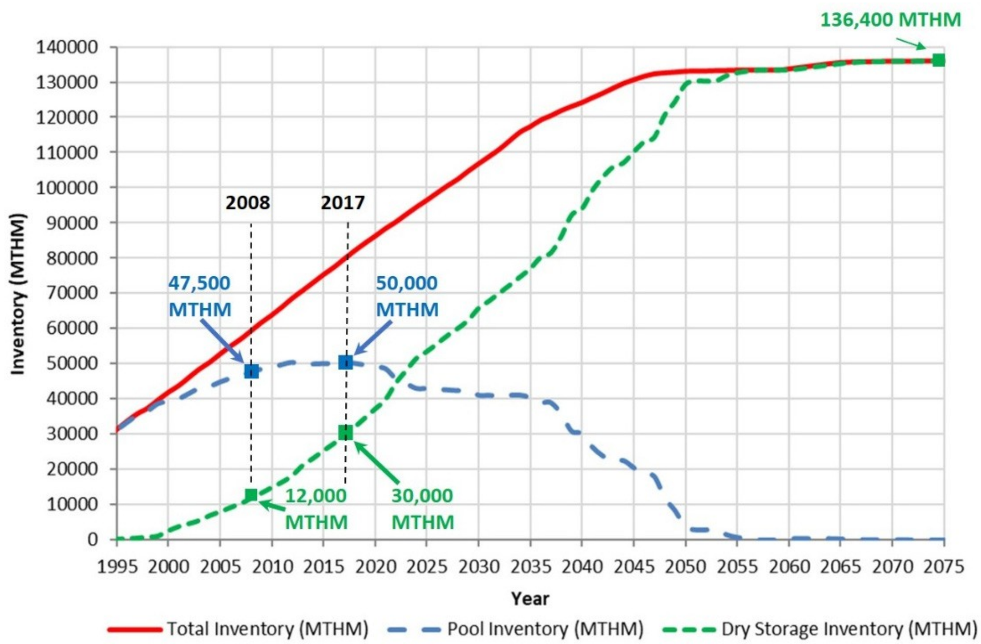


**Figure A-1. Projected Inventory of Commercial Spent Nuclear Fuel in Storage.**
Note: Figure taken from Freeze et al. (2019; Fig. 1-5) and revised for clarity. The projections of inventory with time developed by Vinson and Metzger (2017) and used by Freeze et al. (2019) assumed: (i) 93 of the 99 reactors operating at the end of 2017 would receive license renewals and would be decommissioned after 60 years of operation, (ii) the six existing reactors that have announced shutdown dates as of 2017 would continue operating until those shutdown dates, (iii) no new reactors would be constructed, (iv) no commercial SNF would be reprocessed, and (v) there would be no options for permanent disposal and all commercial SNF would remain in storage. The SNF pool inventory decreases from 2017 to later years as commercial reactors cease operations and begin decommissioning, during which the SNF pools are emptied and the SNF is placed into dry storage.

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

8 The projected SNF inventory shown in Figure A-1 after 2017 is dependent on a number of assumptions that are summarized in the notes under the figure caption.

At the Board's July 2020 public meeting, the U.S. Department of Energy (DOE) described a cost analysis by Freeze et al. (2019) of commercial SNF management alternatives. According to Freeze et al. (2019), the analysis "describe[s] the fundamental features of each alternative scenario and provide[s] simple and credible cost estimates for comparative evaluations." The objective of the cost analysis was "to inform the DOE in future decision making and policy development that can optimize the management of commercial SNF" (Freeze et al. 2019). The "rough-order-of-magnitude" cost analysis focused on the cost implications of delays in disposal and of alternative choices for SNF storage, transportation, and disposal. It used the proposed Yucca Mountain repository as the basis for a final repository because Yucca Mountain remains the option mandated for evaluation by the Nuclear Waste Policy Act (NWPA) and because a detailed "Total System Life Cycle Cost" (TSLCC) analysis for disposal at Yucca Mountain that DOE completed in 2008 (DOE 2008) provides a suitable baseline for comparison. The TSLCC analysis was based on the acceptance, transport, and permanent disposal at the Yucca Mountain repository of all projected commercial and defense SNF[9] and high-level radioactive waste (HLW). Also, it used numerous assumptions that were consistent with DOE's Yucca Mountain repository application for construction authorization. For example, the maximum annual rate of acceptance of commercial SNF at the repository was assumed to be 3,000 MTHM.

