U.S. Nuclear Waste Technical Review Board

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

Board Activities for the Period January 1, 2019-December 31, 2021

November 2022

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

November 2022

The Honorable Nancy Pelosi
Speaker
United States House of Representatives
Washington, DC 20515

The Honorable Patrick J. Leahy
President Pro Tempore
United States Senate
Washington, DC 20510

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

Dear Speaker Pelosi, Senator Leahy, and Secretary Granholm:

Congress created the U.S. Nuclear Waste Technical Review Board in the 1987 Nuclear Waste Policy Amendments Act (NWPAA) (Public Law 100-203) to evaluate the technical and scientific validity of activities undertaken by the Secretary of Energy to implement the Nuclear Waste Policy Act. In accordance with provisions of the NWPAA directing the Board to report its findings and recommendations to Congress and the Secretary of Energy, the Board submits this *Report to the U.S. Congress and the Secretary of Energy*. The Report summarizes Board activities, conclusions, and recommendations for the period, January 1, 2019, through December 31, 2021.

During the period covered by the Report, the Board focused its review on research, development, and demonstration activities undertaken by the U.S. Department of Energy (DOE) on four critical technical issues. The Board evaluated DOE activities related to disposal in a mined geologic repository, management and disposal of DOE's high-level radioactive waste (HLW) and spent nuclear fuel (SNF), packaging, storage and transportation of HLW and SNF, as well as an integrated SNF and HLW management and disposal system.

The Board hopes 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,

{signed}

Jean M. Bahr
Chair

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EXECUTIVE SUMMARY

The U.S. Nuclear Waste Technical Review Board (Board) was established by Congress in the 1987 Nuclear Waste Policy Act Amendments (Public Law 100-203). Pursuant to the Act, the Board is charged with evaluating the technical and scientific validity of activities undertaken by the U.S. Department of Energy (DOE) related to the management and disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW). The Board also reports the results of its independent reviews and evaluations, along with its findings, conclusions, and recommendations, to Congress and to the Secretary of Energy.

Between January 1, 2019 and December 31, 2021, the period of Board activities summarized in this report, the Board focused its evaluation of DOE's efforts on four critical issues related to geologic disposal and on four important technical areas related to packaging, storage, and transportation of SNF and HLW that are destined for interim storage or geologic disposal. The Board also continued to explore in depth the crosscutting issues associated with developing an integrated waste management system. Figure ES-1 depicts a timeline of activities the Board completed in the 2019 to 2021 reporting period, including correspondence with DOE, Board reports to Congress and the Secretary of Energy, and fact-finding and public Board meetings with DOE.

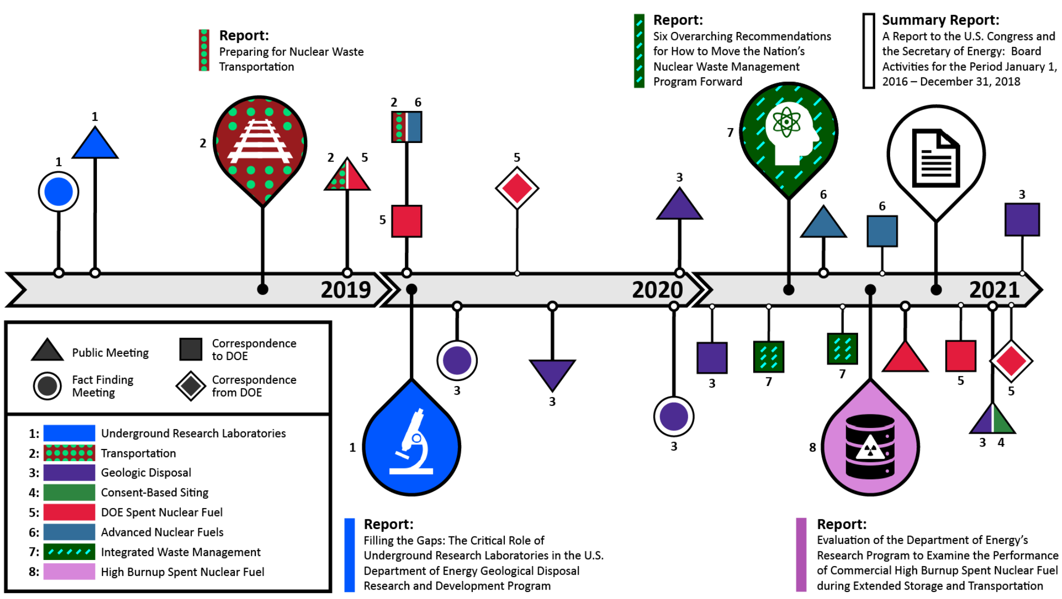

Figure ES-1. Timeline of Board activities, meetings, and correspondence from January 1, 2019 to December 31, 2021.
See legends to the bottom left: subject matters are color-coded, and shapes indicate a type of activity. Board reports are offset with large balloons; triangles and circles symbolize meetings; and squares and diamonds symbolize correspondence to or from DOE, as indicated.

The Context of the Board's Review

The suspension of DOE's efforts on the Yucca Mountain, Nevada, repository program in 2010, and DOE's 2013 strategy for managing and disposing of SNF and HLW, guided DOE's activities during this reporting period. The strategy included a phased, adaptive, and consent-based approach to siting and implementing an integrated waste management and disposal system. DOE's 2013 strategy:

> "endorses a waste management system containing a pilot interim storage facility; a larger, full-scale interim storage facility; and a geologic repository in a timeframe that demonstrates the federal commitment to addressing the nuclear waste issue, builds capability to implement a program to meet that commitment, and prioritizes the acceptance of fuel from shut-down reactors."

In its strategy, DOE acknowledged that full implementation required legislative changes but indicated that it was undertaking activities within existing congressional authorization to plan for the eventual transportation, storage, and disposal of SNF and HLW. These activities included research and development (R&D) on the suitability of various host rocks for a repository. These non-site-specific geologic repository studies focused on disposal in a mined repository constructed in salt, clay/shale, and crystalline host rocks. The studies were intended to provide a basis for several evaluations, including an assessment to determine if the canisters used for SNF storage at nuclear power plant sites could be disposed of in these host rocks. DOE also indicated it was undertaking transportation evaluations that could prioritize DOE's acceptance of SNF from shut-down reactors.

DOE's strategy also included initiatives for R&D on the deep borehole disposal concept as well as consent-based siting. In 2017, the Administration of President Donald Trump terminated both initiatives and focused on restarting the Yucca Mountain, Nevada, repository program. Without congressional appropriations for restarting the Yucca Mountain program, DOE continued its efforts through 2021 to develop an integrated waste management system that was consistent with its 2013 strategy and existing legislative authority. Practically, this meant that DOE continued to conduct R&D on storage, packaging, transportation, and non-site-specific geologic disposal options for both commercial and DOE SNF and HLW and developing the system capabilities and infrastructure for transportation of the waste.

In 2020, Congress appropriated $20 million that was directed to be used for interim storage. In 2021, the Administration of President Joseph Biden refocused the interim storage effort and DOE began to develop a consent-based siting process for siting federal interim storage facilities.

Geologic Disposal

The Board focused its evaluation of DOE activities in four critical technical areas related to geologic disposal: non-site-specific (generic) disposal R&D activities, underground research laboratories, disposal of SNF in dual-purpose canisters, and the geologic disposal safety assessment framework.

Non-site-specific (generic) disposal R&D activities

DOE's non-site-specific disposal R&D focuses on geologic disposal concepts in three potential host rocks—crystalline, salt, and argillite—and utilizes laboratory, field (e.g., underground research laboratories [URLs]), and modeling studies. DOE's goals are to provide a sound technical basis for developing alternative, viable disposal options for SNF (e.g., disposal in dual-purpose storage and transportation canisters) and HLW, to increase confidence in the robustness of non-site-specific disposal concepts, and to develop tools (e.g., the geologic disposal safety assessment framework) needed to support disposal concept implementation. The Board reviewed DOE's R&D program and its R&D prioritization process that incorporated information on disposal research strategies and key lessons learned from other countries, including those that are at early program stages, comparable to DOE's program, regarding site selection and R&D scope.

The Board found that successful repository implementation needs a legal framework that clearly describes the roles of the implementer, regulator, and society, and success requires a long-term political commitment. Waste programs in other countries believe, based on their experiences, that the major challenges for repository implementation are not primarily technical, but rather, involve fully addressing the societal concerns and challenges, including taking account of societal perspectives as well as technical objectives in developing the technical research to be conducted. Overall, the Board found that DOE has made good progress toward developing the technical bases and the tools to support the evaluation of multiple disposal options. It has effectively used collaborations, especially in URLs, to develop and rapidly advance its program. The Board found that DOE can increase its chance of success by benefitting from lessons learned by other countries and organizations. DOE can advance its program by fostering additional stakeholder engagement, consistently and clearly discussing with stakeholders the various disposal options, better defining the safety functions of the engineered barriers and geologic setting for each disposal option and using natural analogue information. The Board made nine recommendations to improve DOE's non-site-specific disposal R&D program.

Underground research laboratories

DOE's URL collaborations have been an important component of DOE's geologic disposal R&D, and the Board documented its evaluation of DOE's efforts in a report (Figure ES-1). The Board found that DOE participation in URL-related international research has greatly benefited the U.S. geologic disposal R&D program, but further work by DOE on its coupled thermal-hydrological-mechanical-chemical models and URL- and laboratory-based research can strengthen its program. The Board also found that URLs are essential to the overall success of repository programs and that the more developed repository programs in other countries have focused on creating and strengthening their safety cases and making them more transparent to the public using URLs.

The Board recommended that DOE should pursue one or more domestic URLs to advance the development and demonstration of disposal concepts and to provide a platform for training the next generation of U.S. scientists, engineers, and skilled technical workers. In addition, DOE should expand its collaborative international URL activities to enhance its capacity for R&D on geologic repositories and should make systematic use of URL R&D results to regularly update generic repository safety cases that can be easily understood and can be demonstrated to the public, including safety cases relevant to direct disposal of dual-purpose canisters in different host rocks. The Board recommended that DOE should continue advancing its thermal-hydrological-mechanical-chemical focused research and accompanying model development and should pursue more URL- and laboratory-based studies, particularly at elevated temperatures.

Disposal of SNF in dual-purpose canisters

Decisions in the near term on the disposability of SNF in dual-purpose cannisters (DPCs) and the direction of the nation's geologic disposal program are needed because their interdependence will shape waste management and disposal activities over many years. The Board observed that 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 criticality after repository closure (post-closure criticality). The Board also observed that there were practical limitations of applying the current Standard Contract, which requires that DOE take delivery of individual SNF assemblies from the utilities, which would mean opening welded DPCs and repackaging the SNF into other containers that can be transported, stored, and used for disposal.

The Board recommended that DOE should 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. The Board recommended that DOE focus more effort on the degradation of baskets that contain the SNF and use data on the as-loaded damaged fuel assemblies to strengthen its analysis of post-closure criticality. The Board suggested improvements to post-closure criticality consequences analyses and R&D on filling canisters with a material such as a flowable grout that would solidify, as a potential method to inhibit post-closure criticality.

Geologic Disposal Safety Assessment framework

For several years, DOE has been developing a computational framework known as the Geologic Disposal Safety Assessment (GDSA) framework for evaluating the post-closure repository performance for HLW and SNF in various host rock types and with different disposal options. The Board found that DOE has a technically valid approach to developing its geologic disposal safety assessment capability that will enable it to evaluate the post-closure performance of potential SNF and HLW repositories in different host rocks and with different disposal options. The Board recommended that DOE needs to define a clear strategy and intended outcome for the use of the framework in the near term, to better prioritize what needs to be incorporated in the software framework and to apply it systematically to a broad range of reference cases. The Board also recommended that DOE prioritize and expedite the development of the framework to assess the performance of different engineered barriers and solicit input on the development of the GDSA Framework from a broader spectrum of stakeholders, including the public and the regulator.

Packaging, Storage, and Transportation of SNF and HLW

The Board focused its evaluation of DOE activities in four critical technical areas related to packaging, storage, and transportation: management of DOE SNF, preparing for nuclear waste transportation, back-end issues associated with advanced nuclear fuels and accident tolerant fuels for light water reactors, and the long-term dry storage and transportation of high burnup commercial SNF.

Management of DOE SNF

Congress specifically appropriated funds to DOE to address some of the Board's 2017 report recommendations on DOE's management of its SNF. The Board had recommended that DOE develop an improved technical basis for proposed drying procedures for DOE SNF, particularly aluminum-clad SNF (ASNF), before packaging it in multi-purpose (storage, transportation, and disposal) canisters. The Board recommended that DOE should measure and monitor conditions of the SNF during dry storage. During the current reporting period, DOE has made progress in closing technical and knowledge gaps related to packaging, drying, and dry storage of ASNF. DOE has been conducting research relating to corrosion of aluminum-based cladding, radiolysis processes, gas generation rates, and drying processes to remove bound water from the cladding corrosion layers. DOE has advanced its understanding of ASNF corrosion and gas generation through experiments, such as the scale-up radiolysis testing of ASNF and surrogates in a mini-canister environment, through modeling and simulation results for ASNF in the DOE Standard Canister and through development of wireless sensor technology for in-situ monitoring of ASNF in vented canisters. The Board encouraged DOE to continue the drying experiments and to support additional surface characterization of surrogate specimens. The Board suggested that DOE explore more fully the maximum expected dose for ASNF in the DOE inventory, which is related to the amount of radiolysis, to evaluate further the fate of oxygen produced during radiolysis of water in sealed SNF canisters, and to implement a well-documented verification and validation process for its modeling software.

Packaging and transportation of SNF and HLW

In a Board report pertaining to transportation of DOE SNF and HLW (Figure ES-1), the Board identified 30 technical issues that DOE would need to address before it commences any future nationwide transportation campaign of SNF and HLW to either an interim storage facility or to a disposal site. Some issues apply if DOE decides it will accept only bare commercial SNF assemblies[1] from utilities and other issues apply if DOE accepts SNF pre-packaged in casks or canisters—decisions that DOE has not yet made. The Board commended DOE's development of system analysis and planning tools and its significant progress in its test programs to evaluate and demonstrate safe transportation of an SNF cask with fuel assemblies using various transportation modes, such as truck, cargo ship, and train, under various accident conditions. The Board also commended DOE for its international collaborations and effectively leveraging resources for accomplishing such research endeavors.

The Board noted that DOE needs to address technical issues in a more integrated and comprehensive manner. The Board recognized that, although some of the issues may be addressed more quickly and easily, other issues could take considerably longer to address. The Board recommended that DOE prioritize and carefully sequence the technical issues to be addressed to support the integrated operation of a future nationwide transportation program. The Board commended DOE for proactive efforts to inspect and evaluate the readiness of nuclear power plant storage sites to remove commercial SNF, but the Board recommended that DOE give high priority to evaluating the removal of commercial SNF from shut-down nuclear power plant sites and to sharing evaluations and lessons learned with other operators of waste storage sites to prepare those sites for eventual transportation of waste. The Board also noted the need for early planning by DOE for the development of casks and canisters for DOE SNF and HLW. The Board recommended that, for planning purposes, DOE should allow for a minimum of a decade to develop new cask and canister designs for SNF and HLW storage and transportation, or that DOE should conduct its own detailed evaluation of the time needed to complete the design, licensing, fabrication, and testing of new casks and canisters.

Impact of advanced nuclear fuels including accident tolerant fuels

DOE has started planning work to identify technical gaps and data needs as it considers the implications of new and advanced nuclear fuels, including accident tolerant fuels, on SNF management and disposal. The Board noted that DOE was in the early stages of considering the potential implications of new fuels and claddings during storage and transportation of the SNF originating from the use of advanced nuclear fuels, but that DOE needs to prioritize its R&D efforts on SNF management issues related to near-term advanced fuels technologies. DOE should incorporate lessons learned from other countries that have further advanced those countries' plans for waste management of advanced nuclear fuels. DOE has performed a gap analysis and has planned experiments and modeling efforts to better understand the performance of the SNF (thermal modeling, criticality, etc.) originating from deploying these new fuel types and advanced reactors. However, the Board noted that DOE had only focused its gap analysis on storage and transportation scenarios and has not yet considered disposal aspects of advanced nuclear fuels, including accident tolerant fuels.

[1] Bare SNF assemblies are not sealed inside SNF canisters.

Long-term dry storage and transportation of high burnup commercial SNF

DOE continued its research tasks related to evaluating the performance of high burnup fuel (HBF) during extended storage and subsequent operations. The Board commended DOE for its progress and efforts on the tasks and for closing some important data and knowledge gaps. The Board agreed with DOE-identified technical information needs and priorities with one exception: the Board felt that the fuel performance modeling, which integrates thermal, mechanical, and materials modeling aspects, should be included among the DOE's priority research efforts. The Board released a report on management of HBF (Figure ES-1) and made some general and specific recommendations to DOE. For SNF drying, DOE needs to further evaluate the amount of residual water after SNF drying processes, and DOE needs to improve and validate its gas sampling methods with a particular focus on water vapor sampling and measurement. For hydrogen effects in HBF cladding, the Board recommended standardization of data collected from various test methods for examining hydride reorientation so that the data may be compared and analyzed more readily. For sister rod testing, DOE should associate the specific sister rod test to a corresponding technical information need and explain how the technical information need is addressed by the data and analysis of the sister rods. Overall, the Board commended DOE for its work in advancing and sponsoring HBF modeling capabilities but noted that DOE should rigorously ensure that its thermal models are validated. The Board recommended that DOE should quantify the uncertainties introduced by the use of unirradiated assembly components and surrogate components, such as concrete mock-SNF assemblies, in experiments DOE is using to benchmark its structural model.

Integrated SNF and HLW Management and Disposal System

The Board released a synthesis report (Figure ES-1) of its nearly decade-long experience reviewing DOE's activities related to the management and disposal of SNF and HLW and put forth six overarching recommendations for DOE's nuclear waste management program in support of developing a successful geologic repository program in the United States. The recommendations dealt with the design and effective operation of an integrated nuclear waste management program, provided guidance on creating a more effective and rigorous science and engineering program, and dealt with building public trust and international engagement to foster success in the program.

As DOE began an effort to site Federal facilities for the temporary, consolidated storage of commercial SNF, the Board commended DOE for undertaking efforts to develop a consent-based approach. The Board noted that including knowledge and expertise on risk communication, public engagement, and inclusiveness from the social-behavioral sciences and the public health sciences would provide DOE a significantly broader and stronger knowledge and experience base from which to draw insights and expertise. The Board noted that it would also be beneficial for DOE to systematically review key lessons that have been learned from siting processes in other nations and that a candid "lessons learned" document on the unsuccessful efforts to site a deep borehole experiment in

Rugby, North Dakota might be used to improve future consent-based siting and stakeholder engagement activities.

International Activities

The Board interacted with other national and international radioactive waste management organizations to gain perspectives to support its review of DOE activities. The Board met virtually with the Swedish National Council, a sister agency, to gain insights on how national approaches to defining and carrying out a multi-decadal disposal research, development, and demonstration (RD&D) program evolve through time. The Board participated in the Advisory Bodies to Government group and the Integration Group for the Safety Case, which both operate under the auspices of the Nuclear Energy Agency. A tour of the Morsleben, Germany radioactive waste repository associated with Advisory Bodies to Government group meeting demonstrated the importance of considering all phases of a repository (construction, operation, and closure) at the beginning of a repository project. A key point raised in an Integration Group for the Safety Case meeting was that as national programs advance to siting and implementation (e.g., Sweden, Switzerland, and France), domestic priorities to submit licensing documents and develop their repository reduce their ability to support international collaborations, such as those in URLs, because the URLs' efforts are no longer considered integral to the national program. DOE currently strongly relies on these collaborations and access to the URLs to accomplish its R&D because it lacks a domestic URL.

PREFACE

Congress established the U.S. Nuclear Waste Technical Review Board as part of the 1987 Nuclear Waste Policy Amendments Act to "evaluate the technical and scientific validity" of the actions taken by the Secretary of Energy to implement the Nuclear Waste Policy Act.

This report provides a summary of the activities carried out by the Board between January 1, 2019 and December 31, 2021. Among those activities are observations, findings, conclusions, and recommendations recorded by the Board in its letters and reports. This report records the views of the Board at the time they were published. The format of observations, findings, conclusions, and recommendations recorded in this report match those in each cited letter and report.

BOARD ACTIVITIES

The Board and Its Mission

The U.S. Nuclear Waste Technical Review Board (Board) was established by Congress in Title V of the 1987 Nuclear Waste Policy Amendments Act of 1987 (NWPAA), P.L. No. 100-203. The Board's mandate is to "evaluate the technical and scientific validity of activities undertaken" by the U.S. Secretary of Energy to implement the Nuclear Waste Policy Act of 1982 (NWPA), P.L. No. 97-425, as amended. Among other things, Congress charged the Board with evaluating the U.S. Department of Energy's (DOE's) site characterization activities, and activities relating to packaging and transporting high-level radioactive waste (HLW) and spent nuclear fuel (SNF).

The Board is an independent federal agency within the Executive Branch. Members of the eleven-person Board serve part-time and are appointed by the President from a list of nominees prepared by the U.S. National Academy of Sciences. For the period covered by this report, the members of the Board who served included: Dr. Jean M. Bahr (Chair); Dr. Steven M. Becker; Dr. Susan L. Brantley; Mr. Allen G. Croff; Dr. Efi Foufoula-Georgiou; Dr. Tissa Illangasekare; Dr. Linda K. Nozick; Dr. Kenneth L. Peddicord; Dr. Paul J. Turinsky (Deputy Chair); and Dr. Mary Lou Zoback.[2] Appendix A contains biographies of each member.

The Board is required to report its findings, conclusions, and recommendations to Congress and the Secretary of Energy. This report summarizes the Board's activities beginning on January 1, 2019 and ending on December 31, 2021.[3] Figure 1 presents a timeline of Board activities, meetings, and correspondence. The Board's website www.nwtrb.gov contains all the correspondence, reports, and meeting materials.[4] In addition, the Board began streaming its meetings over the Internet starting in June 2017. Those webcasts are archived on the Board's website. The Board's strategic plan is also on the website and is reproduced in Appendix B. Appendix C lists and describes all Board reports since its inception and all these reports are archived on the Board's website. Appendix D lists, for this reporting period, each of the meetings and their topics. Appendix E lists and reproduces the correspondence during the period of January 1, 2019 to December 31, 2021.

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[2] Dr. Susan Brantley served from September 25, 2012, until her resignation on July 21, 2021. Dr. Efi Foufoula-Georgiou served from September 25, 2012, until her resignation on May 17, 2021. Dr. Linda Nozick served from July 28, 2011, until her resignation on May 9, 2019. Dr. Mary Lou Zoback served from September 25, 2012, until her resignation on May 17, 2021.

[3] This report does not discuss the Board's 2021 summary report to Congress and the Secretary of Energy (NWTRB 2021a) that summarized Board activities that occurred from January 1, 2016 until December 31, 2018.

[4] The website also contains factsheets that the Board developed solely to provide information on, and increase understanding of, technical issues related to the management and disposal of SNF and HLW.