It is important to note that the statutory limit for the Yucca Mountain repository is 70,000 MTHM. Of that amount, DOE apportioned 63,000 MTHM for commercial SNF. As of December 2019, the total inventory of commercial SNF is ~ 84,600 MTHM of which ~39,200 MTHM of commercial SNF have been loaded into DCSSs (Peters et al. 2020), which is more than 50% of the amount apportioned for commercial SNF for the Yucca Mountain repository. Given the 3,000 MTHM per year design limit for acceptance of commercial SNF at the Yucca Mountain repository, 39,200 MTHM of commercial SNF represents a 13-year backlog of SNF waiting to be transported from reactor sites to the repository.

Because the SNF generation rate of ~2,200 MTHM per year is roughly three-quarters of the annual repository acceptance limit, every three years of SNF generation from the current fleet of reactors will add more than two and a quarter years to the 13-year backlog of SNF waiting to be transported to the repository. As explained later in this Appendix, this growing backlog of SNF at reactor sites, in combination with the repository acceptance rate limit, affect cost estimates of commercial SNF management alternatives.

The 2019 cost analysis by Freeze et al. analyzed a reference scenario that was consistent with the 2008 TSLCC and reflects what might have been had the Yucca Mountain project proceeded as planned, which would have meant initial waste receipt and start of emplacement operations in 2017. For the reference scenario, the analysts made several adjustments to the TSLCC cost information, including an adjustment to reflect the cost for disposal of only commercial SNF. The cost analysis included three future alternative scenarios and variants. For investigating relative cost impacts for commercial SNF management, future alternative scenarios were constructed around three representative dates for the first receipt of spent fuel at the repository:

[9] Note that the 2008 DOE TSLCC projected a total inventory of commercial SNF of 109,300 MTHM, which is lower than the 136,400 MTHM from the more recent Vinson and Metzger (2017) report.

- 2031, which corresponds to an early date for the opening of Yucca Mountain should licensing activities resume immediately;[10]
- 2041, which represents an additional ten-year delay in restarting the Yucca Mountain program; and
- 2117, which represents a 100-year delay in the repository program.

Variants within these scenarios examined the relative cost impacts of various decisions regarding repackaging of SNF from DPCs into transportation, aging, and disposal (TAD) canisters specified in the Yucca Mountain repository license application (DOE 2009a) and/or modifying repository operations to allow for direct disposal of SNF in DPCs without repackaging.

The timing of when specific SNF canisters can be emplaced in the repository is an important factor in analyzing the costs of SNF management alternatives. As explained in the next section, the DPC loading affects the disposal options that are available, both in terms of when SNF could be emplaced and what host rock types could allow its disposal in a few decades rather than hundreds of years in the future. If decisions on commercial SNF management alternatives are not made in the near term, any delays in decision making become a lost opportunity for limiting total waste management system costs and could affect options for commercial SNF management for hundreds of years.

**Implications of Thermal Power Emplacement Limits for the Timing of Dual-Purpose Canister Emplacement in Different Types of Geologic Repository Host Rocks**

The timing of when specific DPCs or the waste package containing them could be emplaced in a geologic repository is dependent on the characteristics of the host rock and engineered barriers that comprise the repository, the canister loading (i.e., number of SNF assemblies in the canister), the fuel burnup,[11] and the aging time [i.e., the amount of time the SNF is in storage and undergoes radioactive decay, thereby lowering the thermal power (the rate at which decay heat is released)]. These relationships are depicted in Figure A-2 for a waste package containing a DPC loaded with 32 pressurized water reactor (PWR) assemblies, which is similar to the number of assemblies in many already loaded DPCs.