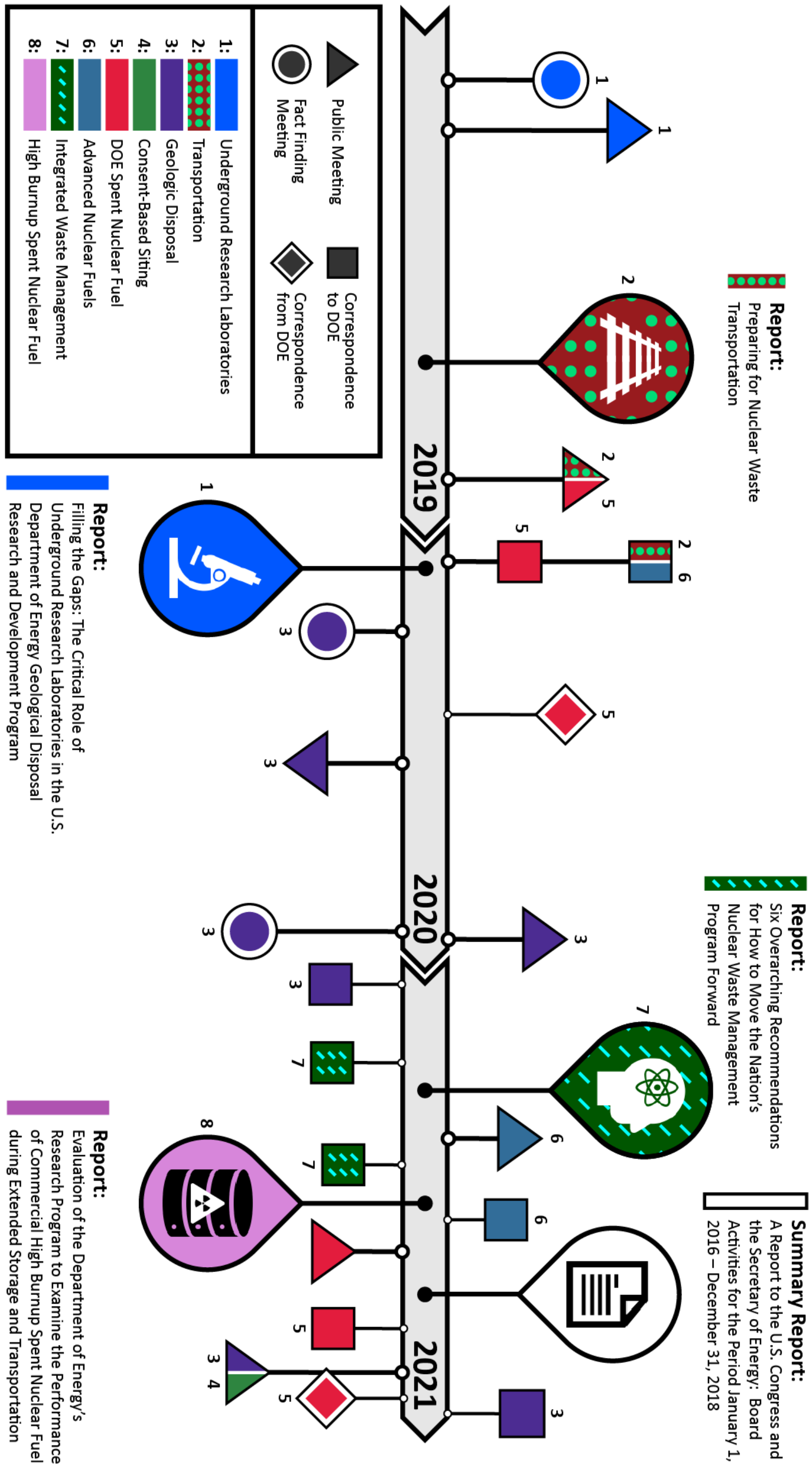

Figure 1. Timeline of Board activities, meetings, and correspondence from January 1, 2019 to December 31, 2021.

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Developments in Nuclear Waste Management

In passing the NWPAA, Congress instructed DOE to limit its efforts to characterize a site for a deep-mined, geologic repository to Yucca Mountain in Nevada. In January 2002, based on a recommendation from Secretary of Energy Spencer Abraham, President George W. Bush informed Congress of his intention to select this site. Overriding the objections from Nevada Governor Kenneth Guinn, Congress ratified the President's decision in July 2002.

In June 2008, DOE submitted an application to the U.S. Nuclear Regulatory Commission (NRC) seeking authorization to construct a repository at Yucca Mountain. In January 2010, however, the Administration of President Barack Obama initiated steps to halt DOE's licensing effort, maintaining that the Yucca Mountain Project was "unworkable," and DOE soon after attempted to formally withdraw the application before the NRC. The NRC's Atomic Safety and Licensing Board (ASLB) denied DOE's petition to withdraw the application. In September 2011, the NRC Commissioners were evenly divided on whether to overturn or uphold the ASLB decision denying DOE's petition (NRC 2011), which left the ASLB decision in place. At the same time, however, the Commissioners, in recognition of budgetary limitations, directed the ASLB to complete all necessary and appropriate activities including disposition of all matters currently pending before it (NRC 2011) by September 30, 2011. Accordingly, the ASLB suspended the proceedings (ASLB 2011).

In August 2013, the U.S. Court of Appeals for the District of Columbia Circuit ruled that the NRC had to continue the licensing process using remaining appropriated funds of approximately $11.1 million.[5] As part of that work, the NRC staff in 2015 released volume five of its safety evaluation report, *Proposed Conditions on the Construction Authorization and Probable Subjects of License Specifications* (NRC 2015). The NRC staff concluded in that volume of the safety evaluation report that DOE had met all the regulatory requirements, subject to the proposed conditions on construction authorization, with the exception of requirements regarding ownership of land and water rights. The NRC staff recommended that a construction license not be granted at that time because DOE had not met regulatory requirements regarding ownership and control of the land and certain water rights. In addition, a supplement to DOE's environmental impact statement had not yet been completed (NRC 2015). Then, in May 2016, the NRC staff completed the supplement to DOE's environmental impact statement. During 2016 to 2017, NRC funded knowledge management reports to capture the insights gained and independent analyses conducted as part of the Yucca Mountain license application review and to describe the preparatory studies for the review. As of December 31, 2021, approximately $0.30 million in unobligated funds remained.

In parallel with seeking to withdraw the license application in 2010, President Barack Obama instructed Secretary of Energy Steven Chu to establish a Blue Ribbon Commission on America's Nuclear Future (BRC). The BRC was charged with recommending a new strategy for managing the backend of the nuclear fuel cycle. In its report, issued in January 2012, the strategy the BRC recommended had several key elements related to the NWPA (BRC 2012):

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[5] *In re Aiken County*, 725 F.3d 255 (D.C. Cir. 2013).

- "A new consent-based approach to siting future nuclear waste management facilities.
- A new organization dedicated solely to implementing the waste management program and empowered with the authority and resources to succeed.
- Access to the funds nuclear utility ratepayers are providing for the purpose of nuclear waste management.
- Prompt efforts to develop one or more geologic disposal facilities.
- Prompt efforts to develop one or more consolidated storage facilities.
- Prompt efforts to prepare for the eventual large-scale transport of spent nuclear fuel and high-level waste to consolidated storage and disposal facilities when such facilities become available."

In January 2013, DOE issued its response to the BRC's report in *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* (DOE 2013). Although many details of implementation were left to future discussions with lawmakers and other interested and affected parties, it included two major outcomes (DOE 2013):

> "The Administration endorses the key principles that underpin the BRC's recommendations. The BRC's report and recommendations provide a starting point for this Strategy, which translates many of the BRC's principles into an actionable framework within which the Administration and Congress can build a national program for the management and disposal of the nation's used nuclear fuel and high-level radioactive waste. …
>
> …[T]his Strategy endorses a waste management system containing a pilot interim storage facility; a larger, full-scale interim storage facility; and a geologic repository in a timeframe that demonstrates the federal commitment to addressing the nuclear waste issue, builds capability to implement a program to meet that commitment, and prioritizes the acceptance of fuel from shut-down reactors."

DOE subsequently advanced four initiatives from its *Strategy* report, each of which had been considered by the BRC. The first followed up on BRC's considerations of whether some DOE-managed HLW and SNF should be disposed of in a dedicated repository that is separate from a repository for commercial SNF (and the remaining DOE-managed HLW and SNF). In March 2015, DOE issued its *Report on Separate Disposal of Defense High Level Radioactive Waste* (DOE 2015a). Revisiting the decision taken by President Ronald Reagan in 1985 to develop a single repository for both defense and commercial HLW and SNF, the report reevaluated the six factors identified in Section 8(b)(1) of the NWPA.[6] Noting the significant changes that had taken place over the intervening three decades in "repository availability," approaches taken to siting disposal facilities, the end of the Cold War, and new environmental obligations, DOE concluded that "a strong basis exists to find that a Defense HLW repository is required" (DOE 2015a). In a Memorandum to the Secretary of Energy Ernest Moniz, President Barack Obama determined that a separate defense HLW repository was in fact "required" under the terms of the NWPA (Obama 2015). That determination provided the opportunity for DOE to proceed with the disposal of its own waste in a repository, in accordance with the authority DOE already held under the Atomic Energy Act. Thus far, however, DOE has not pursued a separate defense HLW repository.

The second initiative responded to the BRC's recommendation (BRC 2012) for:

> "…[F]urther RD&D [research, development and demonstration] to help resolve some of the current uncertainties about deep borehole disposal and to allow for a more comprehensive (and conclusive) evaluation of the potential practicality of licensing and deploying this approach, particularly as a disposal alternative for certain forms of waste that have essentially no potential for re-use."

Supported by a report from Sandia National Laboratories (SNL) (SNL 2015), DOE issued a Request for Proposal for vendors to conduct a Deep Borehole Field Test (DBFT) (DOE 2015b).

Consent-based siting of nuclear waste storage and disposal facilities was the subject of DOE's third initiative. In a *Federal Register* notice (DOE 2015c), DOE stated that it was implementing:

> "[A] consent-based siting process to establish an integrated waste management system to transport, store, and dispose of commercial spent nuclear fuel and high level defense radioactive waste. In a consent-based siting approach, DOE will work with communities, tribal governments and states across the country that express interest in hosting any of the facilities identified as part of an integrated waste management system."

Evaluating options for transportation of SNF from shut-down reactors was the subject of DOE's fourth initiative. In 2013, DOE began evaluating "the inventory, transportation interface, and shipping status of used nuclear fuel at shut-down reactor sites" (DOE 2013). In 2015, DOE awarded a contract to design and develop a prototype 12-axle railcar that would meet the American Association of Railroads' standard for transport of SNF and HLW. DOE's prototype transport cask car, called the "Atlas railcar," was designed for transport of commercial SNF. In 2020, DOE began a similar development effort for an 8-axle prototype transport cask car, called the "Fortis railcar."

[6] These included cost efficiency, health and safety, regulation, transportation, public acceptability, and national security.

The *Strategy* (DOE 2013) noted that DOE was undertaking activities within existing congressional authorization to plan for the eventual transportation, storage, and disposal of SNF. DOE's activities included conducting R&D on the suitability of various geologic environments for a repository. These non-site-specific studies focused on disposal in a mined, geologic repository constructed in salt, clay/shale, and crystalline host rocks.

In 2017, the Administration of President Donald Trump redirected budget priorities and changed DOE's program direction. DOE terminated both the consent-based siting and deep borehole initiatives consistent with an administration focus on restarting the Yucca Mountain, Nevada repository program. Without congressional appropriations for restarting the Yucca Mountain program, however, DOE continued through 2021 its efforts to develop an integrated waste management system that was consistent with the *Strategy* (DOE 2013). This meant that DOE conducted R&D on storage, packaging, transportation, and non-site-specific geologic disposal options for both commercial and defense SNF and HLW.

In 2020, the Administration of President Donald Trump requested funding "dedicated to performing activities that would lay the groundwork necessary to ensure near-term deployment of interim storage to ensure safe and effective consolidation and temporary storage of nuclear waste." Congress appropriated $20 million that was directed to be used for interim storage. In 2021, the Administration of President Joseph Biden refocused the interim storage effort and DOE began to develop a consent-based siting process for siting federal interim storage facilities. The Consolidated Appropriations Act of 2022 that provided appropriations for fiscal year 2022, which began in September 2021, provided DOE with $5 million for advanced reactor used fuel disposition R&D to address used fuel from tri-structural isotropic (TRISO)-fueled and metal-fueled advanced reactors.

Fulfilling its obligations under the NWPAA, the Board maintained a "watching brief" over technical and scientific aspects of these initiatives.

Board Review: Disposal in a Mined Geologic Repository

As an option to avoid the complexities, cost, and occupational hazards associated with opening welded DPCs and repackaging the SNF, DOE began conducting R&D activities in 2013 related to evaluating the feasibility for direct disposal (without repackaging) of SNF in DPCs that are stored at commercial utility sites. The Board highlighted in its 2018 review of DOE's DPC disposal R&D that thermal management and post-closure criticality were the key issues that still needed to be analyzed further by DOE (Bahr 2018). DOE's strategies for addressing the potential for post-closure criticality associated with the disposal of DPCs were:

- Direct disposal without modification (a disposal strategy that addresses the risk [probability and consequence] from post-closure criticality events).
- Modification of already-loaded DPCs with injectable filler material.

- Modification of DPCs to be loaded in the future, or the fuel they contain, by changing loading maps, adding disposal criticality control features, or basket redesign.

In this reporting period, DOE continued to develop and evaluate different disposal concepts that would apply across the inventory of commercial and defense SNF and HLW. DOE's disposal R&D is intended to support the development of a sound technical basis for multiple viable disposal options, to increase confidence and robustness in generic disposal concepts, and to develop science and engineering tools to implement disposal concepts. DOE's non-site-specific disposal research program included host-rock (argillite, crystalline, and salt) and cross-cutting investigations (Figure 2). DOE has relied heavily on its international collaborations in disposal research (Figure 2), especially from underground research laboratories (URLs), to obtain data and understanding of the characteristics and processes that would occur in repositories sited in the three host rocks. One potential disposal option is to dispose of existing DPCs, currently stored at operating, decommissioning, and decommissioned commercial nuclear power sites, directly without removing the commercial SNF and repackaging it into other, smaller, containers that are designed for disposal. Although DOE designates this option as direct disposal of DPCs, it acknowledges that in most cases some type of disposal overpack surrounding the DPC would be required prior to disposal. A key aspect of DOE's disposal R&D program is the development of the Geologic Disposal Safety Assessment (Figure 2) software framework that evaluates post-closure repository performance in various host rock types.

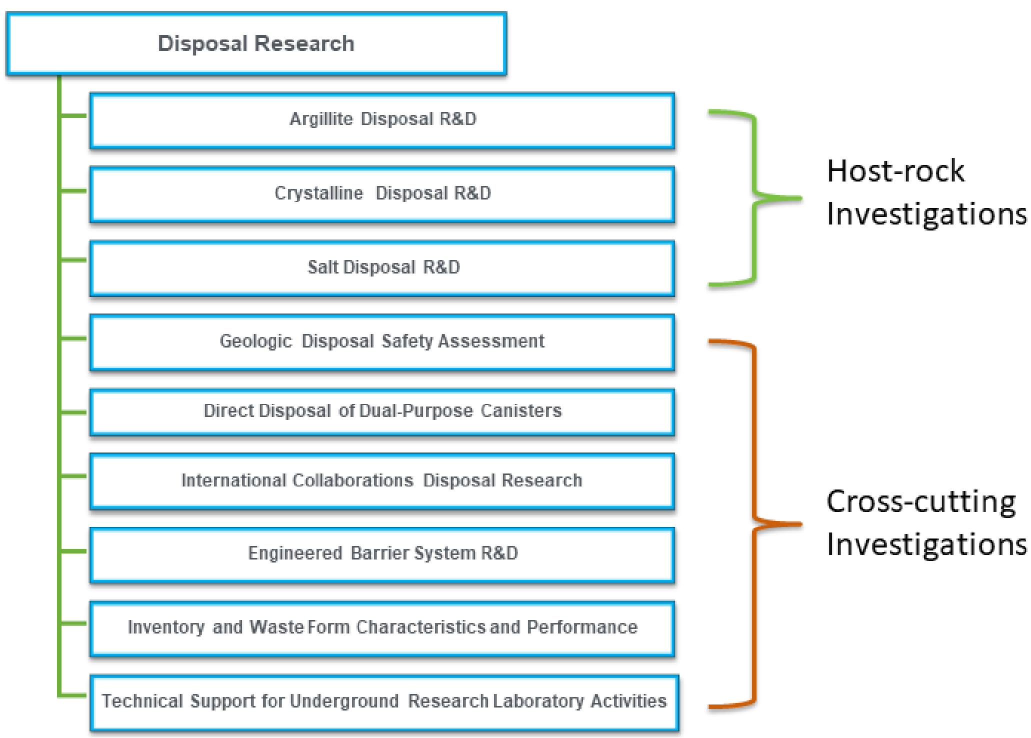

Figure 2. DOE disposal research investigations.
Note: Revised from **(Gunter 2020)**. The technical support for underground research laboratory activities program area is focused on domestic underground research laboratories.

The Board's efforts focused on an overall assessment of DOE's non-site-specific disposal R&D program and DOE's use of URLs. The Board continued its focused review of DOE's R&D on the disposal of DPCs and began reviewing DOE's development of its Geologic Disposal Safety Assessment (GDSA) software framework.

Non-site-specific disposal R&D

Between 2012 and 2019, DOE implemented a roadmap (DOE 2012) for its generic (i.e., non-site-specific) disposal R&D concepts and priorities. In 2018, DOE began to review its R&D progress since its 2012 roadmap report (DOE 2012) to assess whether the R&D conducted had closed technical gaps or identified new technical gaps and to determine whether new program direction required new areas of focus. DOE also began a process to update its R&D priorities and develop a roadmap update to the 2012 report.

In 2019, DOE finalized efforts to update their 2012 R&D roadmap (DOE 2012). In January 2019, DOE organized a workshop, observed by a Board staff member, to achieve consensus on the prioritization of R&D activities. Members of the Board staff also attended the DOE Spent Fuel and Waste Disposition Annual Working Group Meeting in Las Vegas, Nevada, May 2019, to obtain updates on DOE's R&D activities and its reprioritization efforts. DOE's updated roadmap focuses on disposal R&D concepts in three potential host rocks—crystalline, salt, and argillite (Sevougian, et al. 2019) and identified the need to better understand and model high temperature processes associated with the disposal of DPCs.

Based on its reprioritization effort, DOE began to develop higher temperature disposal concepts that would accommodate disposal of DPCs. From the roadmap update process, DOE also recognized the need to more regularly update its R&D portfolio and priorities. In 2020, DOE completed its initial Disposal Research R&D 5-Year Plan (Sassani, et al. 2020) that identified near-term (1–2-year timeframe) and longer-term (3–5-year timeframe) priorities. Since then, DOE has been producing annual updates to the 5-year R&D plan.

Based on DOE's efforts to reprioritize its non-site-specific disposal R&D, the Board decided to conduct an overall assessment of DOE's disposal R&D program. In November 2020, the Board held a fact-finding meeting to gather information and updates on DOE's disposal R&D program and help the Board prepare for the December 2020 public meeting.

In the December public meeting, DOE representatives provided an overview of the disposal R&D program. The Board heard presentations from DOE national laboratory researchers on the technical direction and R&D activities related to various host rocks—crystalline, salt, and argillite. National laboratory researchers described the prioritization of crosscutting R&D activities (Figure 2). There were presentations on an unsaturated alluvium reference case, disposal of DPCs, and the GDSA framework. National laboratory researchers addressed the engineered barrier system (EBS) R&D and the HotBENT (High Temperature Effect on Bentonite Buffers) experiment in Switzerland. The final presentation from the national laboratories staff described DOE's prioritization of its international activities and the disposal research R&D 5-year plan (Sassani, et al. 2020). The Board also heard about disposal research strategies and key lessons learned from other countries that are at early program stages, comparable to DOE's program, regarding site selection and R&D programs.

Presentations from the United Kingdom's Radioactive Waste Management organization and the IGD-TP (Implementing Geological Disposal of radioactive waste Technology Platform) group, which is a consortium of 142 member organizations across 29 countries, provided context for the Board's review of DOE's program. After carefully considering the information gathered from the fact-finding and public meetings, the Board provided its findings, conclusions, and recommendations in a letter to DOE (Bahr 2021a). The Board's findings and conclusions are summarized below.

- Successful repository implementation needs a legal framework that clearly describes the roles of the implementer, regulator, and society. Procedures for conducting the site selection and implementing the repository program must be accepted by all these parties. Success requires a long-term political commitment.

- Other countries believe, based on their experiences, that the major challenges for repository implementation are not primarily technical, but rather, involve fully addressing the societal concerns and challenges, including taking account of societal perspectives as well as technical objectives in developing the technical research to be conducted.

- DOE collaborated with other countries that are considering the development of repositories in crystalline rock, salt, and argillite that use host-rock-specific repository designs and took account of information and experience from their programs in developing and rapidly advancing its R&D program.

- DOE can increase its chance of success by benefitting from lessons learned by other countries and organizations like the IGD-TP group, such as the need to clearly communicate why a disposal option should be considered safe.

- Overall, DOE has made good progress toward developing the technical bases and the tools to support the evaluation of multiple disposal options.

- DOE can advance its program by fostering stakeholder engagement, consistently and clearly explaining to stakeholders the various disposal options, better defining the safety functions of the engineered barriers and geologic setting for each disposal option, and by using natural analogue information that can inform understanding of the performance of bentonite and argillite at high temperatures over long periods.

The Board's recommendations are summarized as follows:

- **DOE should use a well-developed technology maturity scoring method as one of the factors in setting R&D priorities.**

- **DOE should assess the need for and scope of new technical siting guidelines for a repository for each of its potential disposal concepts (e.g., disposal in an argillite host rock).**

- **When DOE is developing models for disposal options, there should be more focus on how the experimental data that are needed to set values of modeling parameters will be acquired.**

- **DOE should include all processes within the repository that would occur upon instantaneous dissolution of DOE SNF in the GDSA framework or provide a technical basis that demonstrates those processes would not adversely impact engineered barriers and overall system performance.**

- **DOE should assess whether it needs to develop reference cases and identify supporting R&D for disposal options in domal salts and brittle argillites and, if DOE decides these are not needed, provide a rationale for the decision.**

- **DOE's testing and models should address the effects of clay layers in bedded salt formations and their impact on salt repository performance.**

- **DOE should consider natural analogues in its strategic planning and determine whether a natural analogue exists that could be used to evaluate the consequences of aging of bentonite and argillite at high temperatures over longer periods than those possible in laboratory or underground research experiments.**

- **DOE should become a member of the IGD-TP organization and focus on lessons learned, mainly societal information sharing, communication, and ways of building public confidence and trust, from countries that have advanced their repository programs beyond concept evaluation.**

- **DOE should make clear and effective communication of its disposal options, and their associated barriers, barrier functions, and supporting technical bases, and pre-disposal management activities such as any repackaging or storage that are required prior to disposal, an integral part of its disposal R&D program. DOE should use a communication approach that is informed by stakeholder input and can consistently describe in verbal and graphic forms the claims, argument and evidence supporting the disposal option.**

During the reporting period, members of the Board staff also attended three meetings related to DOE's non-site-specific disposal R&D:

- 10th U.S./German Workshop on Salt Repository Research, Design, and Operation in Rapid City, South Dakota, May 2019, to obtain information on international R&D activities on salt repository science, design, and operation.

- Actinide Brine Chemistry in a Salt-Based Repository (VI) Workshop and Nuclear Energy Agency Thermochemical Database Project Working Group Meeting in Karlsruhe, Germany, June 2019, to obtain information on U.S. and international R&D activities on actinide and brine chemistry relevant to salt repositories.

- Twenty-Third Meeting of the Integration Group for the Safety Case (IGSC), held virtually in October 2021, to obtain updates on DOE's efforts in the IGSC, including its participation in groups focused on disposal in crystalline and salt host rocks.

Underground research laboratories

A number of countries, including the United States, have operated underground research laboratories (URLs) in different types of potential host rocks to support developing deep geologic repositories for the disposal of SNF and HLW. URLs have permitted the collection of data at temporal and spatial scales (Figure 3) that can test and support the safety case for a repository, and allowed the demonstration of technologies that can address engineering challenges and enhanced public understanding of and confidence in geologic disposal (NWTRB 2020).

Since 2012, DOE has engaged in active collaborations with the geologic disposal programs of several countries, including participation in research conducted in several URLs in Europe and Asia. DOE's international collaborations have been an important component of its geologic disposal research (Figure 2). According to DOE, these collaborations have provided access to data and to decades of experience gained in various disposal environments in a cost-effective manner, enabled DOE-funded researchers to gain research experience and to take advantage of established URLs in a short period of time, and provided opportunities for peer reviews of DOE data and analyses by experts from other countries (NWTRB 2020).