Finite-element models have shown that the waste package thermal power at emplacement is correlated with peak temperature in the host rock and engineered barrier system (Hardin et al. 2013). This relationship allows the selection of a waste package emplacement power limit that would minimize deleterious heat effects to the host rock or the engineered barrier. In Figure A-2, the horizontal green, blue, magenta, and red lines depict the waste package thermal power limit, at emplacement, associated with peak temperature targets for the different disposal concepts that are described in the text boxes in the figure. The black curves are the thermal

[10] The Board notes that if the Yucca Mountain licensing process were restarted, it likely would take about 13 years for disposal operations to begin, given the time needed for completing the construction authorization licensing and DOE's estimate of the time needed to begin operations after construction authorization has been received (GAO 2017; DOE 2009b).

[11] Burnup is the amount of energy extracted per unit mass of the fuel. Typical units for burnup of commercial SNF are gigawatt-days per metric ton (GWd/MT) of uranium originally contained in the fuel. Higher burnup SNF emits more heat than lower burnup SNF.

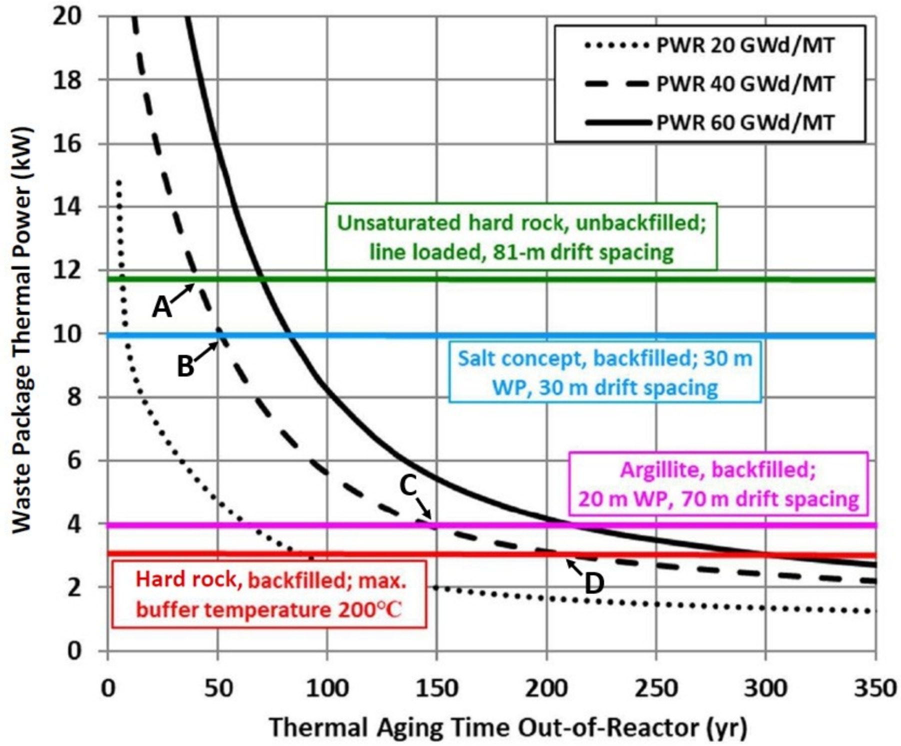


**Figure A-2. Thermal Power Versus Age for a Waste Package Containing a Dual-Purpose Canister with 32 Assemblies of Pressurized Water Reactor Spent Nuclear Fuel.**
Note: Figure taken from Hardin (2020; Slide 18) and revised for clarity. The horizontal green, blue, magenta, and red lines depict the approximate waste package thermal power limit, at emplacement, for the different disposal concepts that are described in the text boxes. The points A, B, C, and D depict that a waste package containing a dual-purpose canister with 32 assemblies having a burnup of 40 GWd/MT would require <50 years, 50 years, 150 years, and >200 years, respectively, of aging prior to emplacement in a repository in the described unsaturated hard rock, salt, argillite, and saturated hard rock repository, respectively.