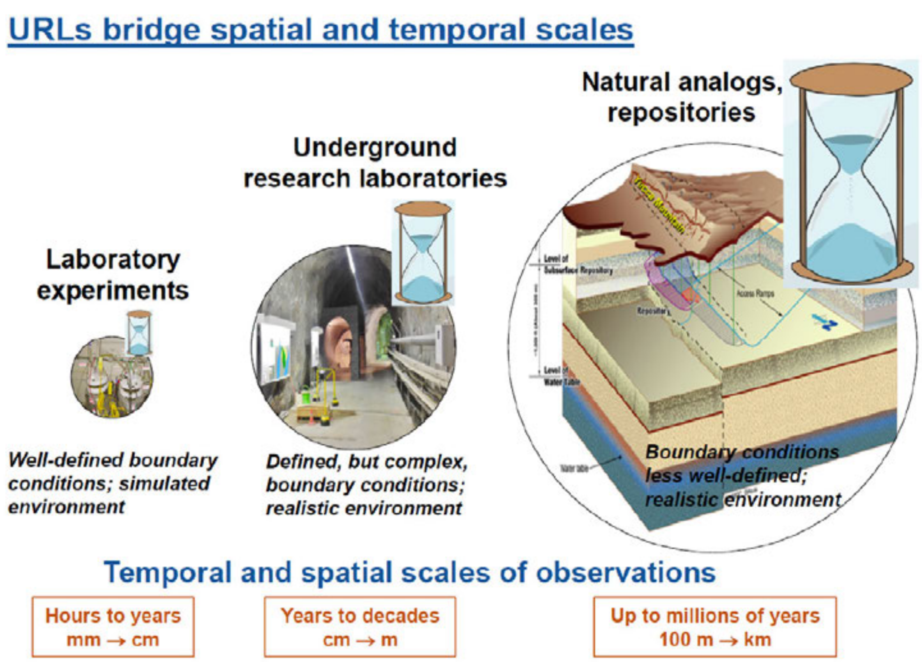

Figure 3. Spatial upscaling and temporal extrapolation (NWTRB 2020).

In February 2019, the Board held a fact-finding meeting with DOE to gather information on DOE's R&D activities and international collaborations in URLs. In April 2019, the Board held a technical workshop on recent advances in repository science and operations from international URL collaborations. The Board organized the workshop to review the technical and scientific validity of DOE's R&D activities related to URLs. The Board also elicited information on international URL R&D programs (e.g., Sweden, France, Switzerland, and the United Kingdom) useful to the Board in its review and to DOE in its implementation of these activities. The workshop included two full days of formal presentations and an informal evening poster session (Figure 4).

Figure 4. Members of the Board and staff attend a poster session at the Board's URL workshop. International workshop participants contributed the majority of twenty posters that were displayed and discussed.

In January 2020, the Board released a report, *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program* (NWTRB 2020). Based on the Board's evaluation of information presented and discussed at the workshop, at the fact-finding meeting, and from reports published by DOE and others, the Board offered a number of conclusions, specific findings, and recommendations in the report.

The following summarizes the Board's conclusions documented in that report. The Board concluded that siting, developing, and operating a geologic repository for HLW and SNF was a multi-generational endeavor and URLs were crucial to repository programs. URLs provided training opportunities for scientists, engineers, and skilled technical workers and provided continuity to disposal programs. Experience in URLs in other countries demonstrated that solving the technology challenges associated with construction and emplacement of waste and other engineered barriers (i.e., pre-closure activities) has been as important to the overall repository program as addressing the post-closure safety issues. Until 2018, DOE's URL-based R&D activities focused on the disposal concepts of the URL host countries and not on a disposal concept that could apply to most of the U.S. inventory of commercial SNF, i.e., the direct disposal of SNF in large DPCs. Internationally, a safety case with prescribed safety functions for each engineered and natural barrier has been the technical foundation for each repository program and guided the R&D that was conducted in the laboratory and in URLs. DOE has not yet developed generic safety cases, and associated safety functions and technical bases, for disposal of DPCs in crystalline, argillite, and salt host rocks.

From the report's specific findings, the Board made four principal findings on DOE's URL-related R&D activities. The summarized principal findings in the report were:

- DOE participation in URL-related international research has greatly benefited the U.S. geologic disposal R&D program by furthering its understanding of generic and site-specific disposal issues relevant to alternative repository host rocks and environments and benefited the URL-related research of other countries.

- The more developed repository programs in other countries have focused on creating and strengthening their safety cases and making them transparent to the public and have used URLs to explain the technical bases underlying their safety cases, periodically reassess knowledge gaps and define new activities to strengthen the technical bases, and demonstrate the technology that will allow implementation of the proposed safety concept.

- DOE needs domestic URLs to advance geologic disposal efforts over the next decades and further its ability to train the next generation of scientists, engineers, and skilled technical workers.

- DOE's international URL collaborations have advanced its generic disposal R&D program, including development of modeling capabilities recognized internationally as state-of-the-art, but further work on its coupled thermal-hydrological-mechanical-chemical models and URL- and laboratory-based research can strengthen its program.

Based on its principal findings, the Board made recommendations that are summarized as follows:

- DOE should expand its collaborative international URL activities and should consider (i) making use of R&D in URLs to address the technical needs for the design, licensing, construction, and operation of geologic repositories in different host rocks that consider the types of waste in the U.S. inventory; (ii) pursuing international URL R&D partnerships, including those involving non-nuclear waste applications (e.g., carbon sequestration) that require underground knowledge and operations, in which DOE could participate in the design, construction, and operational phases of the collaborations; and (iii) compiling best practices, innovative approaches, and notable successes and failures in public outreach, engagement, and risk communication from the experiences of URL programs in other countries.

- DOE should make systematic use of URL R&D results to regularly update generic repository safety cases that can be easily understood by and demonstrated to the public, including safety cases relevant to direct disposal of dual-purpose canisters in different host rocks.

- DOE should pursue one or more domestic URLs to advance the development and demonstration of disposal concepts and provide a platform for training the next generation of U.S. scientists, engineers, and skilled technical workers and evaluate whether underground sites in the U.S. with existing infrastructure could be used. If DOE expands its domestic URL program in this way, then it should consider (i) broadening its URL R&D program from one focused on the technical issues relevant to post-closure repository performance to one that includes developing and demonstrating the construction and operational concepts for disposal; (ii) supporting larger, more formal training opportunities in underground disposal research in disciplines needed for the waste disposition mission; and (iii) making domestic URLs broadly accessible to researchers from the U.S. and other countries, including those outside the DOE geologic disposal R&D program.

- DOE should continue advancing its thermal-hydrological-mechanical-chemical-based research and model development and pursue more URL- and laboratory-based studies, particularly at elevated temperatures and should consider (i) designing and conducting technical activities in URLs to test hypotheses and assumptions; (ii) employing an iterative process involving laboratory experiments focused on fundamental processes, modeling, and field experiments and observations; (iii) including geomechanical constraints and thermal effects in fracture flow and transport models; and (iv) focusing on bedded salts and using the heater tests at the Waste Isolation Pilot Plant to improve the constitutive models of salt behavior.

Since the Board's report was released, the Board has continued to review DOE's URL R&D efforts as part of Board meetings associated with non-site-specific disposal R&D activities, disposal of SNF in DPCs, and the GDSA framework. A Board staff member also attended the Japan Ministry of Economy, Trade, and Industry (METI) and Nuclear Energy Agency (NEA)-sponsored virtual international workshop on "Joint Utilization of Underground Research Laboratories for Research and Development Project," at which staff members of DOE and the national laboratories participated.

Disposal of SNF in dual-purpose canisters

In the United States, commercial SNF is stored at over 80 sites across the country, including operating and decommissioned nuclear power plants, and is continuing to be generated at a rate of more than 2,000 metric tons of uranium per year. Much of the SNF is in dry storage inside canisters that have been designed with a dual purpose, for both storage and transportation of SNF. These dual-purpose canisters (DPCs) are welded closed after the SNF has been loaded, and while they have been designed for the dual purpose of storage and transportation, it was not anticipated that they would be potentially utilized for geologic disposal of SNF. If so utilized, storage times before disposal may need to be greatly extended if SNF heat loads exceed the repository design limit as adopted in other countries, shown in Figure 5, are relied upon.

In Figure 5 the horizontal green, blue, magenta, and red lines depict the approximate waste package thermal power limit, at emplacement, for the different disposal host rocks that are described in the text boxes. For example, the argillite repository design includes waste packages placed every 20 m in an emplacement drift that is then backfilled with bentonite. Adjacent emplacement drifts are 70 m away from the centerline of each emplacement drift. 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/MTU 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. These aging durations depend on repository design and assumed tolerances to temperature of material used for backfill, which is an area of active research.

Repackaging the SNF from DPCs into smaller waste packages that are consistent with other countries' repository designs would be a major undertaking. If DOE chooses not to repackage SNF into smaller waste packages and decides to dispose of higher-heat load and large waste packages, then it would need to develop the technical bases for new repository designs and operations that are beyond what other countries are implementing.

During the reporting period, the Board continued its review of DOE's R&D efforts to support the potential disposal of commercial SNF in DPCs. As part of its review effort, the Board held a fact-finding meeting with DOE in March 2020. Then, the Board held a public meeting which occurred virtually in July 2020 that solely addressed DOE's DPC disposal R&D activities. The Board's meeting addressed the feasibility of direct disposal of DPCs, post-closure criticality and its consequences, flowable cements (typically not common Portland cement) as a potential canister filler material, and cross-cutting research topics (Figure 2).

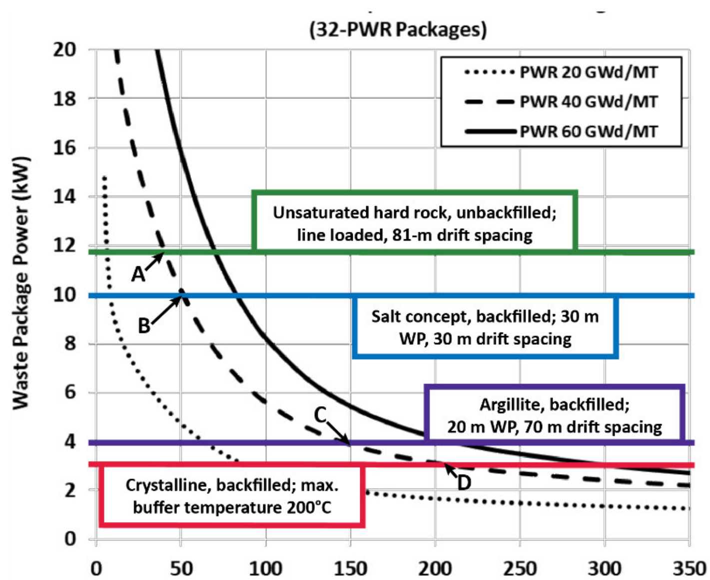

Figure 5. Thermal power versus age for a waste package containing a DPC with 32 assemblies of pressurized water reactor SNF.
Note: Figure taken from **(Hardin 2020)** and revised for clarity.

At the public meeting, DOE summarized past DPC studies and recent R&D that addressed the technical basis for engineering feasibility of disposal of SNF in DPCs. Presentations addressed model development that would be important for DPC criticality analysis, including a multi-physics criticality consequence modeling tool that was under development to simulate DPC criticality. Another model development effort focused on improvement to PFLOTRAN[7] for doing performance assessment calculations for hypothetical repository cases that accounted for a post-closure criticality event.

Based on the July public meeting and information provided in presentations and discussions, in January 2021, the Board corresponded with DOE and provided its observations and recommendations (Bahr 2021b). The Board's observations and recommendations highlighted the need for the data that will be acquired from the R&D activities that considers direct disposal of DPCs because the data helps inform important near-term decisions about SNF disposition. The Board noted that decisions in the near term

[7] PFLOTRAN is a state-of-the-art, parallel subsurface flow and reactive transport code that is an open-source computer code.

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. The Board observed that 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 post-closure criticality. The Board also observed that there were practical limitations of applying the current Standard Contract, which requires that DOE take delivery of individual SNF assemblies from the utilities, as this would require opening welded DPCs and repackaging the SNF into other containers. Also, the Board made observations on the need for more evaluations on SNF management and disposal due to the possible impacts of the eventual transition by the commercial light water reactor fleet to advanced fuel designs, including accident tolerant fuels, HALEU,[8] and other advanced fuels. In the letter, the Board also made observations on how DOE could improve its cost analyses of waste management alternatives by considering other relevant costs and related uncertainties (Bahr 2021b). The Board's recommendations are summarized as follows:

- **DOE should 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.**

- **DOE should (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.**

- **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.**

- **DOE should focus more effort on characterizing basket degradation.**

- **The Board suggests that, as DOE continues to examine the potential consequences with respect to long-term repository performance of criticality events that might occur in DPCs during the post-closure period of a hypothetical repository, it should consider the following:**

    - **Examine more realistic degradation rates of engineered barriers (i.e., DPCs and bentonite buffers).**

[8] High-assay low-enriched uranium (HALEU) is enriched between 5.00 and 19.75% uranium-235 (U-235). The existing light water reactor fleet uses fuel that is enriched up to 5% U-235.

- **Evaluate scenarios in which more than one DPC experiences a criticality event.**
- **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., 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.**
- **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.**
- **Start to develop and document an approach that can be used to validate the coupled models used in consequence analysis.**

- **The Board understands the canister filler testing 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 to be filled in order to eliminate the potential for nuclear 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.**
    - **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.**

Geologic Disposal Safety Assessment framework

Since 2013, DOE has been working on developing a modeling capability for evaluating the post-closure performance of potential repositories for SNF and HLW disposal. The modeling capability includes different geologic host rock types and different disposal options. During the reporting period, the Board monitored DOE's GDSA development progress by reviewing relevant reports and attending DOE's 2019 roadmap update workshop and its Spent Fuel and Waste Disposition Annual Working Group Meetings in May 2019 and 2021.[9]

After the release of the April 2021 Board report titled *Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward* (NWTRB 2021b), the Board decided to begin a focused, high-level review of DOE's GDSA efforts. The Board felt that DOE's efforts in developing the GDSA framework have the capability to address several of the report's recommendations, namely, to anticipate the required high-performance computing and data management infrastructure required for a multi-decade waste management program, and to facilitate the application of iterative and adaptive approaches to the development of a geologic repository.

The Board held a virtual technical fact-finding meeting on the GDSA framework in October 2021 and a public meeting the following month. In November 2021, the Board held a virtual public meeting and heard presentations from national laboratory researchers on R&D activities related to the GDSA framework, its capabilities, and its applications. Two members of the NRC staff provided perspectives on developing and applying computer codes based on their collective experiences at the NRC and their participation in international collaborations. The Board heard about the United Kingdom's Radioactive Waste Management organization's experience with the development of environmental safety case models that will support geologic disposal of the United Kingdom's radioactive waste. After discussing and examining the information presented at the fact-finding meeting and the public meeting, the Board made several observations, findings, and recommendations. The Board provided its observations, findings, and recommendations in a letter to DOE (Bahr 2022). The Board's findings and conclusions are summarized below.

- *The Board finds that DOE has a technically valid approach to developing its geologic disposal safety assessment capability that will enable it to evaluate the post-closure performance of potential SNF and HLW repositories in different host rocks and with different disposal options. DOE is competently carrying out the development of the GDSA Framework and is making great progress in this effort while recognizing some of the challenges.*

  The Board encourages DOE to continue its GDSA Framework development efforts.

- *The Board finds that DOE needs to more clearly define and articulate the near-term goals and applications of the GDSA Framework in order to better prioritize what*

[9] DOE cancelled the 2020 annual meeting due to circumstances related to the COVID-19 pandemic.

needs to be incorporated into the software framework at different stages of the repository program.

The Board recommends that DOE define a clear strategy and intended outcome for the use of the GDSA Framework in the near term and systematically apply it to a broad suite of reference cases.

- *The Board finds that the GDSA Framework currently does not have an adequate capability to assess the performance of engineered barriers, which may be necessary for evaluating engineered barrier capability and different disposal options.*

  The Board recommends that DOE expedite the development of the GDSA Framework such that it has sufficient capability to assess the performance of different engineered barriers and DOE also take account of near-field processes that could affect the performance of engineered barriers.

- *The Board finds that the development of the GDSA Framework can be improved by peer reviews by a broader spectrum of stakeholders.*

  The Board recommends that DOE solicit input on the development of the GDSA Framework from a broader spectrum of stakeholders, including the public and the regulator.

Board Review: Packaging, Storage, and Transportation of SNF and HLW

Packaging, storage, and transportation of SNF and HLW were topics of a Board review during the 2019 to 2021 period (Figure 1). After the suspension of the Yucca Mountain project, the nation's nuclear waste management priorities and strategies began to shift dramatically, and the Board began reviewing the scientific and technical information related to the extended storage and subsequent transportation of commercial SNF. By December 2010, the Board had published the report, *Evaluation of the Technical Basis for the Extended Dry Storage and Transportation of Used Nuclear Fuel* (NWTRB 2010). The report reviewed publicly available literature and identified key research needs to address any technical issues with storage or handling that are anticipated for extended dry storage and transportation of commercial SNF after long storage periods. Since 2010, the Board has conducted numerous review activities on DOE's packaging, storage, and transportation R&D efforts related to both commercial and DOE SNF and HLW (NWTRB 2010, 2016, 2021a). The Board continued to review DOE's activities related to management of DOE SNF at the three main DOE Office of Environmental Management (DOE-EM) sites: Hanford, Idaho National Laboratory (INL), and Savannah River Site (SRS) during the reporting period of 2019 to 2021.

Advances in fuel technology and operational changes by the commercial nuclear power plant industry have impacted the resulting SNF inventory and management activities. Over the past few decades, SNF was increasingly being discharged from commercial nuclear power reactors at higher burnup[10] levels. As defined by NRC, nuclear fuel utilized beyond 45 gigawatt days per metric ton of uranium (GWd/MTU) is considered high burnup fuel (HBF). Compared to data on dry storage of low burnup fuel (nuclear fuel utilized for less than 45 GWd/MTU), the data on HBF performance during dry storage and transportation were lacking. Thus, R&D on extended dry cask storage and transportation of HBF became increasingly important in the past decade (NWTRB 2010, 2016). In 2012, DOE solicited proposals to develop an R&D project on extended dry storage of HBF; the award went to the Electric Power Research Institute (EPRI) to develop what is now known as the High Burnup Dry Storage Cask Research and Development Project (formerly abbreviated as CDP but the acronym was re-designated as the HDRP) (EPRI 2014).

For the 2019 to 2021 reporting period, the Board held two public meetings addressing the management of DOE SNF, sent three letters to DOE, and received two responses from DOE-EM. Members of the Board staff began to attend DOE's Spent Nuclear Fuel Working Group meetings.[11] Board interactions with DOE included one letter of correspondence with DOE that stemmed from a public Board meeting that addressed DOE's packaging, storage, and transportation R&D. The Board's public meeting in November 2019 and the ensuing correspondence addressed DOE SNF, commercial HBF, and advanced nuclear fuels. The associated information for each type of fuel is addressed in the corresponding sections of this report. Additionally, the Board and staff participated in public meetings in which DOE attended and gave presentations, such as the EPRI Extended Storage Collaboration Program (ESCP) meetings. The Board completed and transmitted to DOE and Congress two extensive Board reports—one on technical issues that need to be addressed by DOE in planning for future nationwide transportation of large-scale shipments of DOE SNF and one on the DOE evaluations of the performance of high burnup commercial SNF during extended storage and transportation.

Management of DOE SNF

In 2017, the Board released a comprehensive report on DOE SNF titled *Management and Disposal of U.S. Department of Energy Spent Nuclear Fuel* (NWTRB 2017). Three main issues addressed in the report were aging management, packaging, and disposal of DOE SNF. This type of SNF does not include commercial SNF. The report included characteristics of all types of DOE SNF and focused on the significant inventory of aluminum-clad spent nuclear fuel (ASNF) that will need to be adequately dried during packaging prior to transportation and disposal. As of 2017, INL has approximately 1.8 metric tons of heavy metal [MTHM] in dry storage; the Hanford site stores approximately 3 MTHM of ASNF in road-ready dry storage configuration; while SRS has approximately 7 MTHM in wet storage. Extended long-term dry storage of ASNF (over 50 years) produces some additional technical

[10] Fuel burnup is a measure of the thermal energy generated in a nuclear reactor per unit mass of nuclear fuel and is typically expressed in units of gigawatt-days per metric ton of uranium (GWd/MTU). The yearly average burnup of SNF placed into storage increased from an average of about 35 GWd/MTU in the 1990s to over 45 GWd/MTU in 2018. Most SNF currently stored in the United States is low burnup fuel.

[11] The DOE Spent Nuclear Fuel Working Group was chartered in 2014 to provide a forum in which DOE organizations could identify, discuss, and analyze any DOE SNF-related issues and advise DOE management by recommending appropriate actions to avoid or resolve such issues.

challenges related to corrosion of aluminum cladding and the potential for radiolytic gas generation. Some spent fuel pools are also showing signs of aging.

Since 2017, DOE has been sponsoring and conducting research for extended dry storage of ASNF, relating to corrosion of aluminum cladding, radiolysis processes, gas generation rates, and drying processes to remove bound water from the cladding corrosion layers. As DOE has removed SNF from the water-filled basins at INL, it has moved ASNF into temporary unsealed dry storage containers. Since 2017, DOE has been planning to repackage the ASNF at INL and remove the SRS SNF from wet storage, dry it, and move it to long-term dry storage until a final disposition path is chosen. In 2022, DOE changed its SNF disposition plan for SRS SNF in wet storage, which now precludes the need for dry storage of ASNF at SRS.[12]

In November 2019, the Board held a public meeting to hear from DOE-NE and national laboratory researchers on DOE R&D related to packaging, drying, and dry storage of commercial SNF. At the meeting, there was also a presentation that provided a high-level overview of DOE-EM activities related to long-term dry storage of ASNF. The Board also heard a presentation from an expert on UK SNF drying and the potential implications for ASNF disposition.

Following the November public meeting, the Board sent a letter to DOE-NE and DOE-EM in January 2020 that provided its conclusions and recommendations on the R&D activities being supported by DOE related to the packaging, transportation, and dry-storage of commercial SNF and DOE SNF. The Board noted the need for DOE-EM and DOE-NE to interact more regarding the R&D being conducted on ASNF, and that the information presented at the Fall 2019 meeting was limited and provided an insufficient opportunity for the Board to pursue areas of technical inquiry as a part of its review and mission (Bahr 2020a, 2020b). In the Board's correspondence to DOE, the Board provided recommendations only on the packaging, transportation, and storage activities. The Board's summarized recommendations related to DOE's SNF R&D are as follows:

- *Recommendation. DOE should pursue an increased understanding of the effect of moisture on SNF in dry storage and continue its efforts to identify alternative methods of obtaining moisture measurements from inside SNF dry cask storage systems used by the nuclear industry and undertake similar efforts for the DOE Standard Canister.*

- *Recommendation. Regarding the DOE Standard Canister, DOE should engage early with the NRC to ensure that the DOE Standard Canister project team is aware of all applicable regulatory requirements, including requirements for criticality safety and limiting hydrogen concentrations, and develop a firm path forward and schedule for*

[12] DOE approved a new plan that will accelerate the disposition of SNF at SRS by more than 20 years and result in a savings of more than $4 billion dollars. Under the newly approved approach, called Accelerated Basin De-inventory, SRS will dissolve the SNF at the site's H Canyon chemical separations facility (without uranium recovery) and send it through the site's liquid waste program to be vitrified and safely stored onsite until a federal repository is identified.

completing development of the DOE Standard Canister and obtaining the necessary NRC approvals.

After the November 2019 meeting, the Board also wrote a letter to DOE-EM senior managers requesting establishment of a framework for more regular interactions between DOE-EM and the Board (Bahr 2020a, 2020b). The Board was concerned that DOE-EM elected to participate in the meeting in a limited fashion, with only an overview presentation of the ASNF work and no presentation on the DOE Standard Canister activities. Thus, the Board suggested there should be more regular interaction with DOE-EM at a senior management level to help foster better coordination for DOE-EM participation in future Board meetings.

In May 2020, DOE-EM responded (DOE 2020) to the Board's January letter (Bahr 2020b) and stated that DOE-EM would interact directly with the Board and keep DOE-NE informed of those interactions. DOE-EM also provided a point of contact to the Board (DOE 2020).

In August 2021, the Board and staff conducted a virtual public meeting to gain updates and to review recent results of technology development related to ASNF drying, packaging, and extended dry storage. INL leads an integrated technology development (TD) program for ASNF packaging, drying, and dry storage activities grouped into six subtasks with varying levels of completion and an additional task, the Instrumented Lid Project. DOE-EM described their plans to support the research on ASNF and their plans to eventually move the ASNF to dry storage at INL and SRS (as previously noted, the SRS plan for ASNF changed in 2022 following the approval of the Accelerated Basin De-inventory project). Presentations addressed the overall scope of their TD program, summarized tasks that had been completed, and described details of ongoing tasks and a summary of recent results. Research activities on the drying of ASNF surrogates (both laboratory-grown and commercially sourced) help inform which methods of drying are most effective for ASNF dry storage. Presentations described investigations of radiolytic gas generation and hydrogen chemistry pertaining to ASNF corrosion layers and updates to the scale-up radiolysis testing of ASNF and surrogates in a mini-canister environment. Presenters described modeling and simulation results for ASNF in the DOE Standard Canister and updated the Board on the development of wireless sensors for dry storage of ASNF as a part of the instrumented lid project.

In October 2021, the Board corresponded with DOE-EM and thanked them for their presentations at the Summer 2021 public meeting on ASNF (Bahr 2021c). The Board commended DOE for sponsoring the ASNF research with INL managing the integrated TD program for DOE. The Board noted that DOE incorporated recommendations from the Board's 2017 report on DOE-managed SNF (NWTRB 2017), as well as recommendations from a DOE Spent Nuclear Fuel Working Group report to provide the framework for its research. The Board commended DOE and INL for enabling independent peer review of TD tasks by the Pacific Northwest National Laboratory. The Board also commended DOE and the national laboratories for their progress on developing experiments to perform drying tests to better understand the different drying processes and removal of residual water, and for collaborating with industry and universities to conduct the ASNF research.

The Board's letter to DOE also provided some suggestions on ASNF R&D for DOE and national laboratories to pursue. Those suggestions are summarized here:

- Continue the drying experiments by providing resources (personnel, facility access, etc.) for follow-on research as the TD program progresses, which can generate useful data to inform predictive models and to validate results obtained from surrogate materials.

- Explore more fully the maximum expected dose for ASNF in the DOE inventory to ensure the testing is bounding.

- Conduct a more detailed evaluation of the fate of oxygen that is produced during radiolysis of water in sealed SNF canisters to provide support for assumptions in modeling and simulations.

- Support additional surface characterization of surrogate sample materials prior to future drying tests.

- Implement a well-documented verification and validation process for its modeling software.

- Include formal uncertainty quantification in its modeling efforts to improve confidence in model predictions, since decisions related to safely storing ASNF for an extended time period will be based mainly upon these model predictions.

The Board noted that development work for the instrumented lid task had many parallels with work sponsored by DOE-NE to develop remote sensor technology applicable to canisters holding commercial SNF. As DOE continues to develop sensors for the instrumented lid demonstration, the Board suggested that DOE-EM coordinate with DOE-NE and EPRI on the development of wireless sensors for SNF canisters. Finally, the Board letter to DOE encouraged DOE to consider the following future activities as an extension of the work leading to dry storage of ASNF:

- Ensure that the Nuclear Regulatory Commission transportation requirements are considered when planning follow-on research on ASNF and in advancing the design of the DOE Standard Canister for DOE-managed SNF.

- Evaluate the amount of residual water that may remain in an ASNF canister after drying and evaluate the potential consequences of that water (e.g., corrosion, creation of flammable gas mixtures, and pressure buildup).

- Continue to develop the wireless sensor technology and to look for other applications (e.g., use in waste disposal environments), while also paying close attention to cybersecurity precautions.

In November 2021, DOE responded to the Board's October letter (DOE 2021) and noted that DOE continues to provide resources (personnel, facility access, etc.) for follow-on research as the technology development program progresses. DOE thanked the Board for its positive comments on DOE's ASNF TD program and assured the Board that DOE remains committed to supporting this important research (DOE 2021).

Members of the Board and staff also attended meetings during the reporting period in which DOE gave updates or made presentations related to its management and disposal of DOE SNF:

- Waste Management Symposium in Phoenix, Arizona, March 2019, to obtain updates on nuclear waste management issues, interact with representatives of the national and international waste management programs, and present a paper on the Board's report (NWTRB 2017).

- Institute of Nuclear Materials Management 34th Spent Fuel Management Seminar in Alexandria, Virginia, January 2019, to interact with representatives of Government and commercial nuclear organizations, and to present a paper on SNF management programs in other countries.

- DOE SFWD Annual Working Group Meeting, May 2021, to gain updates on storage, transportation, and disposal R&D activities from DOE and national laboratory researchers.

Preparing for nuclear waste transportation

DOE activities related to supporting future transportation of SNF and HLW were the subject of the Board's ongoing review during the 2019 to 2021 period (Figure 1). In September 2019, the Board released a report, *Preparing for Nuclear Waste Transportation* (NWTRB 2019), with the main purpose of identifying technical issues that will need to be addressed in preparing a future nationwide effort to transport large quantities of SNF and HLW to a geologic repository or interim storage site. Regardless of the approach adopted for the disposition path for the waste, the waste will have to be transported from the originator's site to where the policymakers decide it should go. During the reporting period, members of the Board and staff attended seven meetings that provided updates on, or relevant to, DOE transportation and packaging research activities.

As of 2019, SNF and HLW were stored at more than 80 locations in 35 states across the United States. Small-scale shipments of SNF have occurred frequently in the past, such as the periodic shipments of naval SNF by the U.S. Navy. DOE has also transported small quantities of packaged HLW between facilities within the boundaries of DOE sites. However, DOE has not transported this waste off-site, and it is anticipated that large shipments of SNF and HLW will be made in the future. Transporting large quantities of SNF and HLW will require significant planning and coordination by DOE. DOE is the agency responsible for transportation of the waste under the NWPA, and in addition, the shipments of SNF and HLW must meet regulatory requirements of the Department of Transportation and the NRC.

A well-planned and well-integrated effort will be required by the nuclear waste management program in the United States to address unresolved issues before DOE can commence a future nationwide transportation effort for SNF and HLW. For instance, the DOE SNF and HLW inventory is vast and includes a diverse collection of waste forms, waste storage containers, storage conditions, storage locations, waste transportation containers, and respective regulatory requirements and licensing. Current waste storage sites also present varying degrees of accessibility for large transport vehicles or railcars. In Figure 6, a SNF rail transportation cask that was used by DOE for a small-scale shipping effort is shown.

Figure 6. SNF rail transportation casks.
DOE used these rail transportation casks to transport commercial SNF by rail from the West Valley Demonstration Project in New York to the Idaho National Laboratory. The average dimensions and weight of currently approved rail casks, on average, are approximately 7.1 m (23.3 ft) in length, 3.3 m (10.8 ft) in diameter, and 125 metric tons (275,000 lbs.) in weight when loaded. Photo source: **(DOE 2022a)**

Moreover, there are two main possible scenarios regarding DOE's acceptance of commercial SNF, and depending on the scenario, DOE's decisions will directly affect the technical issues to be addressed before it commences a nationwide transportation campaign. Specifically, DOE must determine whether it will accept only bare commercial SNF assemblies[13] from utilities (the first scenario) or whether it will accept SNF pre-packaged in casks or canisters (the second scenario). The Board report also covered evaluations of issues associated with packaging DOE-managed SNF and HLW into canisters and preparing the canisters for transportation. For the non-commercial, DOE-managed SNF and HLW, many of the technical issues that need to be addressed are the same for the commercial SNF and HLW. The Board identified a total of 30 technical issues [listed in Table 2-1 of the report (NWTRB 2019) and identified as Board-identified issues below] that need to be addressed in preparing a nationwide effort to transport SNF and HLW.

During its review, the Board also considered DOE's priority ranking of technical information needs and consulted other sources related to the extended storage and transportation of commercial SNF. In addition, the Board considered the length of time it may take for DOE to address specific technical issues. The Board recognized that although some of the issues may

[13] Bare SNF assemblies are not sealed inside SNF canisters.

be addressed more quickly and more easily than others, e.g., the development of a new transportation cask, some issues could take considerably longer to address.

The Board summarized its evaluation in three points. First, technical issues should be addressed in an integrated and comprehensive manner. Second, DOE's evaluations of shut-down storage sites for nuclear waste should continue. Third, advance planning for the development of casks and canisters for SNF and HLW is needed. The following summarizes the Board's findings and recommendations documented in that report:

> ***Finding 1.*** *The Board finds that many interrelated technical and integration issues must be addressed in preparing for a nationwide effort to transport SNF and HLW to their eventual destination. The technical issues must be prioritized and their resolution properly sequenced to ensure that the overall program will be operationally feasible and unhindered by delays.*
>
> ***Recommendation 1.*** *As DOE continues its analyses and research for a nationwide waste management and transportation system, the Board recommends that DOE ensure the 30 Board-identified issues of this report are addressed. The Board also recommends that the Board-identified issues and any other issues identified by DOE be prioritized and carefully sequenced to support the integrated operation of a nationwide transportation program.*
>
> ***Finding 2.*** *The Board finds that DOE's effort to evaluate the readiness to move commercial SNF from shut-down nuclear power plant sites has gathered important information that will be needed to support the removal of commercial SNF from these sites for transportation. However, not all shut-down sites have been fully evaluated. Furthermore, DOE has not conducted similar reviews at DOE facilities that store DOE-managed SNF and HLW.*
>
> ***Recommendation 2.*** *The Board recommends that DOE give higher priority to evaluating the removal of commercial SNF from shut-down nuclear power plant sites and to evaluating DOE sites that store DOE-managed SNF and HLW. DOE should also share the results of the evaluations with operators of waste storage sites, so they can apply lessons learned, retain critical site transportation infrastructure, and be better prepared for the eventual transportation of the wastes.*
>
> ***Finding 3.*** *The Board finds that DOE will have to complete existing canister designs or develop new cask and canister designs for storing and transporting SNF and HLW. The Board also finds that developing new cask or canister designs for SNF or HLW could take longer than a decade. Therefore, DOE will need to allow for considerable advance planning and early coordination with NRC during the development of new cask and canister designs.*
>
> ***Recommendation 3.*** *The Board recommends that, for planning purposes, DOE should allow for a minimum of a decade to develop new cask and canister designs for SNF and HLW storage and transportation, or DOE*

should conduct its own detailed evaluation of the time needed to complete the design, licensing, fabrication, and testing of new casks and canisters.

As part of its ongoing review of DOE's packaging and transportation research activities, members of the Board and staff also participated in multi-organizational meetings that involved DOE representatives and addressed DOE R&D or issues relevant to the Board's review of DOE activities. Those meetings relevant to DOE's packaging and transportation R&D activities were the following:

- Nuclear Energy Institute Used Fuel Transportation Tabletop Exercise, Prairie Island Nuclear Generation Plant in Welch, Minnesota to observe a tabletop exercise simulating the transport of SNF to an interim storage facility.

- 2019 National Transportation Stakeholders Forum in Arlington, Virginia.

- The 19th International Symposium on the Packaging and Transportation of Radioactive Materials in New Orleans, Louisiana to present papers on two Board reports (NWTRB 2017, 2019).

- Western Interstate Energy Board, High Level Radioactive Waste Committee, Fall 2019 Meeting in Las Vegas, Nevada to provide a presentation to the Committee on the Board's transportation report (NWTRB 2019).

- NRC Fuel Facilities and Spent Fuel Storage and Transportation Business Lines Briefing, in Rockville, Maryland.

- San Onofre Nuclear Generating Station's Community Engagement Panel in San Onofre, California to participate in a meeting and give a presentation on two Board reports (NWTRB 2017, 2019).

- 2020 Institute of Nuclear Materials Management 34th Spent Fuel Management Seminar in Alexandria, Virginia to present the Board's transportation report (NWTRB 2019).

Advanced nuclear fuels and accident tolerant fuels for light water reactors

During the reporting period the Board held two meetings that addressed advanced nuclear fuels and accident tolerant fuels for light water reactors (LWR), sent two letters to DOE, and received one response back from DOE-NE. The Board and staff participated in public meetings in which DOE attended and gave presentations, such as the Advanced Fuels working group meetings that are a part of EPRI ESCP.

The current United States commercial fleet of 93 nuclear power reactors are LWR designs. Since the March 2011 Fukushima Daiichi nuclear accident in Japan, there has been significant R&D in several countries to enhance the accident tolerance of these reactor fuels. Later in 2011, Congress directed the Secretary of Energy and DOE-NE, through the Consolidated Appropriations Act of 2012, P.L. 112-74, to give "priority to developing enhanced fuels and cladding for light water reactors to improve safety in the event of accidents in the reactor or spent fuel pools" and to give "special technical emphasis and funding priority…to activities aimed at the development and near-term qualification of meltdown resistant, accident-tolerant nuclear fuels that would enhance the safety of present and future generations of LWRs."

Since 2012, DOE-NE and its national laboratories have been supporting R&D with nuclear fuel vendors (Westinghouse, GE-Hitachi (GE)/Global Nuclear Fuel (GNF), and Framatome) related to the development of various claddings and fuel matrix enhancements that constitute accident tolerant fuel (ATF) for current LWRs (Figure 7). In 2012, DOE mentioned in an R&D gap analysis report (PNNL 2012) that the back-end implications of advanced fuels including ATFs would be addressed later in its R&D program. In early November 2019, a few members of the Board and staff attended the EPRI ESCP, Fall 2019 Meeting in Charlotte, North Carolina, which included the *Workshop on Evaluating Advanced Fuels Impacts (Accident Tolerant Fuels and Higher Burnup/Enrichment) on Back-end Operations*.

In late November 2019, the Board held a public meeting to review DOE R&D related to the dry-storage of commercial SNF and DOE-managed SNF. After an overview presentation on DOE's R&D, the Board asked DOE about what planning is being done now to assess the potential impacts of new nuclear fuel designs, including ATFs, on the back end of the fuel cycle, especially disposal in a geologic repository. The Board pointed out that some of the newly proposed fuels include materials that are considerably different from those used in contemporary U.S. nuclear fuels. Examples of these materials are chromium coatings on

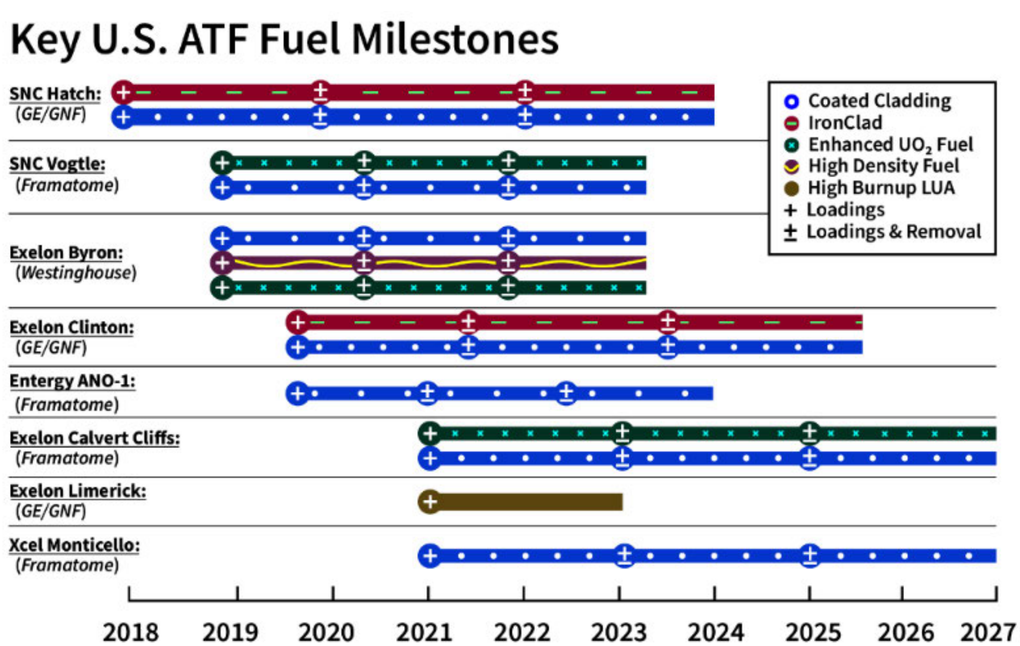

Figure 7. Key accident tolerant fuel milestones and timeline of activities for 14 lead test assemblies at 8 U.S. commercial nuclear power plants.
Industry-led lead test assembly insertions and removal timelines are shown in the above figure. The vendor name appears in parentheses under the power plant facility names to the left. Courtesy: Nuclear Energy Institute, 2021. Acronyms: LUA [lead use assembly]; GE/GNF [General Electric/Global Nuclear Fuel].

zircaloy, uranium-silicide fuel material, and silicon-carbide cladding. The number and variety of these new materials raise questions about possible unintended consequences of their use, including their behavior after disposal in a geologic repository. Based on the information that DOE provided, the Board made the following recommendation in the correspondence to DOE on the meeting (Bahr 2020a).

Recommendation. The Board recommends that DOE give higher priority to evaluating how advanced nuclear fuels and accident tolerant fuels may impact later operations, including SNF packaging, transportation, and disposal in a geologic repository.

In May 2021, the Board held a virtual public meeting on advanced nuclear fuels, including accident tolerant fuels (ANF/ATF) for LWRs, and the impact of these fuels on SNF management and disposal. Speakers from the DOE Offices of Nuclear Fuel Cycle and Supply Chain, and Spent Fuel and Waste Disposition, and their supporting national laboratories, described their R&D in support of ATFs and their perspectives on the impact of ATFs on SNF storage, transport, and disposal. DOE described an updated gap analysis report (SNL 2021) that covered the current LWR reactor design ATF R&D but also gaps in the future advanced fuel forms including sodium fast reactor metallic fuels, TRISO fuels, and more. The Board heard about the timelines for the industry-led irradiation of lead test assemblies (see Figure 7) loaded with new cladding materials and Cr-coated claddings paired with high density nuclear fuels (e.g., nitride fuels, Cr and Al- doped fuels, etc.) at commercial power plants. A representative from the nuclear industry described the characteristics and development path for their metallic fuel, and long-term plans for SNF management. NRC staff speakers provided some regulatory perspectives on the impact of ATF on storage and transportation but did not address disposal. Speakers from other countries, as well as Sweden, Switzerland, and United Kingdom described their country's nuclear fuel cycle and approach to approving and licensing new fuel types and waste management of ANF/ATFs. A panel discussed the key implications for ANF/ATFs on spent nuclear fuel storage, transportation, and disposal.

Following the Board's Spring 2021 meeting on ANF/ATFs, the Board corresponded with DOE and provided its findings, conclusions, and recommendations (Bahr 2021d). The Board's findings and conclusions are summarized as follows:

- Certain other countries developing ATFs, in contrast to the United States, have taken waste management issues (disposability, cost, fuel matrix composition, etc.) into account when approving new fuel designs for use in nuclear reactors.

- Development of ANF/ATF is one of DOE-NE's highest priority R&D programs; however, the current coordination and level of integration on R&D activities among the two involved DOE-NE offices responsible for ANF/ATF development (the Office of Nuclear Fuel Cycle and Supply Chain) and spent ANF/ATF disposition (the Office of Spent Fuel and Waste Disposition) appear to be limited, and only preliminary considerations have been made regarding plans for storage and transportation of the SNF that will result from the use of ANF/ATF.

- The Board commends DOE for funding work on a variety of topics related to ATFs and helping to facilitate collaborative research with international partners, but the Board notes that collaborative international research on SNF management including disposal of ANF/ATF is also warranted.

- Since the 2011 Fukushima Daiichi accident, early stakeholder and general public engagement on advancements in nuclear technology have had an impact on public trust in nuclear energy. Within the DOE-funded ATF program, in contrast to some other countries where early stakeholder and public engagement in ATF development occur in all parts of the fuel cycle, there is currently only limited information available to the public regarding the impacts of the new fuels on the various stages of the fuel cycle.

- Relevant fuel vendor data and results, international lessons learned, and preliminary disposal considerations for ATF and other advanced fuels would enhance the next update of the gap analysis report (SNL 2021) on managing SNF resulting from the use of ANF/ATF.

- ANF/ATF may require different approaches and facilities to perform post-irradiation examination of SNF than DOE uses for zirconium alloy-clad "sibling pins" in DOE's HDRP.

- DOE's investment in ATF and its commitment to support fuel vendors is substantial; thus, DOE may be able to leverage that support to obtain some of the fuel performance data it needs from the vendors to prioritize R&D programs and to optimize the entire fuel cycle, including disposal.

Based on the findings and conclusions, the Board made recommendations that are summarized as follows:

1. *DOE Office of Spent Fuel and Waste Disposition should coordinate and integrate in an ongoing fashion with the DOE Office of Nuclear Fuel Cycle and Supply Chain on preparing for the storage, transportation, and disposal of SNF resulting from deploying ANF/ATF in existing LWRs.*

2. *The next update to the DOE's gap analysis report for SNF management should be expanded in scope beyond storage and transportation to include disposal of SNF resulting from the use of ANF/ATF.*

3. *DOE-NE should work to improve its access to fuel characterization data obtained during DOE-sponsored ANF/ATF development programs.*

4. *DOE should evaluate the approaches used and experiences gained in other countries regarding early consideration of the potential impacts of new ANF/ATF designs on SNF storage, transportation, and disposal. Based on the lessons learned in other countries, DOE should implement mechanisms to provide feedback to ANF/ATF*

development work that accounts for the impact of these new fuels on SNF management and disposal.

5. *DOE should increase the accessibility of ATF information to the general public in the interest of clearly demonstrating openness, facilitating public engagement, factoring in public concerns in planned R&D, and avoiding the perception that there may be unexplored or unresolved issues (including issues affecting SNF management and disposal) related to the introduction of the new fuel designs.*

On April 7, 2022, DOE formally responded to the Board's letter (DOE 2022b). Their response is reproduced in Appendix E of this document.

For fiscal year 2022, Congress directed DOE to conduct R&D for advanced reactor used fuel disposition to address used fuel from TRISO-fueled and metal-fueled advanced reactors. The Board envisions continuing its review of DOE R&D related to advanced nuclear fuels and accident tolerant fuel for LWRs in an integrated waste management system and expanding its review to address DOE's TRISO-fuel and metal-fuel disposition R&D activities.

Long-term dry storage and transportation of high burnup commercial SNF

During this reporting period, the Board continued its focused review of DOE's R&D related to long-term dry storage and transportation of high-burnup[14] commercial SNF (HBF). The Board attended two multi-organizational meetings that involved DOE's HBF R&D, held a public meeting related to DOE's HBF R&D, and issued a report in 2021, titled *Evaluation of the Department of Energy's Research Program to Examine the Performance of High Burnup Spent Nuclear Fuel During Extended Storage and Transportation* (NWTRB 2021c) that documented the Board's focused review effort.

Historically, dry storage of commercial SNF began in the 1980s when utilities needed to remove SNF from on-site storage pools to allow space for additional SNF to be stored from reactor discharges. Ample prior research and studies have provided confidence that no change in the performance of low burnup fuel was expected during dry storage over a period of 20 years and during subsequent transportation (EPRI 2000, 2002). However, two notable circumstances have emerged since this earlier situation. The first is related to the longer-term conditions of the SNF in dry storage systems, and of the dry storage systems themselves, during extended periods of dry storage. Second, there have been advances in reactor fuel technology along with changes in power plant operations, including the introduction of fuel assembly designs by fuel vendors that would allow the fuel to achieve higher burnups. Since the 1990s, an increasing quantity of the SNF loaded to dry storage casks has been HBF. HBF has some different characteristics compared to low burnup fuel (Figure 8).

[14] Nuclear fuel utilized beyond 45 gigawatt days per metric ton of uranium (GWd/MTU) was defined by the NRC as high burnup fuel.