decay curves for a waste package with a DPC containing 32 PWR assemblies at three burnup values (20, 40, and 60 GWd/MT). The figure shows that, in order to meet the waste package thermal power limit for an unbackfilled repository in hydrologically unsaturated hard rock, a waste package with 32 PWR assemblies having a burnup of 40 GWd/MT would require an aging time of < 50 years (Point A) prior to emplacement to reduce thermal power so that temperature limits are met. Longer aging times would be required for the other repository concepts illustrated in Figure A-2: 50 years for a backfilled repository in salt (Point B), 150 years for a backfilled repository in hydrologically saturated argillite (Point C), and > 200 years for a backfilled repository in hydrologically saturated hard rock (Point D).

The largest DPCs currently in use can hold 37 PWR assemblies or 89 BWR assemblies, which emit more heat and, thus, will require longer aging times than the 32-PWR waste package evaluated in Figure A-2. Also, most fuel currently in commercial power reactors will have burnups > 45 GWd/MT when discharged from the reactors.[12] This means that waste packages containing newer DPCs will require longer aging times than those with older DPCs.

[12] Average discharge burnup for all assemblies permanently discharged during a calendar year increased from about 30 GWd/MT in 1980 to just over 45 GWd/MT in 2002 [Figure 1.5.1-2 in DOE (2009a)].

Given this background, the waste package thermal power limits must be considered when deciding on the timing of DPC emplacement. Disposal of SNF in DPCs in a backfilled repository located in the hydrologically saturated zone of either argillite or hard rock will require hundreds of years of thermal aging prior to emplacement. This extended period of DPC storage may strongly influence the site selection process in terms of the choice of potential host rock and repository design assumptions. *The potential range of costs of this extended DPC storage period for the different repository potential host rocks needs to be reflected in any comparative cost analysis of commercial SNF management alternatives.*

**Cost Estimates Supporting Decision Making on Disposal of Dual-Purpose Canisters**

As described in the preceding section, the 2019 cost analysis (Freeze et al. 2019) evaluated two future alternative scenarios, which were based on disposal of commercial SNF only, at the proposed Yucca Mountain repository beginning in 2031 and 2041. The analysis also considered a scenario with disposal of commercial SNF beginning in 2117 at a repository with characteristics and costs equivalent to the Yucca Mountain repository. In the following paragraphs, the Board discusses its evaluation of the 2019 cost analysis and identifies areas where additional information could be provided so decision makers can understand the shortcomings in the 2019 cost analysis, and any future cost analyses, and the implications for future disposal options.

The comparative cost analysis in Freeze et al. (2019) identifies common costs that are the same across all scenarios and variants (Figure A-3). The analysis also identifies costs that vary between scenarios and between scenario variants and which may be fundamental to deciding which scenario and variant to follow in developing the waste management program. The potentially discriminatory costs evaluated are those concerning repository disposal, transportation, taxpayer liability, TAD canisters, utility packaging, repository packaging, and a new facility for variants that include a consolidated interim storage facility. In the cost analysis, the taxpayer liability includes costs primarily associated with extended dry storage and includes payments to the utilities for the cost of loading DPCs, the annual costs of independent spent fuel storage installation (ISFSI) administration and maintenance, and associated ISFSI costs for up to 10 years following availability of a repository or centralized interim storage facility.[13]