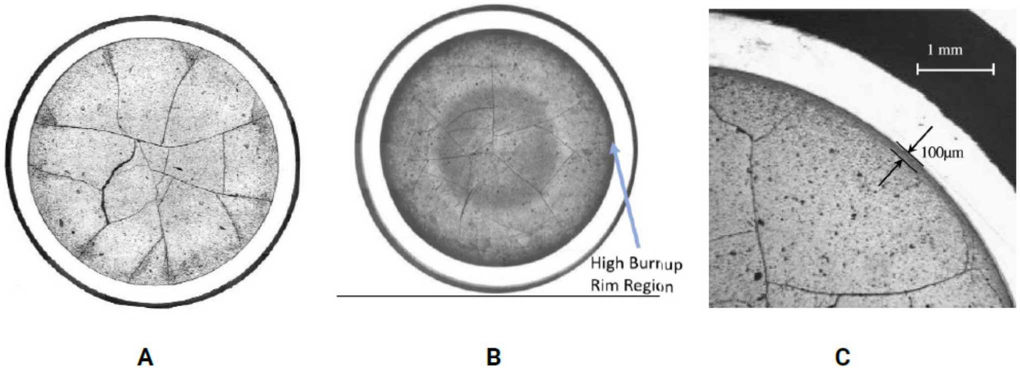

Figure 8. Microscopy images showing cross sections of PWR fuel pellets
Images of (A) a 35 GWd/MTU (average) PWR fuel pellet **(Tsai and Billone 2003)**; (B) a 67 GWd/MTU (average) PWR fuel pellet, indicating the high burnup rim region near the outer circumference of the fuel pellet (Tsai Billone 2003); and (C) a 59 GWd/MTU (average) PWR fuel pellet, indicating the high burnup rim region within 100 µm of the outer circumference of the fuel pellet **(Fors, et al. 2009).**

DOE has been conducting R&D with the aim of obtaining data that can enhance the understanding of the characteristics and performance of HBF during extended storage and transportation conditions, and also during subsequent operations expected to occur at a geologic repository site, which could include repackaging of SNF. Due to the vast range of SNF types subjected to a range of reactor operating conditions and storage conditions, sophisticated fuel performance models are needed to predict the characteristics, condition, and performance of SNF, including HBF, in a variety of storage and transportation conditions. The DOE HBF-related R&D has addressed SNF drying, hydrogen effects in HBF cladding, HBF performance under normal conditions of dry storage through the HDRP and thermal modeling, HBF performance under normal conditions of transportation, and fuel performance modeling. Since 2016, DOE has completed several gap analyses with prioritization ranking to determine what technical information is needed to improve the understanding of the characteristics and performance of SNF, including HBF, during extended storage and transportation.

After drying SNF, including HBF, residual water inside the SNF cask or canister, including water inside breached SNF rods, could cause several technical issues. Residual water can undergo radiolytic decomposition, generating hydrogen and oxygen gases, which can lead to pressure buildup inside the cask or canister and contribute to corrosion of the SNF cladding and internal components of the cask or canister. Hydrogen effects in HBF cladding are important because the presence of hydrogen can lead to embrittlement of the cladding material, increasing the probability of cladding breach under sufficiently high physical shocks or stresses. DOE in collaboration with EPRI is sponsoring the HDRP, where HBF assemblies have been loaded into a dry cask storage system and will be stored for a period of at least ten years. From this effort, the detailed characterization of selected HBF rods (called "sister rods" or "sibling pins") was conducted. A "sister rod" is a fuel rod that had been determined to have very similar characteristics to one that will be stored in the HDRP cask (see Figure 9). The "sister rods" can be sourced from either assemblies having similar operating histories to those assemblies that have been chosen for storage in the HDRP cask or actual fuel assemblies selected for storage. For instance, the properties of the fuel rods that must be similar are fuel cladding type, initial enrichment, the relative reactor core location, and the reactor operating history when the fuel was being irradiated.

During normal conditions of transportation, SNF, including HBF, is subjected to a variety of stresses that can strain the SNF cladding. DOE has cosponsored research on transporting surrogate SNF by truck, ship, and rail to measure the shock and vibrational loads experienced by the SNF and other system components.

Fuel performance needs to be predicted over a large range of SNF types subjected to a range of reactor operating conditions and storage conditions. DOE has been sponsoring several efforts to develop computer models in order to predict the characteristics and performance of SNF, including HBF, in a range of storage and transportation conditions.

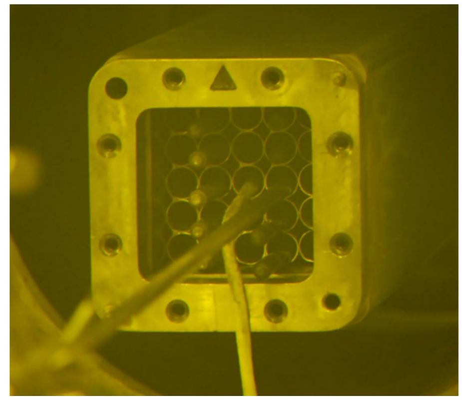

Figure 9. NAC-LWT basket with 10 sister rods in a hot cell facility
The NAC-LWT is a steel-encased, lead-shielded shipping cask and the above image shows a fuel basket for that cask **(Larson 2019).**

In November 2019, the Board held a public meeting to hear from DOE and national laboratory researchers on DOE R&D related to packaging, drying, and dry storage of SNF. The Board heard presentations from DOE and national laboratory researchers on recent results obtained from the HDRP and updates on thermal modeling of SNF storage casks. Following the November public meeting, the Board sent a letter to DOE in January 2020 that included its conclusions and recommendations on the DOE's R&D activities related to the packaging, transportation, and dry storage of commercial SNF (Bahr 2020a). The Board observed that by continuing the HDRP, even in light of the lower cladding temperature reached during drying, and by exploring new solutions to project challenges, DOE and the project team have obtained valuable results. For example, data collected on SNF temperatures have been used to improve SNF cask thermal-hydraulic modeling. The Board's summarized recommendations related to DOE's HBF-related R&D are as follows:

- *The Board recommends that DOE-NE pursue an increased understanding of the effect of moisture on SNF in dry storage and continue its efforts to identify alternative methods of obtaining moisture measurements from inside SNF dry cask storage systems used by the nuclear industry.*

- *The Board recommends that greater emphasis be placed on validating computer models before applying them to particular dry cask storage systems.*

- *As DOE continues to develop and use computer models to predict SNF dry cask storage system parameters, the Board recommends that DOE ensure all assumptions and uncertainties be properly identified and accounted for, computer models be validated against data from real-world systems, fuel performance models be* *integrated within the multiphysics models, and enhanced coordination be achieved between model developers and experimentalists.*

Based on a critical evaluation of information obtained from Board public meetings, through site visits to DOE national laboratories during the period of 2016 to 2018, through attendance of conferences and meetings in 2019 to gain additional updates, and through the preparation of correspondence to DOE related to the Board's review, the Board released a report in July 2021 titled *Evaluation of the Department of Energy's Research Program to Examine the Performance of Commercial High Burnup Spent Nuclear Fuel During Extended Storage and Transportation* (NWTRB 2021c). Overall, the Board commended DOE for its progress and efforts on this important topic. The Board agreed with DOE-identified technical information needs and priorities with one exception; the Board felt that the DOE-sponsored fuel performance modeling, which integrates thermal, mechanical, and materials modeling aspects, should be included among the priority research efforts. The focus of the report was the Board's evaluation of the appropriateness of the DOE projects to address the technical information needs.

The following summarizes the Board's summary findings and recommendations documented in that report:

1. *General Recommendations:*

    a. *Summary Finding: The results of DOE-sponsored research on HBF have been reported by a variety of organizations and in a variety of formats but there is no compendium that contains the results of all DOE research related to extended storage and transportation of HBF.*

       Recommendation: Following the completion of HDRP sister rod examinations and drop testing of surrogate SNF assemblies, DOE should prepare a document that compiles the results of DOE research on extended storage and transportation of HBF, with the purpose of providing the technical bases for conclusions reached regarding HBF performance during extended storage and transportation.

    b. *Summary Finding: Important research relevant to extended storage and transportation of HBF is being sponsored by organizations outside of DOE, both in the U.S. and in other countries.*

       Recommendation: DOE should continue to review the results of the Electric Power Research Institute's Extended Storage Collaboration Program and research in other countries to determine if the results of ongoing HBF studies either change the priorities for DOE's planned research or add technical information needs requiring new research.

    c. *Summary Finding: 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.*

Recommendation: DOE should 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.

2. *Spent Nuclear Fuel Drying*

    a. *Summary Finding: Chemisorbed water remaining inside SNF dry cask storage systems may cause corrosion of SNF cladding of the internal components of the system and significant uncertainty remains regarding the quantities of hydrogen and oxygen gases that can be generated due to radiolysis of the remaining water.*

    Recommendation: DOE should evaluate the extent to which chemisorbed water remains after the drying process is completed and whether this water could affect the ability of SNF cask or canister systems and their contents to continue to meet storage and transportation requirements.

    b. *Summary Finding: Few gas samples have been obtained from inside dry cask storage systems containing commercial SNF.*

    Recommendation: DOE should further explore the possibility of monitoring the moisture content and gas composition of dry cask storage systems loaded by nuclear utilities with HBF for an extended period and improve and validate gas sampling methods before the next samples are obtained.

3. *Hydrogen Effects in High Burnup Fuel Cladding*

    a. *Summary Finding: Data obtained from testing of unirradiated cladding does not replicate data obtained from testing of irradiated cladding.*

    Recommendation: As the need for new testing of HBF cladding is identified, DOE's research efforts should make use of irradiated samples rather than unirradiated samples to avoid the large uncertainties and difficulties in interpreting test results that arise from using unirradiated samples.

    b. *Summary Finding: There are a variety of test methods for examining hydride reorientation in HBF cladding and that the results of the testing are reported with significant format variations that make comparison of results difficult.*

    Recommendation: DOE should define a standard set of test parameters (e.g., fuel burnup, test temperatures, rod internal pressures) and results, where possible, that must be recorded for all DOE-funded research related to hydride reorientation.

c. Summary Finding: Data on the characteristics of HBF (e.g., HBF rod internal pressure) and results of research on hydride formation and hydride reorientation in zirconium-based alloys are reported by a variety of organizations and saved in a variety of information archives.

Recommendation: DOE should gather into one database all relevant information that is publicly available on hydride-related testing of zirconium-based alloys to provide the basis for (1) evaluating the effects of variables that influence hydride reorientation; (2) supporting the ongoing development of new standards for inducing hydride reorientation in test samples and quantifying hydride reorientation and its effects; (3) explaining the differences in hydride reorientation and its effects among cladding types; and (4) developing computer models to predict hydride formation and reorientation in all zirconium-based cladding types, including those that have not been tested.

4. *High Burnup Fuel Performance under Normal Conditions of Dry Storage*

High Burnup Dry Storage Research Project

a. Summary Finding: DOE has not clearly indicated how the data obtained from the HDRP and related sister rod testing will be used to meet the DOE-identified technical information needs or support modeling of HBF performance during dry storage and transportation.

Recommendation: DOE's test plan for the HDRP sister rods should (a) link each proposed test to one or more of the technical information needs identified in the most recent DOE report on technical information needs and (b) explain how the results of each proposed test will be used to meet the technical information needs or support modeling of HBF performance during dry storage.

b. Summary Finding: Obtaining and characterizing the sister rods has been a worthwhile but expensive undertaking and these rods constitute a valuable asset for future research and development.

Recommendation: DOE should preserve selected sister rods (or rod segments and components) for future use in follow-up studies to the HDRP, if needed, or in support of other programs.

Thermal Modeling

c. Summary Finding: DOE-sponsored thermal models will be valuable tools for calculating realistic SNF cladding temperatures during drying and storage in dry cask storage systems if realistic input data are used and if the predicted temperature uncertainty due to all sources of uncertainty can be quantified and defensibly bounded.

Recommendation: DOE should continue its activities to ensure its thermal models are rigorously validated, including industry-standard uncertainty quantification, for use on SNF storage or transport systems.

5. *High Burnup Fuel Performance under Normal Conditions of Transport*

   a. *Summary Finding: DOE structural model development and validation efforts for a structural model that can be used to predict the structural response of SNF, SNF cask or canister systems, and SNF transport vehicles under normal conditions of transport include a number of uncertainties stemming from the use of dummy or surrogate fuel assemblies and unirradiated fuel material properties.*

      Recommendation: DOE should quantify the uncertainties introduced by the use of unirradiated assembly components and surrogate components, such as concrete mock-SNF assemblies, in experiments being used to benchmark the DOE structural model. DOE should exercise the structural model to evaluate HBF cladding strains for different cask and canister types, fuel types, and degree of pellet-cladding bonding.

6. *Fuel Performance Modeling*

   a. *Summary Finding: Limited testing of irradiated HBF provides a potentially insufficient database of mechanical properties and other HBF characteristics required to develop accurate fuel performance models.*

      Recommendation: DOE should continue to develop fuel performance models (e.g., BISON) that are validated utilizing experimental data with performance model developers clearly identifying the data they need to develop and validate, and experimentalists clearly explaining the capabilities and limitations of their experimental equipment and facilities, to setup and collection of data needed to improve the models and achieve a better understanding of HBF characteristics and performance.

As part of the Board's review of DOE's HBF efforts, Board staff also attended multi-organizational meetings that involved DOE. Those activities in which the Board participated include the following:

- NRC's Advisory Committee on Reactor Safeguards, Subcommittee on Metallurgy and Reactor Fuels 2019 Meeting in Rockville, Maryland on the NRC's staff report on NUREG-2224, *Dry Storage and Transportation of High Burnup Spent Nuclear Fuel*.

- ASTM International's 2019 Winter Meeting C26.13 on Spent Fuel and High-Level Waste in Houston, Texas that included a workshop on drying of SNF.

Board Review: Integrated Waste Management and Disposal System

Three Board activities addressed DOE's efforts to develop and implement an integrated waste management and disposal system. The Board members synthesized their nearly decade-long experience reviewing the DOE's activities related to the management and disposal of SNF and HLW. The Board documented its synthesis in the *Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward* report (NWTRB 2021b). In 2021, DOE began an effort to site Federal facilities for the temporary, consolidated storage of commercial SNF using a consent-based approach as part of an overall strategy for an integrated waste management system. In a November 2021 Board public meeting, the Board reviewed DOE's description of its consent-based siting process. As described in the advanced nuclear fuels and accident tolerant fuels section, in this reporting period, the Board began reviewing DOE's efforts to incorporate these fuels into an integrated waste management system.

Six recommendations on the nation's nuclear waste management program

The DOE nuclear waste management program encompasses the management and disposal of commercial and DOE SNF and HLW. The goal of the Board members' synthesis was to communicate six high-level recommendations to the Secretary of Energy and senior DOE managers (Bahr 2021e) and to inform Congress. Board members believed that the recommendations, if adopted by DOE, would support the creation of a robust, safe, and effective nuclear waste management capability for the nation, including laying the groundwork for a successful geologic repository. The recommendations and associated action items emphasized the knowledge gained by the Board members over the last decade reviewing numerous DOE technical programs. They were also informed by the study of and a number of visits to programs and facilities in other countries. The recommendations focused on addressing overarching aspects of how the nuclear waste management program is performed and communicated (Figure 10), rather than on individual projects. The Board members strongly believed the progress the nation was making in developing its waste management capability, as well as public and stakeholder engagement and trust, could be improved with regard to both timeliness and effectiveness by adopting these recommendations as core principles of the nuclear waste management program.

The Board identified several significant challenges that need to be addressed to ensure the development of a successful nuclear waste management program in the United States. These challenges include the current lack of a plan for developing a repository and concomitant funding, the complex array of stakeholders responsible for implementing different stages of the nuclear fuel cycle, and the unprecedentedly long timescale for which a repository must be designed to protect the health and safety of the public and the environment.

Figure 10. Six overarching recommendations for DOE's nuclear waste management program in support of developing a successful geologic repository program in the United States.

The Board put forth the recommendations (Figure 10) to facilitate the timely and effective implementation of a successful nuclear waste management program in support of developing a geologic repository. The first two recommendations dealt with the design and effective operation of an integrated nuclear waste management program under DOE. The next two recommendations provided guidance on creating a more effective and rigorous science and engineering program. The final two recommendations dealt with building public trust and international engagement to foster success in the program.

The Board associated each recommendation with a set of action items. The Board recognized that some of the action items identified require important contributions from entities that are beyond DOE's control and require both authorization and appropriations by Congress. Nonetheless, the Board members offered some specific actions intended to help DOE turn the recommendations into core principles for developing the nuclear waste management program, including the successful development of a geologic repository.

The Board viewed integration as one of the most important factors that contribute to the development of a robust, effective, and safe waste management capability and recommended that DOE ensure an integrated organizational approach (Figure 10). Regarding better program integration across the DOE program, the Board recommended the following actions to DOE management:

- Foster broader sharing of information among DOE offices, national laboratories, and contractors (e.g., university researchers supported by Nuclear Energy University Program grants).

- Further enhance integration of R&D programs executed by DOE-EM, DOE-NE, and other DOE offices to optimize collaboration, minimize duplication, and maximize the effectiveness of the effort.

The Board recommended the following specific actions for DOE management to improve integration with the nuclear industry:

- Find ways to work with utilities, cask vendors, fuel manufacturers, and others in the nuclear industry in an ongoing manner to more effectively develop and implement the nuclear waste management program.

- Find additional innovative ways of information sharing through DOE-led conferences or workshops that might encourage utilities, cask and fuel vendors, SNF title owners, and transporters to improve communications and engagement.

The Board recommended DOE anticipate required infrastructure and personnel needs (Figure 10). The Board noted that solving a problem as complex as nuclear waste management depends upon having an adequate physical infrastructure that includes facilities, equipment, and information technology, as well as the requisite human resources to provide technical, management, and public outreach capacity. The Board observed that the multi-decades it takes to design and develop a repository requires a long-term plan for maintaining such infrastructure and educating personnel into the future. Developing the needed infrastructure for the U.S. nuclear waste management program has required decades and will continue. The Board noted that the needs in terms of physical and human capital must similarly be explicitly addressed for the long term, and continually re-evaluated. Regarding infrastructure and personnel needs, the Board recommended the following actions to DOE management:

- Develop and communicate an integrated plan regarding physical infrastructure, information technology, and personnel needs over the next decade.

- Formulate and implement research programs and other supporting infrastructure consistently to anticipate the effects of aging of facilities.

- Develop and maintain the capability to utilize DOE's leading-edge, high-performance computing resources for the analysis and simulation of processes and systems related to the back-end of the fuel cycle.

- Develop infrastructure for and implement data management systems that can meet the needs for long-term, open, and efficient retrieval of information from current and, to the extent possible, previous relevant R&D programs.

- Address the challenges of an aging workforce by expanding mentorship of a new generation of staff through technical training programs; more effectively targeting undergraduate scholarships, graduate fellowships, and post-doctoral fellowships in areas of need; establishing internships at underground research laboratories (URLs); and promoting careers in nuclear waste management.

The Board recommended that DOE expand its research paradigm to embrace hypothesis testing (Figure 10). Based upon its reviews of research approaches in other countries and observations of the DOE program, the Board recommended the following actions for DOE to expand its research strategy:

- Anticipate surprises or unexpected results that may arise during the R&D program and assure all research programs include ample provisions to accommodate possible changes in direction and focus.

- Test alternative hypotheses using careful experimental design over multiple scales from laboratory to full-scale in-situ tests in a URL.

- Continue to make new measurements to build a database that tests the abilities of existing models to capture important processes and evaluate the possible need for new conceptual models to improve estimates of system properties and thus prediction accuracy.

- Use results of repeated testing of existing and evolving hypotheses to enhance the usefulness of models in performance assessment.

- Establish one or more dedicated domestic URLs that will provide the necessary opportunities for researchers and students to conduct in-situ investigations into subsurface processes at scale, test models, and further international collaboration.

The Board recommended that DOE apply an iterative, adaptive approach in developing and managing the nuclear waste management program (Figure 10). Regarding an iterative and adaptive approach, the Board recommended that DOE undertake the following actions:

- Iterate between testing individual components of the nuclear waste management program and testing integrated models of the entire waste management system, always being ready to adapt each approach based on what is learned from such testing.

- Be open and structured to adapt to surprises during all aspects of the nuclear waste management program and always be willing to reevaluate and rethink previous decisions.

- Establish mechanisms as part of ongoing evaluations to facilitate and incentivize solicitation of input and feedback from all affected stakeholders, including independent scientists and engineers outside of the nuclear waste management program; local, state, and tribal governments; nuclear utilities; and the interested public.

The Board recommended that DOE expand engagement with the international community to benefit from lessons learned (Figure 10). The international community has vast experience in program integration, siting, iterative adaptive staging, research strategy, and demonstrating potential repository operations. To better integrate lessons learned from the international community, the Board recommended that DOE undertake the following actions:

- Build on current initiatives and continue to expand engagement with the international community.
- Sustain active engagement in international programs given the tangible benefits derived from close involvement.
- Continue and expand participation in collaborative international URL activities. If DOE develops one or more URLs, it should encourage international participation.
- Emphasize engagement with countries that have advanced to the demonstration and/or construction authorization stages of repository development to enhance knowledge of these stages.

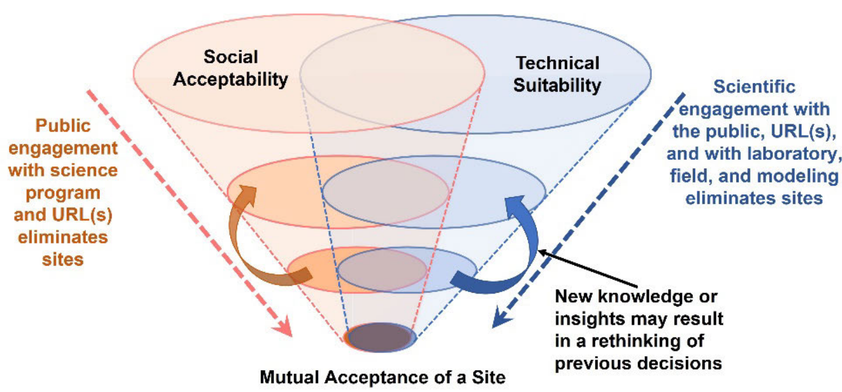

Figure 11. Development of a convergent pathway for siting a geologic repository. Based on NWTRB (2015).

The Board recommended that DOE strongly embrace openness, transparency, and engagement in its approach (Figure 10). The international community also has vast experience on the importance of transparency, public dialogue, and engagement of stakeholders in moving programs forward. Experience in the United States and in other countries has demonstrated that geologic disposal of waste is as much a social challenge as a technical challenge (NWTRB 2015). The technical and social challenges may be addressed simultaneously or sequentially to enable licensing and construction of a repository (NWTRB 2015) and may require some review and design modification as surprises emerge. Figure 11, from the Board's *Six Overarching Recommendations Report* (NWTRB 2021b), illustrates these ideas by emphasizing the importance of both the technical and social "filters." If a siting program for a geologic repository is to move ahead, the site must meet the criteria specified by the two filters (i.e., the overlapping zone in Figure 11). The figure also illustrates that site selection is likely to be iterative and adaptive.

To address embracing openness, transparency, and engagement, the Board recommended that DOE implement the following specific actions in the nuclear waste management program, acknowledging that some of these actions only apply if the site selection process is reinitiated:

- Inform and engage the public and other affected stakeholders early in the planning and review of all aspects of the nuclear waste management program.

- Be transparent in decision-making and provide support for meaningful stakeholder participation.

- Take account of lessons learned in other countries about listening to and informing the public, in order to improve communications, better understand community perspectives, and avoid unnecessary delays of the program.

- Though not a license requirement for any new site selected for a repository, DOE should develop and make available a clear characterization of the facility early in the process that describes the waste management concept and its multiple barriers and other attributes that contribute to safety. DOE must also clearly acknowledge and communicate its commitment that the safety concept will be revised to update it as new information and input are received.

- Develop site-suitability criteria prior to the start of site selection so as to minimize any ambiguity and latitude in their interpretation, thus helping to ensure the objectivity of the process and public confidence in its outcome. If, at any point during the siting process, the criteria need to be changed, a transparent and meaningfully participatory process to do so needs to be followed.

- If the United States develops one or more URLs, these laboratories, in addition to their research function, should be utilized for outreach and public engagement, to provide access to the subsurface and to build public confidence and trust in the science and engineering behind the safety concept as well as in the operational capabilities for remote handling of waste underground.

Because of the over-arching nature of the report's recommendations, the Board briefed staff from two Congressional committees, four Congressional subcommittees, a Representative's staff member, the Congressional Research Service, DOE, NRC, and the Nuclear Energy Institute on the report's recommendations. The Board attempted to brief the Secretary of Energy (Bahr 2021e) but ended up briefing only senior managers in DOE-EM and two acting Assistant Secretaries for Nuclear Energy.

The Board met with Dr. Kathryn Huff,[15] Acting Assistant Secretary for Nuclear Energy, to explain the report and the Board's role in reviewing DOE activities related to the management of SNF and HLW (Bahr 2021f). The Board noted (Bahr 2021f) that the legislative history of the Nuclear Waste Policy Amendments Act of 1987 indicates that, in response to recommendations from the Board, "it is assumed that the Department will heed those views or clearly state its reasons for disagreeing." The Board noted that it was pleased that Dr. Huff indicated her intent to follow this guidance and respond to letters and reports that contain Board recommendations, which has not always been the case (Figure 1).

On June 8, 2022, DOE formally responded to the Board's report (DOE 2022c). Their response is reproduced in Appendix C of this document.

Consent-based siting of federal interim storage facilities

At the Board's November 2021 meeting, DOE described its current efforts on a consent-based approach to siting a federal interim storage facility for SNF, and also summarized the work DOE-NE has been conducting to prepare for an integrated waste management system. DOE stated that it was committed to a consent-based approach to siting a federal interim storage facility that fully embraces principles of openness, transparency, public engagement, equity, environmental justice, and broad participation including that of historically underrepresented groups and communities. DOE indicated that it was incorporating expertise in the social sciences and resources from the national laboratory system to help move the program forward.

The Board reviewed the information presented at the meeting in correspondence to DOE (Bahr 2022). The Board commended DOE for starting a new effort on consent-based siting of an interim storage facility and for recognizing the crucial importance of effective risk communication, full public engagement, and inclusiveness in the siting process. The Board was pleased DOE noted that its path forward for a consent-based siting process was well-aligned with the recommendations in the Board's *Six Overarching Recommendations Report* (NWTRB 2021b) . The Board noted that including knowledge and expertise on risk communication, public engagement, and inclusiveness from the social-behavioral sciences and the public health sciences would provide DOE with a significantly broader and stronger knowledge and experience base from which to draw insights and expertise.

The Board noted that as DOE further developed its strategy for communication, engagement, and inclusiveness, it would be beneficial to systematically review key lessons that have been learned from siting processes in other nations. For example, the Board noted in its *Six Overarching Recommendations Report* (NWTRB 2021b) that DOE's 2016 proposal to conduct a deep borehole experiment in Rugby, North Dakota, encountered difficulties partly due to a lack of sufficient transparency and early engagement with the public. The Board suggested that as a follow-on to that project, DOE could do a detailed analysis of how the project was developed and the strategies for public engagement identified and produce a candid "lessons learned" document that might be used to inform future consent-based siting and stakeholder engagement activities. The Board observed that strategies for effective

[15] Dr. Huff was confirmed as DOE's Assistant Secretary for Nuclear Energy on May 5, 2022.

communication, public engagement, and inclusiveness that DOE applies or develops in its current effort could be applicable to a future siting of a geologic repository for SNF and HLW. In its correspondence, the Board noted that it looked forward to hearing more in the future about DOE's consent-based siting activities. Given the future substantial DOE effort that was described in the meeting, the Board envisions continuing a focused review of DOE's consent-based siting of federal interim storage facilities.

Board Interactions with Congress

Between 2019 and 2021, the Board provided no testimony to Congress. The Board had no correspondence with Congress aside from the distribution of Board reports to members of Congress and Congressional staff. The Board continued to brief staff of members of Congress and committee staff on Board reports. During this reporting period, the Board continued briefing Congressional Research Service staff on each new Board report submitted to Congress and the Secretary of Energy and began briefing them on key Board correspondence to DOE.

International Activities

Between 2019 and 2021, the Board interacted with radioactive waste management programs abroad. The Board traveled to Germany and met with the Advisory Bodies to Government group and toured the Morsleben radioactive waste repository. Separately, the Board participated in virtual meetings with the Nuclear Energy Agency. The Board met virtually with the Swedish National Council, a sister agency, during the Council's review of the Swedish Nuclear Fuel and Waste Management Company's (SKB's) triennial disposal RD&D plan. The Council is an independent agency and reports the results of its review of SKB's plan to the Swedish government. The Board undertook this interaction to gain insights on how national approaches to defining and carrying out a multi-decadal disposal RD&D program evolve through time. During this period, the Board also hosted representatives of some international programs when they visited the United States and included them in Board meetings, when appropriate. In its virtual meetings, the Board had speakers from the United Kingdom, France, Sweden, and Switzerland that represented industry, national laboratories, implementers, and an umbrella organization that is focused on implementing geologic disposal. These activities broadened the Board's basis for reviewing DOE's R&D activities and highlighted issues that affect the success of national programs for the management and disposal of SNF and HLW.

Board participation in the activities of the Advisory Bodies to Government

In 2004, the Nuclear Energy Agency, a unit of the Organization for Economic Cooperation and Development, established an informal group called the Advisory Bodies to Government. Since then, the number of countries involved in these activities has included seven countries: France, Germany, Japan, Sweden, Switzerland, the United Kingdom, and the United States. The purpose of the group was to bring together the chairs of entities, such as the Board, which provide advice concerning nuclear waste management to policymaking levels of the national government. The group has met roughly every 18 months on a rotating host-country basis. These interactions broadly included meetings with counterparts from Advisory Bodies to Government which tended to discuss common issues and a related visit to a host country's radioactive waste management or disposal-related facility. These gatherings have provided the Board opportunities to obtain direct information on developments in each country's radioactive waste management program. The Board participated in the group's meeting, which focused on extended storage of SNF and HLW, in Braunschweig, Germany in June 2019.

Meeting participants visited the Morsleben repository for low- and intermediate-level radioactive waste. The repository is in a former potash and salt mine (Figure 12). The repository developer emplaced waste without considering facility closure. Decommissioning of the mine and disposal areas will be difficult. The German federal company for radioactive waste disposal (BGE) is testing disposal tunnel and mine shaft sealing concepts (Figure 13). The experience at Morsleben points to the importance of considering all phases of a repository (construction, operation, and closure) at the beginning of a repository project.

Figure 12. Waste material in the Morsleben low- and intermediate-level radioactive waste repository.
Salt bedding is visible in the cavern's ceiling. Unlike the Waste Isolation Pilot Plant transuranic waste repository in the US, bedding of the salt at Morsleben is mainly near vertical, which leads to much greater stability of tunnels and caverns in the mine. Tectonic deformation (folding) has rotated the original horizontal salt layers towards a vertical orientation.

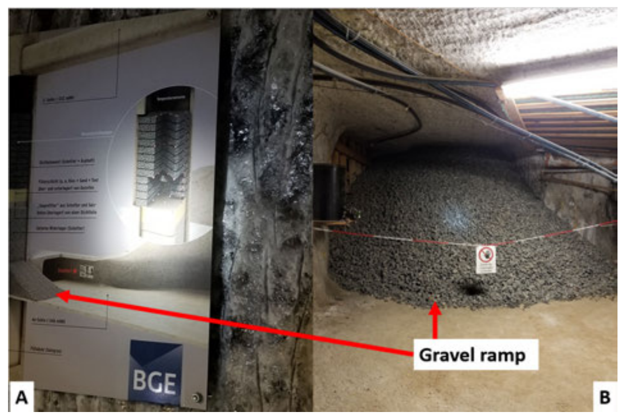

Figure 13. Shaft sealing experiment.
A). Depiction of shafting sealing design with repeating layers of gravel and asphalt (gray and black layers in the circle at the right of the display). The gravel layer at the bottom of the shaft flows into mining opening. B). Bottommost gravel layer in shaft sealing experiment forms a ramp in the mine tunnel.

Board participation in the activities of the Nuclear Energy Agency

During the reporting period, a Board staff member was nominated and appointed as an official US representative to the Integration Group for the Safety Case. The group operates under the auspices of the Nuclear Energy Agency and consists of 48 members representing 16 countries and the European Commission. Members represent implementers (including DOE), regulators, technical support organizations such as a national laboratory, and advisory organizations such as the Board. Participation in the group allows the Board to gain insights on developing safety cases for geologic disposal that have been crucial to the success of national waste disposal programs outside of the United States.

The Board staff representative attended two virtual meetings. The International Workshop on "Joint Utilization of Underground Research Laboratories (URL) for Research and Development (R&D) Project" in September 2021 provided updates on national waste disposal programs and international URL efforts. Participants described an international roundtable on final disposal of HLW and SNF launched by the Ministry of Economy, Trade, and Industry of Japan, DOE, and the Nuclear Energy Agency. The roundtable participants concluded that international cooperation is valuable, and transparency and early involvement with local communities in deep geological repository programs appear to be crucial for success. The roundtable participants also concluded that international roundtables are effective and international dialogues on policy need to remain flexible and should ensure sharing of resources. The 23rd meeting of Integration Group for the Safety Case provided updates on the group's efforts and other Nuclear Energy Agency activities. A key point raised in the meeting was that as national programs advance to siting and implementation (e.g., Sweden, Switzerland, and France), domestic priorities constrain their ability to support international collaborations, such as those in URLs.

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ACRONYMS

ANF	advanced nuclear fuel
ANF/ATF	advanced nuclear fuels, including accident tolerant fuels
ASLB	Atomic Safety and Licensing Board
ASNF	aluminum-clad spent nuclear fuel
ATF	accident tolerant fuel
Board	U.S. Nuclear Waste Technical Review Board
BRC	Blue Ribbon Commission on America's Nuclear Future
CDP	High Burnup Dry Storage Cask Research and Development Project
DBFT	Deep Borehole Field Test
DPC	dual-purpose canisters
DOE	U.S. Department of Energy
DOE-EM	U.S. Department of Energy, Office of Environmental Management
DOE-NE	U.S. Department of Energy, Office of Nuclear Energy
EBS	engineered barrier system
EPRI	Electric Power Research Institute
EPRI ESCP	Electric Power Research Institute Extended Storage Collaboration Program
GAIN	Gateway for Accelerated Innovation in Nuclear
GDSA	Geologic Disposal Safety Assessment
GWd/MTU	gigawatt-day per metric ton of uranium
HALEU	high-assay low-enriched uranium
HBF	high burnup fuel
HDRP	High Burnup Dry Storage Cask Research and Development Project
HLW	high-level radioactive waste
HotBENT	High Temperature Effects on Bentonite Buffers

IGD-TP	Implementing Geological Disposal of radioactive waste Technology Platform
INL	Idaho National Laboratory
LWR	light water reactor
MTHM	metric tons of heavy metal
NEA	Nuclear Energy Agency
NRC	U.S. Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
NWPAA	Nuclear Waste Policy Amendments Act
PNNL	Pacific Northwest National Laboratory
PWR	pressurized water reactor
R&D	research and development
RD&D	research, development, and demonstration
SFWD	Spent Fuel and Waste Disposition
SKB	Swedish Nuclear Fuel and Waste Management Company
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
SRS	Savannah River Site
TRISO	tri-structural isotropic
TD	technology development
URL	underground research laboratory

GLOSSARY

Aging management program A program that evaluates the changes in a component over its expected usage period to determine if these changes will affect the component's ability to perform its function.

Aluminum-based SNF The term "aluminum-based SNF" is used by the U.S. Department of Energy for aluminum-clad, uranium oxide spent nuclear fuel; aluminum-clad, uranium-aluminum alloy spent nuclear fuel; and spent nuclear fuel without cladding stored in aluminum cans. See also **fuel cladding**.

Backfill The material used to refill excavated parts of a repository during and after waste emplacement.

Bentonite A soft, light-colored clay formed by chemical alteration of volcanic ash. Bentonite has been proposed for backfill and buffer material in many repositories.

Canister (in a dry storage system for spent nuclear fuel) A metal cylinder that is sealed at both ends and may be used to perform the function of confinement in a dry cask storage system for spent nuclear fuel. Typically, a separate overpack or horizontal storage module performs the radiological shielding and physical protection function.

Cask A heavily shielded container used for the dry storage or shipment (or both) of radioactive materials such as spent nuclear fuel or other high-level radioactive waste. Casks are often made from lead, concrete, or steel.

Chemisorbed water Water that is bound to species by forces whose energy levels approximate those of a chemical bond.

Clays Minerals that are essentially hydrated aluminum silicates or occasionally hydrated magnesium silicates, with sodium, calcium, potassium and magnesium cations. Also denotes a natural material with plastic properties which is essentially a composition of fine to very fine clay particles. Clays differ greatly mineralogically and chemically and consequently in their physical properties. Because of their large specific surface areas, most of them have good sorption characteristics.

Clay/shale (host rock) Denotes a sedimentary deposit of clay that has not hardened into a sedimentary rock or shale deposit. Both clay and shale have relatively low permeability and relatively high capacity for sorption of positively charged chemical species.

Consent-based siting An approach to siting facilities that focuses on the needs and concerns of people and communities.

Containment Methods or physical structures designed to prevent the dispersion of radioactive substances. Although approximately synonymous with confinement, containment is normally used to refer to methods or structures that prevent radioactive substances being dispersed in the environment if confinement fails.

Crystalline (host rock) A generic term for igneous rocks and metamorphic rocks (e.g., granite, gneiss, and basalt).

Deep borehole disposal Waste disposal in a cylindrical excavation drilled into deep, basement rock.

Deep-mined, geologic disposal A facility for disposal of radioactive waste located underground (usually several hundred meters or more below the surface) in a geological formation intended to provide long-term isolation of radionuclides for the biosphere.

Engineered barrier The designed or engineered components of a repository, including waste packages and other features.

Fission gas Gaseous fission products that are produced from the splitting of fissile radionuclides.

Fuel assembly A structured group of fuel rods (long, slender, metal tubes containing pellets of fissionable material, which provide fuel for nuclear reactors). Depending on the design, each reactor vessel may have dozens of fuel assemblies (also known fuel bundles), each of which may contain 200 or more fuel rods.

Fuel cladding Also referred to as “cladding” generally. Cladding is the thin-walled metal tube that forms the outer jacket of a nuclear fuel rod. It prevents corrosion of the fuel by the coolant and provides containment against the release of fission products into the coolant. Aluminum, stainless steel, and zirconium alloys are common cladding materials.

Fuel rod A long, slender, metal tube containing pellets of fissionable material, which provide fuel for nuclear reactors. Fuel rods are assembled into bundles that are called fuel assemblies, which are loaded individually into the reactor core.

Fuel pellet A thimble-sized ceramic cylinder (approximately 3/8-inch in diameter and 5/8-inch in length), consisting of uranium (typically uranium oxide, UO_2), which has been enriched to increase the concentration of uranium-235 (U-235) to fuel a nuclear reactor. Modern reactor cores in pressurized-water reactors and boiling-water reactors may contain up to 10 million pellets, stacked in the fuel rods that form fuel assemblies. See also **fuel rod** and **fuel assembly**.

High burnup spent nuclear fuel Reactor fuel with burnups exceeding 45 gigawatt-days per metric ton. Burnup is a measure of reactor fuel consumption expressed as the percentage of fuel atoms that have undergone fission, or the amount of energy produced per unit weight of fuel, measured in gigawatt-days per metric ton of uranium in the fuel (GWd/MTU).

Hydrogeologic environment Subsurface waters, their movement, and effects in basement rock.

Independent spent fuel storage installation A complex designed and constructed for the interim storage of spent nuclear fuel; solid, reactor-related, greater than Class C waste; and other associated radioactive materials. A spent fuel storage facility may be considered independent, even if it is located on the site of another NRC-licensed facility.

Multi-canister overpack A stainless steel container for interim storage of spent nuclear fuel. The multi-canister overpack is a cylindrical tube with a plate welded at the bottom and a shield plug at the top; five or six baskets loaded with intact fuel rods or fuel pieces are stacked inside the multi-canister overpack.

Multiphysics Simulations that involve multiple physical models or multiple simultaneous physical phenomena.

Shale A fine-grained sedimentary rock that forms from the compaction of silt and clay-size mineral particles that we commonly call "mud."

Sodium-bonded SNF After commercial SNF, sodium-bonded SNF comprises the next largest SNF inventory at Idaho National Laboratory. This type of SNF originated from reactors that used molten sodium as a coolant and some of the fuel used in the reactor was fabricated with sodium between the fuel and the cladding.

Vitrification Mixing processed radioactive waste with glass fragments in a furnace to stabilize the waste into a form that will neither react nor degrade for extended periods of time.

Volcanic tuff A general term for volcanic rocks that formed from fragmented magma and fragments of other rocks, and that erupted from a volcanic vent, flowed away from the vent as a suspension of solids and hot gases, or fell from the eruption cloud, and consolidated at the location of deposition. Tuff is the most abundant type of rock at the proposed Yucca Mountain repository site.

Waste package The waste form and any containers, shielding, packing and other absorbent materials immediately surrounding an individual waste container.

Zircaloy The trademark name for a family of alloys of zirconium and small amounts of tin, iron, chromium, and nickel.

APPENDICES

A. Board Members During the Reporting Period

B. Board Strategic Plan 2022–2026

C. Board Publications

D. Board Meetings: January 1, 2019–December 31, 2021

E. Correspondence with the U.S. Department of Energy: January 1, 2019–December 31, 2021

Appendix A
Board Members During the Reporting Period

JEAN M. BAHR, PH.D., CHAIR

Dr. Jean M. Bahr was appointed to the U. S. Nuclear Waste Technical Review Board by President Barack Obama on September 25, 2012 and was designated by the President to serve as Chairman of the Board on January 5, 2017.

Dr. Bahr is an Emeritus Professor at the University of Wisconsin-Madison. Prior to retirement, she was on the faculty of the Department of Geoscience, a member of the UW-Madison Geological Engineering Program Faculty, and a faculty affiliate of the Nelson Institute for Environmental Studies. She served as chair of Geoscience (formerly Geology and Geophysics) from 2005 to 2008 and of the Nelson Institute's Water Resources Management Graduate Program from 1995 to 1999. Dr. Bahr's research explores physical, geochemical, and biogeochemical controls on the movement of water and associated solutes in subsurface geologic systems.

Dr. Bahr has served on many advisory committees through the National Research Council of the National Academies and was a member of the Board on Radioactive Waste Management from 1992 to 1997. She chaired the Committee on Restoration of the Greater Everglades Ecosystem, and from 2004 to 2006 she was a member of the Committee on Research Priorities in Earth Science and Public Health. In addition to her service for the National Academies, Dr. Bahr has been a member of proposal review panels for the National Science Foundation, the U.S. Environmental Protection Agency, the U.S. Department of Energy, and the international Ocean Drilling Program. She served terms on the editorial boards of the journals *Water Resources Research*, *Ground Water*, and *Hydrogeology.*

Dr. Bahr was elected to Sigma Xi in 1984, named a fellow of the Geological Society of America (GSA) in 1996, and received the GSA Hydrogeology Division's Distinguished Service Award in 2006. She was the 2003 GSA Birdsall-Dreiss Distinguished Lecturer and was elected President of GSA for 2009–2010. She was named a lifetime National Associate of the National Academies in 2002 and was the 2012 recipient of the Association for Women Geoscientists Outstanding Educator Award. She received the American Geophysical Union's Ambassador Award in 2017. She is the 2022 recipient of the American Geosciences Institute Ian Campbell medal for Superlative Service to the Geosciences.

Dr. Bahr received a B.A. in geology and geophysics from Yale University in 1976, and an M.S. and a Ph.D. in 1985 and 1987, respectively, in applied earth sciences (hydrogeology) from Stanford University.

Dr. Bahr resides in Millbrae, California and Madison, Wisconsin.

STEVEN M. BECKER, PH.D.

Dr. Steven M. Becker was appointed to the U.S. Nuclear Waste Technical Review Board by President Barack Obama on September 25, 2012.

Dr. Becker is Professor of Community and Environmental Health at Old Dominion University in Norfolk, Virginia. He is a leading international expert on emergency planning, disaster preparedness and response, public health preparedness, and risk communication for radiological, chemical and nuclear incidents as well as other new and emerging health challenges. Dr. Becker has served as principal investigator for several major research studies aimed at improving emergency messages for the general public, first responders, and hospital and healthcare professionals. In addition, he has extensive on-the-ground experience at the sites of accidents, emergencies, and disasters around the world. In 2011, he was a member of a three-person assistance team invited to Japan in response to the earthquake-tsunami disaster and the emergency at the Fukushima Daiichi nuclear plant. While on scene, the team carried out a rapid site assessment, interfaced with Japanese disaster professionals, and provided training to more than 1,100 Japanese hospital and healthcare personnel and emergency responders.

Dr. Becker's research on emergency preparedness, public health, and risk communication has been recognized with awards from such scientific organizations as the Health Physics Society and Oak Ridge Associated Universities. For the last 19 years, he also has been an invited faculty member for the Harvard School of Public Health training course on radiological emergency planning.

Dr. Becker holds a B.A. from George Washington University, an M.A. from Columbia University, and a Ph.D. from Bryn Mawr College. He also was a Dozor Visiting Scholar at Ben-Gurion University of the Negev in Israel and a Visiting Fellow at the Japan Emergency Medicine Foundation and National Hospital Tokyo Disaster Medical Center. In 2017, Dr. Becker was named a member of the Nuclear and Radiation Studies Board of the National Academies of Sciences, Engineering and Medicine.

SUSAN L. BRANTLEY, PH.D.*

Dr. Susan L. Brantley was appointed to the U.S. Nuclear Waste Technical Review Board on September 25, 2012, by President Barack Obama.

Dr. Brantley is Distinguished Professor of Geosciences in the College of Earth and Mineral Sciences at Pennsylvania State University, where she also is Director of the Earth and Environmental Systems Institute. She has been a member of the faculty at the University since 1986. As a geochemist, Dr. Brantley has concentrated on the chemistry of natural waters, both at the surface of the earth and deeper in the crust. Much of her research focuses on understanding what controls the chemistry of natural water and how water interacts with the rocks through which it flows. Dr. Brantley and her research group investigate chemical, biological, and physical processes associated with the circulation of aqueous fluids in shallow hydrogeologic settings through field and laboratory work and theoretical modeling of observations. Of particular interest are questions concerning the measurement and prediction of the rates of natural processes, including chemical weathering with and without microorganisms. Her recent work has focused on the effect of microbial life on mineral reactivity and measuring and modeling how rock turns into regolith. Dr. Brantley has published more than 160 refereed journal articles and 15 book chapters.

Professor Brantley is a fellow of the American Geophysical Union, a fellow of the GSA, a fellow of the Geochemical Society, a fellow of the European Association of Geochemistry, and a fellow of the International Association for GeoChemistry. She was president of the Geochemical Society from 2006 to 2008. She has served on several National Research Council committees, and she has been a member of the U. S. Department of Energy Council on Earth Sciences since 2009.

In 2011, Professor Brantley received the Arthur L. Day Medal from GSA, as well as an honorary doctorate from the Paul Sabatier University (Toulouse III) in France. In 2012, she received the Presidential Award from the Soil Science Society of America, and she also was elected to membership in the U.S. National Academy of Sciences. In 2016, she received the Wollaston Medal from the Geological Society of London.

Dr. Brantley received an A.B. in chemistry in 1980 and an M.A. and a Ph.D. in geological and geophysical sciences in 1983 and 1987, respectively, from Princeton University.

Dr. Brantley lives in State College, Pennsylvania.