The comparative cost analysis cautions that the disposal starting "dates are chosen simply for the purpose of investigating relative cost impacts associated with delay and should not be interpreted as more or less likely." However, the estimated costs for variants of a specific alternative scenario are dependent on when disposal operations begin and on how long taxpayer liability costs are assumed to extend beyond the start of repository disposal operations. Figure A-1 shows the projected SNF inventory in dry storage in 2031 will be substantially more than 60,000 MTHM. Given the 3,000 MTHM per year limit for acceptance of commercial SNF at the Yucca Mountain repository, by the time repository operations start in 2031, there would be a more than 20-year backlog of SNF needing transport to the repository. Thus, an alternative analysis that takes account of the backlog of SNF at utility sites and the acceptance rate at a repository or

[13] The cost analysis "assumes that the Judgment Fund would provide for ISFSIs operations 10 years after repository or consolidated interim storage availability" (Freeze et al. 2019, pg. 78). The basis for this assumption was not stated.

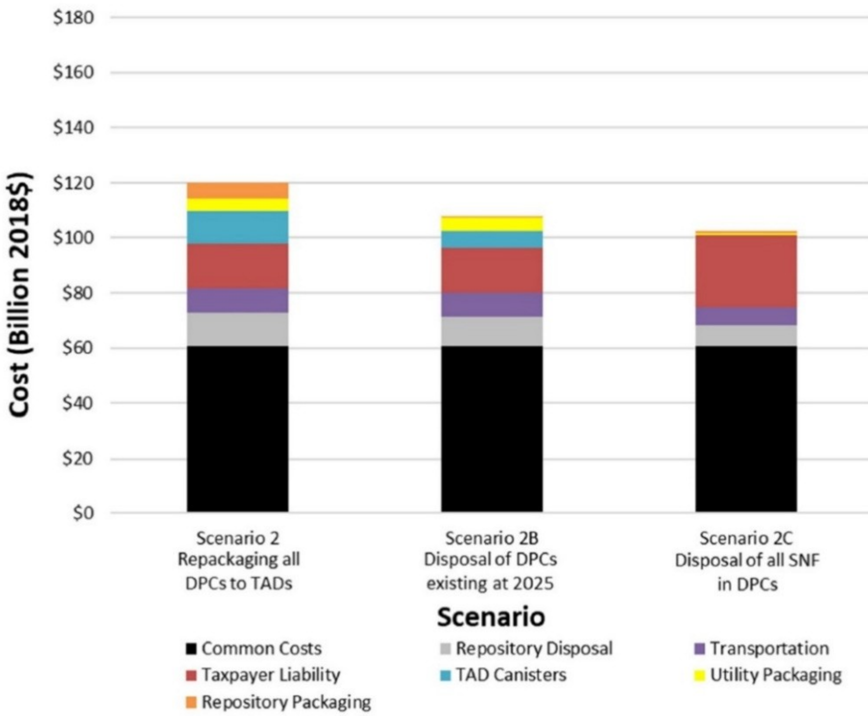


**Figure A-3. Comparison of estimated costs for different DPC disposal variants for the scenario when the repository begins disposal in 2031.**

Modified from Figure ES-3 in Freeze et al. (2019). Scenario 2 includes loading of TADs at utilities starting in 2025 and repackaging of SNF from DPCs (loaded until 2025) into TADs occurring at the repository. Scenario 2B includes loading SNF into TADs at utilities starting in 2025 but disposing of DPCs loaded before then, rather than repackaging into TADs. Scenario 2C includes loading of SNF into DPCs continuing after 2025 and disposing of all SNF in DPCs rather than repackaging into TADs.

consolidated interim storage facility would increase the estimated taxpayer liability for operating costs. *For any future DOE cost analysis, DOE should consider whether estimation of taxpayer liability for all of the scenarios and variants needs to factor in the expected backlog of SNF in dry storage when repository operations begin, rather than simply assuming the liability extends only 10 years beyond when a repository or centralized interim facility begins operations. DOE also could evaluate alternative scenarios that have repository SNF acceptance rates greater than 3,000 MTHM.*