* Dr. Brantley resigned from the Board effective July 21, 2021.

ALLEN G. CROFF, NUCLEAR ENGINEER, M.B.A

Allen G. Croff was appointed to the U.S. Nuclear Waste Technical Review Board by President Barack Obama on February 23, 2015.

Mr. Croff is an adjunct professor in the Civil and Environmental Department at Vanderbilt University in Nashville, Tennessee. His areas of expertise include radioactive waste generation, classification, processing, storage, transportation, and disposal; nuclear fuel cycle systems and economic analysis and regulation; modeling radionuclide production and depletion; radionuclide separation and transmutation; waste repository site identification, regulation, and assessment; and cleanup of U.S. Department of Energy (DOE) legacy sites.

Mr. Croff worked at Oak Ridge National Laboratory for almost 30 years. He is a member of the National Council on Radiation Protection and Measurements (NCRP) and has served on ten committees of the National Academy of Sciences and on its Nuclear and Radiation Studies Board. He was also a member of DOE's Nuclear Energy Research Advisory Committee and served on the staff of the Blue Ribbon Commission on America's Nuclear Future. He was Chairman of the Nuclear Development Committee of the Nuclear Energy Agency for ten years and Vice-Chairman of the Nuclear Regulatory Commission's Advisory Committee on Radioactive Waste Management for four years.

Mr. Croff's writings and publications include contributions to five books, ten National Academy of Sciences reports, an NCRP report, and numerous national laboratory reports and peer-reviewed conference papers.

Mr. Croff received a B.S. (1971) in chemical engineering from the Michigan State University, a Nuclear Engineer Degree (1974) from the Massachusetts Institute of Technology, and an M.B.A. (1981) from the University of Tennessee.

Mr. Croff resides in Saint Augustine, Florida.

EFI FOUFOULA-GEORGIOU, PH.D.**

Dr. Efi Foufoula-Georgiou was appointed to the U.S. Nuclear Waste Technical Review Board by President Barack Obama on September 25, 2012.

Dr. Efi Foufoula-Georgiou is a Distinguished Professor in the Departments of Civil and Environmental Engineering and Earth System Science and the Henry Samueli Endowed Chair in Engineering at the University of California, Irvine. From 1989 to 2016, she was on the faculty at the University of Minnesota as a McKnight Distinguished Professor in the Department of Civil, Environmental, and Geo-Engineering, the Joseph T. and Rose S. Ling Chair in Environmental Engineering, and a Founding Fellow of the Institute on the Environment. Her areas of research are hydrology and geomorphology, with special interest in scaling theories, multiscale dynamics, and space-time modeling of precipitation and landforms.

Dr. Foufoula-Georgiou served on many national and international advisory boards, including the Water Science and Technology Board of the National Academies, the Advisory Council of the Geosciences Directorate of NSF, and the Earth Sciences Subcommittee of the Science Advisory Council of the National Aeronautics and Space Administration. She has also been a member of several National Research Council committees, the most recent one producing the report "Challenges and Opportunities in the Hydrologic Sciences." She served as chair of the Board of Directors of the Consortium of Universities for the Advancement of Hydrologic Sciences and as an elected Trustee of the University Corporation for Atmospheric Research. Dr. Foufoula-Georgiou published over 130 journal-refereed papers and received the John Dalton Medal of the European Geophysical Union, the Hydrologic Sciences Award of the American Geophysical Union (AGU), and the Robert E. Horton Lecture award of the American Meteorological Society (AMS). She is a fellow of AGU and the AMS and is an elected member of the European Academy of Sciences. In 2012, she was elected president of the Hydrology Section of AGU.

Dr. Foufoula-Georgiou received a diploma in civil engineering (1979) from the National Technical University of Athens, Greece, and an M.S. and a Ph.D. (1985) in environmental engineering from the University of Florida.

Dr. Foufoula-Georgiou resides in Irvine, California.

** Dr. Foufoula-Georgiou, resigned from the Board effective May 17, 2021.

TISSA H. ILLANGASEKARE, PH.D., P.E.

Dr. Tissa H. Illangasekare was appointed to the U.S. Nuclear Waste Technical Review Board on January 18, 2017, by President Barack Obama.

Dr. Illangasekare presently holds the AMAX Endowed Distinguished Chair of Civil and Environmental Engineering position at the Colorado School of Mines. He is also the founding director of the Center for Experimental Study of Subsurface Environmental Processes, a university/industry/national laboratory collaborative center. His research experience and expertise are in mathematical and numerical modeling of flow and transport in porous and fractured media, management of hydrocarbon, organic, and nuclear wastes, saturated and unsaturated zone processes, multiphase flow, carbon storage, modeling of land-atmospheric interaction, remediation of contaminated sites, and application of sensor technologies for environmental, soil, and hazard monitoring.

Dr. Illangasekare has served on many national and international advisory boards, including the National Academy of Science's Nuclear and Radiation Studies Board. He has also been a member of several National Research Council committees that include "Subsurface Contamination at DOE Complexes" and "Management of Certain Radioactive Waste Streams Stored in Tanks at Three Department of Energy Sites." He has served as a member of the Board of Directors of the Consortium of Universities for the Advancement of Hydrologic Sciences. He served as President of the International Porous Media Society (InterPore). Dr. Illangasekare served as editor of *Water Resources Research* and *Earth-Science Reviews* and co-editor of *Vadose Zone Journal*. He is currently an editor of American Geophysical Union's (AGU) *Advances* and *Perspectives in Earth and Planetary Systems* and the Section Chief Editor of *Frontiers in Water and Human Health*. He is a Fellow of the AGU, the American Association for Advancement of Science, the American Society of Civil Engineers, Soil Science Society of America, and National Academy of Sciences of Sri Lanka. He is a registered Professional Engineer and a Professional Hydrologist, Board Certified Environmental Engineer by the American Academy of Environmental Engineers (by eminence), and Diplomate of American Academy of Water Resources Engineers. Dr. Illangasekare has published over 200 refereed journal papers and contributed to 15 book chapters. He is the recipient of the 2012 Darcy Medal from the European Geosciences Union for outstanding scientific contributions in water resources research and engineering. He was the 2015 recipient of the AGU's Langbein Lecture Award (Bowie lecture) given in recognition of lifetime contributions to the science of hydrology and received the 7th Prince Sultan Abdulaziz International Prize for Groundwater at the United Nations from the Secretary General in 2016. He was a Shimizu Visiting Professor in the Department of Civil and Environmental Engineering and a Global Climate Energy Program Visiting Professor at the Department of Earth Resources Engineering at Stanford University. He was a Visiting Scholar in the Department of Civil and Environmental Engineering at University of California at Berkeley. He is currently a Visiting Professorial Fellow in the School of Civil & Environmental Engineering at the University of New South Wales, Sydney, Australia.

Dr. Illangasekare received a BSc (Honors) degree in civil engineering (1971) from the University of Ceylon, a M.Eng. degree in hydrology and water resources development from the Asian Institute of Technology (1974), and a Ph.D. (1978) in Civil Engineering from Colorado State University. He also received an Honorary Doctorate in Science and Technology from Uppsala University, Sweden.

Dr. Illangasekare resides in Boulder, Colorado.

LINDA K. NOZICK, PH.D.[***]

Dr. Linda Nozick was appointed to the U.S. Nuclear Waste Technical Review Board by President Barack Obama on July 28, 2011. Dr. Nozick was reappointed to the Board by the President on July 1, 2014.

Dr. Nozick is a professor and the director of civil and environmental engineering at Cornell University. She has also served as the Director of the College Program in Systems Engineering, a program that she co-founded. She has been on the Cornell faculty since 1992 and has been a full Professor since 2003. From 1998 to 1999, Dr. Nozick was Visiting Associate Professor in the Operations Research Department at the U.S. Naval Postgraduate School in Monterey, California. In 1998, she was Visiting Professor in the Operations Research Department at General Motors Research & Development in Warren, Michigan. She played a leading role in developing optimization models for planning and policy to support the National Security Enterprise and Homeland Security.

Dr. Nozick served on two National Academy committees to advise the U.S. Department of Energy on renewal of their infrastructure. She authored more than 60 peer-reviewed publications, many of which focused on transportation, moving hazardous materials, and modeling critical infrastructure systems. She was an associate editor for *Naval Research Logistics* and a member of the editorial board of *Transportation Research Part A*.

She has received numerous awards, including a CAREER award from the National Science Foundation and a Presidential Early Career Award for Scientists and Engineers from President Bill Clinton for "the development of innovative solutions to problems associated with the transportation of hazardous waste." Dr. Nozick also received several recognition awards from Sandia National Laboratories and the National Nuclear Security Administration for developing modeling tools for nuclear stockpile analysis, transporting hazardous/sensitive materials, enterprise planning, and budget analysis.

Dr. Nozick received a Ph.D. and an M.S.E. in systems engineering from The University of Pennsylvania and a B. S. in systems analysis and engineering from The George Washington University.

Dr. Nozick lives in Ithaca, New York.

[***] Dr. Nozick resigned from the Board effective May 9, 2019.

KENNETH LEE PEDDICORD, PH.D., P.E.

Dr. Kenneth L. Peddicord was appointed to the U.S. Nuclear Waste Technical Review Board by President Barack Obama on September 25, 2012. Dr. Peddicord was reappointed to the Board by the President on July 1, 2014.

Dr. Peddicord is a professor of nuclear engineering at Texas A&M University, where he has been a member of the faculty since 1983. From 1972 to 1975, he was employed as a research nuclear engineer at the Eidgenössisches Institut für Reaktorforschung (the Swiss Federal Institute for Reactor Research), now the Paul Scherrer Institut, in Würenlingen, Switzerland. From 1975 to 1981, he was an assistant professor and an associate professor of nuclear engineering at Oregon State University. From 1981 to 1982, he was a Visiting Scientist at the EURATOM Joint Research Centre in Ispra, Italy.

At Texas A&M University, Dr. Peddicord has served as Head of the Department of Nuclear Engineering, Associate Dean and Interim Dean of the College of Engineering, Associate Vice Chancellor and Vice Chancellor of The Texas A&M University System for Research and Federal Relations. From 2007 to 2019, he was director of the Nuclear Power Institute (NPI), a joint institute of the Texas Engineering Experiment Station and Texas A&M University. NPI was a partnership involving universities, community colleges, industry, high schools and junior highs, teachers, students, elected and civic leaders, and government agencies. The focus was to inform, attract, and prepare students for the nuclear industry and to support the development of the peaceful uses of nuclear energy worldwide.

Dr. Peddicord has published more than 200 articles, papers, and reports. His technical interests include nuclear engineering education, human resources and nuclear workforce development, advanced nuclear fuels, and small modular reactors and microreactors. He is a licensed Professional Engineer in the State of Texas.

Dr. Peddicord received a B.S. degree in mechanical engineering from the University of Notre Dame in 1965, and an M.S. in 1967 and a Ph.D. in 1972 in nuclear engineering from the University of Illinois at Urbana-Champaign.

Dr. Peddicord resides in College Station, Texas.

Paul J. Turinsky, Ph.D., Deputy Chair

Dr. Paul J. Turinsky was appointed to the U.S. Nuclear Waste Technical Review Board by President Barack Obama on September 25, 2012. Dr. Turinsky was reappointed to the Board by the President on July 1, 2014.

Dr. Turinsky is Professor Emeritus of Nuclear Engineering at North Carolina State University in Raleigh, North Carolina. He previously was the Chief Scientist for the Department of Energy's (DOE) Innovation Hub for Modeling and Simulation of Nuclear Reactors.

Dr. Turinsky's areas of expertise are computational reactor physics in support of mathematical optimization of fuel management and nuclear fuel-cycle multiobjective decisions; uncertainty quantification and data assimilation in support of optimum experimental design applied to nuclear power plant safety and fuel-cycle assessments; and adaptive model refinement applied to nuclear power plant transient simulation.

Dr. Turinsky's writings and publications include contributions to three books and numerous peer-reviewed technical publications. He is the recipient of the American Society for Engineering Education Glenn Murphy Award, the Edison Electric Institute Power Engineering Educator Award, the U.S. Department of Energy E.O. Lawrence Award in Atomic Energy, and the American Nuclear Society (ANS) Eugene P. Wigner Reactor Physics Award and Arthur Holly Compton Award.

Dr. Turinsky was on the faculty of Rensselear Polytechnic Institute and has held engineering and management positions at Westinghouse Electric Corporation. He also served on the Commissariat à l'énergie Atomique Scientific Committee of the Nuclear Energy Division, the Duke Power Company Nuclear Safety Review Board, the DOE Fuel Cycle R&D External Review Committee, and the Board of Managers of Battelle Energy Alliance.

Dr. Turinsky is a fellow of the ANS and the American Association for the Advancement of Science, and a member of the Society for Industrial and Applied Mathematics and the American Society for Engineering Education, and was elected a member of the National Academy of Engineering.

Dr. Turinsky received a B.S. (1966) in chemical engineering from the University of Rhode Island, an M.S.E. (1967) and a Ph.D. (1970) in nuclear engineering from the University of Michigan, and an M.B.A. (1979) from the University of Pittsburgh.

Dr. Turinsky resides in Raleigh, North Carolina.

MARY LOU ZOBACK, PH.D. ****

Dr. Mary Lou Zoback was appointed to the U.S. Nuclear Waste Technical Review Board by President Barack Obama on September 25, 2012.

Dr. Zoback is a seismologist retired from the U. S. Geological Survey (USGS). She was a senior research scientist at the USGS in Menlo Park, California, where she served, among other positions, as Chief Scientist of the Western Earthquake Hazards team. Her research interests include the relationship between active faulting, deformation and state of stress in the earth's crust, quantifying earthquake likelihood, and characterizing natural-hazard risk.

From 2006 to 2011, Dr. Zoback was Vice President for Earthquake Risk Applications with Risk Management Solutions, a private catastrophe-modeling firm serving the insurance industry. In that role, she utilized the company's commercial risk models to explore the societal role of earthquake insurance and to quantify the costs and benefits of risk reduction.

Dr. Zoback has served on numerous national committees and panels on topics ranging from increasing the nation's resilience to disasters, defining the next generation of Earth observations from space, storing high-level radioactive waste, facilitating interdisciplinary research, and science education. From 1997 to 2000, she was a member of the National Research Council's Board on Radioactive Waste Management.

In 2007, she received from the Geological Society of America (GSA) both the Day Medal "for outstanding distinction in contributing to geologic knowledge through the application of physics and chemistry to the solution of geologic problems" and their Public Service Award. In 2002, she was awarded the Department of Interior Meritorious Service Award, and in 1987, she received the James B. Macelwane Award of the American Geophysical Union (AGU) for "significant contributions to the geophysical sciences by a young scientist of outstanding ability."

In 1995, Dr. Zoback was elected a member of the U. S. National Academy of Sciences (NAS). She is a member of the AGU, the Seismological Society of America, and is a past president of GSA. Dr. Zoback also is past chair of the Advisory Committee for San Francisco's Community Action Plan for Seismic Safety (CAPSS) program. She also served on NAS Disaster Roundtable and the Advisory Committee for the National Earthquake Hazard Reduction Program.

Dr. Zoback received a Ph.D. in 1978, an M.S. in 1975, and a B.S. in 1974, all in Geophysics and all from Stanford University.

Dr. Zoback resides in Stanford, California.

**** Dr. Zoback, resigned from the Board effective May 17, 2021.

Appendix B
Board Strategic Plan 2022–2026

U.S. Nuclear Waste Technical Review Board

Strategic Plan
Fiscal Years 2022 to 2026

March 2022

U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

MESSAGE FROM THE CHAIR

March 2022

It is my pleasure to present the U.S. Nuclear Waste Technical Review Board's *Strategic Plan for Fiscal Years 2022-2026*. This plan supersedes the Board's *Strategic Plan for Fiscal Years 2018-2022*, which was published in 2018. This updated plan describes the Board's mission and the vision and values that guide the Board's work and the development of the Board's Strategic Objectives.

As an independent Federal agency in the Executive Branch, the Board is committed to effectively carrying out its statutory mandate to evaluate the technical and scientific validity of the Department of Energy's activities related to managing and disposing of spent nuclear fuel and high-level radioactive waste. The Board's *Strategic Plan for Fiscal Years 2022-2026* provides a roadmap to guide us in achieving our Strategic Objectives and a benchmark against which to evaluate the Board's performance in meeting those objectives in the years ahead.

Jean M. Bahr
Chair

U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

STRATEGIC PLAN

FISCAL YEARS 2022-2026

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U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD
STRATEGIC PLAN
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OVERVIEW

The U.S. Nuclear Waste Technical Review Board was established as an independent federal agency in the 1987 amendments to the Nuclear Waste Policy Act (NWPA) to "...evaluate the technical and scientific validity of activities [related to managing and disposing of spent nuclear fuel and high-level radioactive waste] undertaken by the Secretary [of Energy], including:

1) site characterization activities; and

2) activities relating to the packaging or transportation of high-level radioactive waste or spent nuclear fuel."

As recorded in the legislative history of the Nuclear Waste Policy Amendments Act (NWPAA), the purpose of the Board is to provide independent expert advice to the Department of Energy (DOE) and Congress on technical issues and to review the technical and scientific validity of activities undertaken by the DOE to implement the NWPA. In accordance with this mandate, the Board conducts objective, ongoing, and integrated technical and scientific peer review of DOE activities related to the disposition of commercial and DOE-managed spent nuclear fuel (SNF) and high-level radioactive waste (HLW). According to the legislative history, the Board is expected to "review the activities [of the Secretary] as they are occurring, not after the fact." The Board reports its findings and recommendations to Congress and the Secretary of Energy.

MISSION STATEMENT

By performing ongoing and independent peer review of the highest quality, the Board will make a unique and essential contribution to increasing confidence in the technical and scientific validity of DOE activities related to managing and disposing of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) and to informing, from a technical and scientific perspective, policy discussions undertaken by decision-makers on managing and disposing of SNF and HLW. The Board will provide objective and relevant technical and scientific information to Congress, the Administration, DOE, and the public on a wide range of technical and scientific issues related to the management and disposition of such waste.

VALUES

The Board's technical and scientific peer review reflects its commitment to the following values:

- **Objectivity**. Board members have no real or perceived conflicts of interest related to the Board's mission. Board findings and recommendations are based on impartial evaluations of the technical and scientific validity of the Secretary's activities.

- **Openness**. Board deliberations are transparent and are conducted in such a way that the Board's integrity and objectivity are above reproach.

- **Technical and Scientific Competence.** Board findings, conclusions, and recommendations are technically and scientifically sound and are based on expert judgment and the best available technical and scientific information and analyses.

- **Timeliness**. Board findings, conclusions, and recommendations are communicated clearly and in time for them to be useful to Congress, the Secretary, and the public.

MEMBERS

The Board is composed of eleven members who are appointed by the President from a list of nominees submitted by the National Academy of Sciences (NAS). Nominees to the Board must be eminent in a field of science or engineering and are selected solely on the basis of established records of distinguished service. The Board is nonpartisan and apolitical.

POWERS

The NWPAA grants significant investigatory powers to the Board: "The Board may hold such hearings, sit and act at such times and places, take such testimony, and receive such evidence as it considers appropriate." At the request of the Board, and subject to existing law, DOE is required to provide all records, files, papers, data, and information necessary for the Board to conduct its technical and scientific review, including drafts of work products and documentation of work-in-progress. According to the legislative history of the NWPAA, Congress indicated this was necessary because the Board's "…effectiveness is dependent upon its ability to affect actions of the Secretary while they are happening, and not just after the fact."

HISTORY AND CONTINUING ROLE

For more than 20 years, DOE focused on developing a permanent geologic repository for disposal of SNF and HLW at Yucca Mountain in Nevada. During that time, the Board performed continuous peer review of DOE's activities and conveyed its findings and recommendations to Congress and the Secretary of Energy in reports, testimony, and activities and correspondence. As the Administration and Congress decide on a path forward for the disposition of nuclear waste, DOE continues to have responsibility under the NWPA for managing and disposing of SNF and HLW, and the Board's statutory responsibility for evaluating DOE's implementation of those activities remains unchanged.

By performing unbiased and ongoing technical and scientific peer review of DOE's nuclear waste management activities, the Board makes an essential contribution to increasing confidence in the scientific process and to informing, from a technical and scientific perspective, decisions on nuclear waste management. The Board provides objective information to Congress, the Administration, DOE, government and non-government organizations, and the public on a wide-range of issues related to SNF and HLW management and disposition.

All Board reports, factsheets, correspondence, testimony, and meeting materials are available on the Board's website at www.nwtrb.gov.

Strategic Objectives

The Board has established three Strategic Objectives for fiscal years (FY) 2022-2026. The Strategic Objectives reflect the Board's continuing commitment to its mission established in the NWPAA, which includes (1) conducting an ongoing, independent technical and scientific evaluation of DOE activities related to the NWPA and (2) advising Congress and the Secretary. During FYs 2022-2026:

- The Board will continue its evaluation of DOE activities related to implementation of the NWPA and relevant amendments to that Act. Based on its evaluation, the Board will report its findings, conclusions, and recommendations to Congress and the Secretary.

- The Board will develop objective technical and scientific information that will be useful to policy makers in Congress and the Administration on issues related to SNF and HLW management and disposal. The Board will communicate such information to Congress and the Secretary in letters, reports, and testimony.

- The Board will compile information and report to Congress and the Secretary on its findings, conclusions, and recommendations from experience gained during thirty-five years of reviewing the U.S. nuclear waste management and disposal program and from observing waste management efforts in other countries.

Achieving the Strategic Objectives

Leadership Engagement – On an annual basis, in accordance with the Government Performance and Results Act, as amended, the Board's leadership identifies Performance Goals that will lead to the accomplishment of the Strategic Objectives. The Performance Goals are included in the Board's Performance Plan.

Ongoing Evaluation of Performance – The Board includes in its annual Congressional Budget Justification an evaluation of the Board's performance in achieving its Performance Goals for the preceding fiscal year.

Evidence Based Evaluation of Board Performance – The Board's Performance Plan for a given year includes its *Strategic Objectives*, its *Performance Goals*, its *Management Goals*, and a description of Board activities and practices supporting the achievement of the Goals. The Board's Performance Plan is updated annually. In updating and implementing the plan, the Board's leadership is committed to using a learning agenda approach by consistently building and using evidence to:

1) proactively evaluate the agency's performance to determine what works well and where performance can be improved;

2) focus on where the needs are greatest to effectively, efficiently, and accountably fulfill the agency's mission; and

3) ascertain how the agency can achieve better results.

Adopting a learning agenda approach ensures that the Board's Performance Goals and Strategic Objectives are prioritized to meet the agency's mission.

The Board uses annual evaluations of its performance as input in developing its Performance Goals for the following fiscal year. The Performance Goals reflect the objectives of the agency leadership and are outcome-oriented. The annual evaluations of the Board's performance are also used as input in developing the Board's budget allocations for the subsequent year. The evaluation of the Board's performance in achieving its Performance Goals is evidence-based, and the referenced documents and meeting records may be accessed on the Board's website at www.nwtrb.gov.

STAKEHOLDER AND PUBLIC ENGAGEMENT

As part of its peer review and information gathering activities, the Board organizes public meetings at which technical information is presented by representatives of DOE, its contractors, and other organizations involved in nuclear waste management and disposal. At these meetings, Board members and Board staff question the presenters, and time is provided for input and comments from interested members of the public. The Board usually holds two or three public meetings per year, either "in-person" or virtually. Meetings are announced in the *Federal Register,* typically four to six weeks before being held, and details of how to access the webcast of an in-person meeting or attend a public meeting are posted to the Board's website in advance of the meeting. Recordings of Board meetings are archived and are available on the Board's website.

TRANSPARENCY, PARTICIPATION, AND COLLABORATION

The Board is committed to the principles of open government, specifically the principles of transparency, participation, and collaboration.

TRANSPARENCY – As discussed in the previous section, the Board holds public meetings, at which it discusses DOE's activities with DOE staff and staff from the National Laboratories, DOE contractors, and other experts. In addition, the Board reports the results of its review of DOE activities to Congress and the Secretary of Energy on an ongoing basis. All Board reports, correspondence, fact sheets, written meeting materials, and meeting webcast videos are posted on the Board's website. When developing or updating its Strategic Plan, the Board seeks comments from the Office of Management and Budget and Congress and posts a copy of the plan on the Board's website.