Because disposal of the nation's commercial SNF at the Yucca Mountain repository by law is still the current option but remains uncertain, and siting of a new repository could occur in other host rock types, a cost analysis on disposal of DPCs that relies on a number of analyses done for the Yucca Mountain repository, or at a repository with characteristics and costs equivalent to the Yucca Mountain repository, is incomplete. At the Board's July public meeting, DOE characterized the cost estimates in the 2019 cost analysis as rough-order-of-magnitude costs. These rough-order-of-magnitude cost estimates are based on the TSLCC associated with the Yucca Mountain repository, or equivalent, for disposal of commercial SNF only. In 2014 and 2015, DOE developed rough-order-of-magnitude cost estimates for a commercial-SNF-only repository sited in different host rocks as part of its technical basis for a decision on the need for a separate defense HLW repository (DOE 2014, 2015).[14] Cost estimates for developing a repository in different host rocks, including the associated cost for storage of SNF (Figure A-2), would allow a comparison of costs of different waste management program configurations. Such an analysis would provide for a better informed decision making and policy development by explicitly tying decisions on SNF repackaging versus direct disposal of SNF in DPCs in a repository to potential disposal options.

In its presentation at the Board's July meeting, DOE stated that, based on the 2019 cost analysis, disposal of SNF in DPCs could result in a cost savings of up to $20 billion compared to repackaging the SNF into other canisters. DOE's analysis indicated that one contributor to the reduction in cost is elimination of disposal of DPC hulls and baskets as low-level waste (LLW). The 2019 cost analysis used as its basis a report that only calculated LLW disposal cost on a volume basis and used outdated information on disposal costs. The U.S. Nuclear Regulatory Commission (NRC) regularly reports LLW disposal costs. In addition to the baseline costs based on waste volume, the most recent information reported by the NRC (NRC 2019) indicates that current LLW disposal costs also depend on the volume-averaged radioactivity and the total amount of radioactivity disposed of annually by each disposer, and that there are cost premiums for large items such as DPCs and non-standard waste packages. These additional cost factors were not taken into account in the Freeze et al. (2019) cost analysis. Current information on LLW disposal could be used to estimate the cost of disposal of DPC hulls and baskets.

Alternatively, there could be cost savings associated with recycling the material or reusing DPCs, which would avoid the need to dispose of as many DPCs as LLW. However, recycling or reuse would incur costs to refabricate or repurpose the DPCs and possibly introduce regulatory uncertainty from using a radioactive material, especially in non-nuclear applications. If DPC recycling or reuse by the utilities is a realistic option, the cost differential between disposal of SNF in DPCs and disposal of the SNF after repackaging in purpose-designed canisters would be different.[15] The Board recognizes that these opportunities for improvement in future cost analyses could allow a better accounting of the costs, but that these improvements 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.

*Based on the information in this Appendix, 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.*

[14] The DOE (2014, 2015) cost estimates for a commercial SNF repository included disposal of commercial HLW, but it represents only a miniscule part of the total cost (e.g., the total inventory included about 50 waste packages of HLW and about 7,500 waste packages of commercial SNF).

[15] At the Board's July meeting, Rob Howard (Oak Ridge National Laboratory) stated that based on his informal discussions with SNF canister vendors, the vendors have mixed views regarding the feasibility of reusing DPCs, but it is something that could be studied (NWTRB 2020, p.153).

For future DOE cost analyses of waste management alternatives, the Board observes that a better accounting of relevant costs and related uncertainties could:

- Consider a larger range of costs associated with extended storage of SNF—the duration of which would depend on the repository host rock type—and with the expected backlog of SNF in dry storage at the time repository or centralized interim facility operations begin when estimating the increase in taxpayer liability, which will continue to accrue as long as the SNF is not removed from nuclear power plant sites;
- Include alternative scenarios that have repository SNF acceptance rates greater than 3,000 MTHM; and
- Take account of current LLW disposal costs and the potential for DPC recycling or reuse.

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