PARTICIPATION – Opportunities for public comment are provided at all Board public meetings. In addition to public meetings held by the full Board, Board panels or other small groups of Board members and staff may hold other meetings, as needed, to investigate specific technical and scientific topics.

COLLABORATION – The Board members and senior professional staff enhance their scientific and technical expertise through knowledge-sharing and peer engagement. Board members and staff participate in technical symposia and conferences related to SNF and HLW management and disposal. On occasion, Board members and/or staff travel to other countries to meet with organizations involved in the management and disposal of SNF and HLW, to observe their technical programs and best practices, perform benchmarking, assess potential analogs, and for other purposes. The information gathered from these visits is used to enhance the Board's evaluation of DOE activities and to advise Congress and the Secretary of Energy.

CROSSCUTTING FUNCTIONS

Many organizations and entities are involved in some aspect of managing and disposing of SNF and HLW. Within the Federal government, these include Congress, the Government Accountability Office, DOE, the Nuclear Regulatory Commission, the Environmental Protection Agency, the Department of Transportation, and the NAS. Outside of the Federal government, interested organizations include the State of Nevada and other state governments, Tribal Nations, affected local governments, the National Association of Regulatory Utility Commissioners, the National Governors Association and regional groups, the National Conference of State Legislatures, the Nuclear Energy Institute, the Electric Power Research Institute, environmental justice organizations, and other environmental organizations, such as the Natural Resources Defense Council.

The Board's technical and scientific evaluation is at once different from and complementary to the activities of most of these entities. The Board is (1) unconstrained by any stake in the outcome of the activities it reviews, beyond technical and scientific validity; (2) charged with advising both Congress and the Secretary of Energy on technical issues related to nuclear waste management and disposal; (3) limited to reviewing the technical and scientific validity of DOE activities (not the policy implications or regulatory compliance); and (4) a permanent independent federal agency whose members are appointed by the President.

MANAGEMENT CHALLENGES

Factors that are outside the Board's control could affect the Board's ability to achieve its Strategic Objectives or Performance Goals. The Board will continue to evaluate the status of the challenges discussed below, identify any new factors, and, if necessary, update its Strategic Objectives and Performance Goals, as appropriate.

- *The Board has no statutory authority to implement, or to require DOE to implement, its recommendations.* The Board is a technical and scientific peer-review body that makes findings, conclusions, and recommendations. The Board's enabling statute does not obligate DOE to comply with Board recommendations. However, according to the legislative history of the NWPAA, in creating the Board, Congress expected that DOE would accept Board recommendations or "…clearly state its reasons for disagreeing". If DOE does not accept a Board recommendation, the Board can reiterate its recommendation, advise Congress, or both.

- *Operational constraints may impede the Board's ability to fully meet its performance goals on the timetable planned*. Operational constraints can affect the Board's ability to complete its review of DOE activities and to provide its technical and scientific findings, conclusions, and recommendations to Congress and the Secretary of Energy in accordance with its annual Performance Goals. Funding levels and allocation decisions may affect the nature and extent of DOE activities that are subject to the Board's review.

- *Administrative, judicial, or legislative actions may alter nuclear waste policy.* Changes to the program or the law made by any of the external entities may also affect the nature or extent of the Board's technical and scientific review. Since passage of the NWPAA in 1987, several administrative or judicial actions have affected the direction of DOE's nuclear waste management program, and these actions have on occasion affected the Board's work.

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Effective Use of Resources

Technical and scientific analyses of DOE waste management and disposal activities are performed by Board members, all of whom are eminent scientists and experts in their fields. The Board members serve part-time and are supported by a small, full-time professional staff whose members are highly credentialed in relevant scientific and technical disciplines. When necessary, the Board is authorized to hire expert consultants to support its in-depth reviews of specific technical topics. Board members and members of the Board's senior professional staff are assigned by the Chair to lead or support Board activities, as appropriate. The Board maintains the option of organizing panels or working groups to help facilitate, integrate, and focus its technical and scientific review, and for other purposes.

Culture of Accountability

The Board considers its independence and objectivity to be among its most important assets. To avoid any real or perceived conflict, the NWPAA stipulates that individuals nominated to serve on the Board may not be an employee of DOE, a laboratory under contract with the DOE, or an entity performing HLW or SNF activities under contract with DOE.

The Board reports its findings, conclusions, and recommendations to Congress and the Secretary of Energy, and the Chair and other members of the Board and Board staff testify before Congress, as requested. Board reports, testimony, correspondence, and other documents related to its activities, along with meeting agendas, transcripts, presentations, webcasts, and public comments, are posted on the Board's website at www.nwtrb.gov.

Appendix C
Board Publications

Board Publications

Survey of National Programs for Managing High-Level Radioactive Waste and Spent Nuclear Fuel: 2022 Update
July 2022.

> The report is an update of a survey report first issued by the Board in 2009 that was updated in 2016. The report describes 30 technical and institutional attributes of nuclear waste programs in 13 countries.

Report to the U.S. Congress and the Secretary of Energy – Board Activities for the Period January 1, 2016 – December 31, 2018
August 2021.

> The report summarizes Board activities, conclusions, and recommendations from January 1, 2016, through December 31, 2018. During the period, the Board focused on activities undertaken by the U.S. Department of Energy related to the packaging, storage, transportation, and disposal of spent nuclear fuel and high-level radioactive waste.

Evaluation of the Department of Energy's Research Program to Examine the Performance of Commercial High Burnup Spent Nuclear Fuel During Extended Storage and Transportation
July 2021.

> The report is a product of a multi-year effort, during which the Board reviewed the U.S. Department of Energy's (DOE) research activities, which have the aim of obtaining data that can enhance the understanding of the performance of high burnup spent nuclear fuel (SNF) in extended storage and transportation conditions.

Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward
April 2021.

> The report is the current Board members' synthesis of their nearly decade-long experience reviewing the U.S. Department of Energy's (DOE's) activities related to the management and disposal of spent nuclear fuel and high-level radioactive waste. The report provides the Board member's six overarching recommendations and associated action items in areas related to (i) ensuring an integrated organizational approach, (ii) anticipating required infrastructure and personnel needs, (iii) expanding the research paradigm to embrace hypothesis testing, (iv) applying an interactive, adaptive waste management program approach, (v) expanding engagement with the international community, and (vi) embracing openness, transparency, and engagement to build public trust.

Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geological Disposal Research and Development Program
January 2020.

The report is a product of the Board's review of the U.S. Department of Energy's (DOE) underground research laboratory (URL)-related research and development activities and their relationship to spent nuclear fuel and high-level radioactive waste disposal program. The Board report presents and evaluates the DOE's research on complex coupled processes and addresses the use of URL R&D results for developing safety cases and knowledge gap analyses. The report describes the critical role of URLs in technology development and demonstration, training, and public confidence building.

Preparing for Nuclear Waste Transportation
September 2019.

This report is based on the Board's review of the U.S. Department of Energy's (DOE) research and analysis to support transporting spent nuclear fuel (SNF) and high-level radioactive waste (HLW). The report compiles and discusses the technical and integration issues that DOE will need to address to ensure that SNF and HLW are ready for a nationwide transportation effort to a nuclear waste repository or an interim storage site.

Geologic Repositories: Performance Monitoring and Retrievability of Emplaced High-Level Radioactive Waste and Spent Nuclear Fuel
May 2018.

In this letter report, the Board presents its observations from a meeting on March 27, 2018. At the meeting, the Board heard from experts from several international repository programs on (i) operational and performance confirmation monitoring of a geologic repository for high-level radioactive waste (HLW) and spent nuclear fuel (SNF) and (ii) retrievability of emplaced HLW and SNF.

Management and Disposal of US Department of Energy Spent Nuclear Fuel
December 2017.

This report is based on the Board's review of the U.S. Department of Energy's (DOE) efforts to manage the spent nuclear fuel (SNF) under its control at four federal facilities. The report records the quantities and characteristics of DOE SNF at each of the four storage sites and examines the technical issues related to DOE SNF packaging and storage that might affect continued storage, transport, and final disposal of SNF.

Report to the U.S. Congress and the Secretary of Energy—Board Activities, January 1, 2013 – December 31, 2015
October 2016.

> The report is one in a series of "summary" reports issued periodically since the beginning of Board operations in 1989 that chronicle Board activities over a defined period of time. The report is archival in nature and does not break new ground. Rather, it documents Board activities, findings, and recommendations for the reporting period. During the period, the Board focused on activities undertaken by the U.S. Department of Energy (DOE) related to the packaging, transportation, and disposal of spent nuclear fuel and high-level radioactive waste.

Survey of National Programs for Managing High-Level Radioactive Waste and Spent Nuclear Fuel: An Update
February 2016.

> This revision of a 2009 report describes 30 technical and institutional attributes of nuclear waste programs in 13 countries. It does not make judgements; rather the report provides factual information for Congress and the Secretary of Energy that can be used for evaluating waste management options.

Technical Evaluation of the U.S. Department of Energy Deep Borehole Disposal Research and Development Program
January 2016.

> This report is based on the Board's evaluation of information presented by the U.S. Department of Energy (DOE) and subject-matter experts from the United States and other countries at a Board workshop on deep borehole disposal held in Washington, D.C. on October 20–21, 2015. In the report, the Board makes technical and scientific findings, conclusions, and recommendations on two topics: (1) technical and scientific issues that may affect the feasibility of the deep borehole disposal option for select radioactive waste forms, and (2) whether results that will be obtained from the DOE Deep Borehole Field Test will provide the necessary technical data and scientific understanding for determining the feasibility of disposing of some radioactive waste forms in deep boreholes.

Designing a Process for Selecting a Site for a Deep-Mined, Geologic Repository for High-Level Radioactive Waste and Spent Nuclear Fuel – Overview and Summary
November 2015.

> To provide information about efforts in the United States and other countries to site a deep-mined, geologic repository for high-level radioactive waste and spent nuclear fuel, the Board prepared two reports that rely on a comparative historical inquiry into two dozen siting efforts that have taken place over the past half century in ten different countries. The *Overview and Summary* provides a short synopsis of the major insights that derive from that study. The *Detailed Analysis*, referred to below, is an in-depth account that provides the empirical foundations for those insights. The

reports contain four recommendations that policymakers might consider if they choose to begin a new siting effort for a first or second repository.

Designing a Process for Selecting a Site for a Deep-Mined, Geologic Repository for High-Level Radioactive Waste and Spent Nuclear Fuel – Detailed Analysis
November 2015

To provide information about efforts in the United States and other countries to site a deep-mined, geologic repository for high-level radioactive waste and spent nuclear fuel, the Board prepared two reports that rely on a comparative historical inquiry into two dozen siting efforts that have taken place over the past half century in ten different countries. The *Overview and Summary*, referred to above, provides a short synopsis of the major insights that derive from that study. The *Detailed Analysis* is an in-depth account that provides the empirical foundations for those insights. The reports contain four recommendations that policymakers might consider if they choose to begin a new siting effort for a first or second repository.

Evaluation of Technical Issues Associated with the Development of a Separate Repository for U.S. Department of Energy-Managed High-Level Radioactive Waste and Spent Nuclear Fuel
June 2015.

The report is based on the Board's review of U.S. Department of Energy (DOE) reports and studies supporting a new DOE initiative involving the development of two mined geologic repositories: one to dispose of defense high-level radioactive waste (HLW) and possibly some DOE-managed spent nuclear fuel (SNF), and another to dispose of commercially generated HLW and SNF, together with other DOE-managed HLW and SNF. The new initiative also includes consideration of options for disposal of smaller DOE-managed waste forms in deep boreholes. In the report, the Board makes technical and scientific findings, conclusions, and recommendations related to the implementation of DOE's new initiative.

A Report to the U.S. Congress and the Secretary of Energy—Board Activities, January 1, 2008 – December 31, 2012
December 2014.

The report is one in a series of "summary" reports issued periodically since the beginning of Board operations in 1989 that chronicle Board activities over a defined period of time. The report is archival in nature and does not break new ground. Rather, it documents Board activities, findings, and recommendations for the reporting period. The five years covered by the Report were consequential for the Board and for the U.S. program to manage and dispose of spent nuclear fuel and high-level radioactive waste.

Review of U.S. Department of Energy Activities to Preserve Records Created by the Yucca Mountain Repository Project
August 2013.

> The report chronicles the Board's review of U.S. Department of Energy (DOE) efforts to preserve records developed over almost 30 years by the Yucca Mountain Repository Project. In 2010, funding for the repository program was eliminated, and DOE notified the Nuclear Regulatory Commission of the Department's intention to withdraw the Yucca Mountain license application. At that point, responsibility for archiving and preserving Yucca Mountain scientific and engineering information was transferred to DOE's Office of Legacy Management. The Board began evaluating DOE activities related to archiving and preserving Yucca Mountain data and information in 2010 as part of its ongoing technical and scientific review and in response to direction from the House Committee on Appropriations.

Nuclear Waste Assessment System for Technical Evaluation (NUWASTE): Status and Initial Results
June 2011.

> The report describes work performed by the Board to evaluate the effects of spent nuclear fuel and high-level radioactive waste management on various fuel-cycle options being considered at that time by the U.S. Department of Energy (DOE). Of particular interest to the Board were the types and quantities of radioactive waste streams that would be generated. The Board developed a computer-based systems analysis tool, the Nuclear Waste Assessment System for Technical Evaluation, or NUWASTE, to support its technical evaluation of DOE activities in this area. Included in the report are initial findings from NUWASTE analyses.

Technical Advancements and Issues Associated with the Permanent Disposal of High-Activity Wastes: Lessons Learned from Yucca Mountain and Other Programs
June 2011.

> The purpose of this report was to extract and record technical and scientific knowledge, while still available, from the Yucca Mountain deep geologic repository program and programs in other countries for managing spent nuclear fuel (SNF) and high-level radioactive waste (HLW). In this report, the Board examined the history of the Yucca Mountain program and several other nuclear waste programs from a technical perspective and discussed technical information and insights that may be useful for future U.S. efforts to manage and dispose of SNF and HLW.

Experience Gained from Programs to Manage High-Level Radioactive Waste and Spent Nuclear Fuel in the United States and Other Countries
April 2011.

> This report explores the efforts of 13 nations to find a permanent solution for isolating high-level radioactive waste and spent nuclear fuel generated within their borders. It builds on information in the Board's 2009 *Survey of National Programs*

for Managing High-Level Radioactive Waste and Spent Nuclear Fuel. Unlike the earlier document, however, this report describes the programs and their histories and discusses inferences that can be drawn from their experiences.

Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel – Executive Summary
December 2010.

The report was prepared to inform the U.S. Department of Energy and Congress about the current state of the technical basis for extended dry storage of spent nuclear fuel (SNF) and for subsequent SNF transportation.

Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel
December 2010.

The report presents an overview of available public literature on spent nuclear fuel (SNF) storage and handling, and the safety of extended SNF dry storage and subsequent transportation.

Survey of National Programs for Managing High-Level Radioactive Waste and Spent Nuclear Fuel
October 2009.

The report describes 30 technical and institutional attributes of nuclear waste programs in
13 countries. It does not make judgements; rather the report provides factual information for Congress and the Secretary of Energy that can be used for evaluating waste management options.

Letter Report to Congress and the Secretary of Energy
October 27, 2009.

This report in letter form updates Congress and the Secretary of Energy on the mission, continuing role, and refocused goals of the U.S. Nuclear Waste Technical Review Board as the U.S. approach to managing spent nuclear fuel and high-level radioactive undergoes an evolution.

Report to Congress and the Secretary of Energy
September 2008.

The report is one in a series of "summary" reports issued periodically since the beginning of Board operations in 1989 that chronicle the Board's activities over a defined period of time. This report focused on Board activities from March 1, 2006, to December 31, 2007. During that time, the Board evaluated critical technical issues dealing with the waste management system, including pre-closure operations and post-closure performance of the proposed Yucca Mountain repository, and the crosscutting issue of thermal management.

Technical Evaluation of U.S. Department of Energy Yucca Mountain Infiltration Estimates: A Report to Congress and the Secretary of Energy
December 2007.

> In this report, the Board presents its evaluation of revised U.S. Department of Energy estimates of water infiltration at Yucca Mountain. The infiltration estimates were revised because violations of quality assurance procedures were alleged to have been committed by U.S. Geological Survey employees involved in gathering and analyzing infiltration data at Yucca Mountain in the 1990s.

Report to Congress and the Secretary of Energy
January 2007.

> This report contains summaries of Board findings and recommendations contained in the following: letters to the Director of the Office of Civilian Radioactive Waste Management (OCRWM) following Board meetings held in February, May, and September 2006; a letter and enclosures sent to OCRWM following a Board workshop on deliquescence-induced localized corrosion in September 2006; and testimony the Board's Chairman presented in May 2006 before the Senate Energy and Natural Resources Committee.

Report to Congress and the Secretary of Energy
June 2006.

> In this report, the Board summarizes its major activities from January 1, 2005, through February 28, 2006. During that period, the Board focused its attention on the U.S. Department of Energy's efforts to develop post-closure performance estimates for the proposed repository at Yucca Mountain in Nevada. Correspondence and related materials are included in the appendices to the report, along with the Board's strategic plan for fiscal years 2004–2009, its performance plans for fiscal years 2005–2006, and its performance evaluation for 2005.

Letter Report to Congress and the Secretary of Energy
December 2005.

> In this letter report to Congress and the Secretary of Energy, the Board presents its views on the status of some important issues related to the technical basis for U.S. Department of Energy activities for designing the nuclear waste management system, including the engineered system, the natural system, the repository system, and the assessment of the performance of the systems. The Board also outlines issues that it expects may continue to be of interest in the future.

Report to Congress and the Secretary of Energy
May 2005.

> In this report, the Board summarizes its major activities from January 1, 2004, through December 31, 2004. During that period, the Board focused on the Department of Energy's efforts to develop a system for accepting, transporting, and

handling high-level radioactive waste and spent nuclear fuel before disposal in the repository proposed for Yucca Mountain. Correspondence and related materials are included in the appendices to the report, along with the Board's strategic plan for fiscal years 2004–2009, its performance plans for 2005, and its performance evaluation for 2004.

Letter Report to Congress and the Secretary of Energy
December 2004.

This letter and enclosure comprise the Board's second report to Congress and the Secretary of Energy for calendar year 2004. The letter briefly summarizes areas where the Board believes the U.S. Department of Energy made progress, areas requiring attention, and the Board's priorities for the coming year. The enclosure contains a more detailed discussion of those topics.

Report to Congress and the Secretary of Energy
May 2004.

In this report, the Board summarizes its major activities from January 1, 2003, through December 31, 2003. During that period, the Board continued its evaluation of U.S. Department of Energy (DOE) activities and held meetings on a range of technical and scientific issues, including seismicity, DOE plans for transporting spent nuclear fuel and high-level radioactive waste, the design and operation of facilities at the Yucca Mountain proposed repository site, performance confirmation activities, and the potential for localized corrosion. Correspondence and related materials are included in the appendices to the report, along with the Board's strategic plan for fiscal years 2004–2009, its performance plans for 2004 and 2005, and its performance evaluation for 2003.

Report to Congress and the Secretary of Energy
December 19, 2003.

This report and attachments constitute the Board's second report to Congress and the Secretary of Energy for calendar year 2003. It is composed of letters on localized corrosion sent to the Director of the Office of Civilian Radioactive Waste Management on October 21, 2003, and November 25, 2003.

Board Technical Report on Localized Corrosion
November 25, 2003.

This technical document supports Board conclusions in its October 21, 2003, letter to the U.S. Department of Energy on the potential for localized waste package corrosion during the thermal pulse.

Report to the Secretary of Energy and the Congress
April 2003.

This report summarizes the Board's major activities between January 1, 2002, and December 31, 2002. During this period, the Board focused on evaluating the technical basis of the U.S. Department of Energy's (DOE) work on analyzing a planned repository site at Yucca Mountain in Nevada. Included in an appendix to the report are letters to DOE on technical issues the Board identified as part of its ongoing review in 2002. Also included in the appendices are the Board's strategic plan for fiscal years 2003–2008, its performance plans for 2003 and 2004, and its performance evaluation for 2002.

Report to the Secretary of Energy and the Congress
April 2002.

This report summarizes the Board's major activities between February 1, 2001, and January 31, 2002. During this period, the Board focused on evaluating the technical basis of the U.S. Department of Energy's (DOE) work on a Yucca Mountain site recommendation, including DOE's characterization of the Yucca Mountain site, DOE's design of the repository and waste packages, and the estimates of how a repository system developed at the site might perform. The report includes a description of activities the Board undertook to develop its assessment of the technical basis for the DOE's repository performance estimates.

Letter Report to Congress and the Secretary of Energy
January 24, 2002.

This Letter Report summarizes the Board's technical and scientific evaluation of the U.S. Department of Energy's investigations and assessments supporting its recommendation of the Yucca Mountain site as a potential location for a deep geologic repository for spent nuclear fuel and high-level radioactive waste.

Proceedings from an International Workshop on Long-Term Extrapolation of Passive Behavior, Arlington, Virginia, July 19-20, 2001
December 2001.

This is a compilation of submissions to a Board workshop on issues predicting corrosion behavior for periods of unprecedented duration. The workshop was held on July 19–20, 2001, in Arlington, Virginia. A panel of three Board members and 14 internationally recognized corrosion scientists, eight of whom were from outside the United States, participated in the workshop. Following the workshop, most panelists submitted papers with their views on issues on predicting very long-term corrosion.

Report to the Secretary of Energy and the Congress
April 2001.

In this report, the Board summarizes its views on four priority areas for evaluating the potential repository at Yucca Mountain:

- Meaningful quantification of conservatisms and uncertainties in the U.S. Department of Energy's performance assessments.

- Progress in understanding the underlying fundamental processes involved in predicting the rate of waste-package corrosion.

- An evaluation and a comparison of the base-case repository design with a low-temperature design.

- Development of multiple lines of evidence to support the safety case of the proposed repository, the lines of evidence being derived independently of performance assessment and thus not being subject to the limitations of performance assessment.

Letter Report to the Secretary of Energy and the Congress
December 2000.

This Letter Report presents a brief update of the Board's views on the status of the U.S. Department of Energy's repository development program.

Report to the U.S. Congress and the Secretary of Energy
April 2000.

In this report, the Board summarizes its major activities in calendar year 1999. Among the activities discussed in the report is the Board's 1999 review of the U.S. Department of Energy's (DOE) viability assessment (VA) of the Yucca Mountain site. The Board's evaluation of the DOE-VA concludes that Yucca Mountain continues to warrant study as the candidate site for a permanent geologic repository and that work should proceed to support a decision on whether to recommend the site for repository development. The Board suggests that the 2001 date for a decision is very ambitious and that focused study should continue on natural and engineered barriers. The Board states that a credible technical basis does not currently exist for the above-boiling repository design included in the VA. The Board recommends evaluation of alternative repository designs, including lower-temperature designs, as a potential way to help reduce the significance of uncertainties related to predictions of repository performance.

Report to the U.S. Congress and the Secretary of Energy
April 1999.

In this report, the Board summarizes its major activities during calendar year 1998. The report discusses the research needs identified in the U.S. Department of Energy's (DOE) recently issued Viability Assessment of the Yucca Mountain site, including plans to gather information on the amount of water that will eventually seep into repository drifts, whether formations under the repository will retard radionuclide migration, the flow-and-transport properties of the groundwater that lies approximately 200 meters beneath the repository horizon, and long-term corrosion rates of materials that may be used for the waste packages. The report describes other activities the Board undertook in 1998, including a review of the hypothesis that there were hydrothermal upwellings at Yucca Mountain, a workshop held to increase understanding of the range of expert opinion on waste package materials, and a review of the DOE's draft environmental impact statement for the Yucca Mountain site.

Report to the U.S. Congress and the Secretary of Energy: Moving Beyond the Viability Assessment
April 1999.

In this report, the Board presents its views on the U.S. Department of Energy's (DOE) December 1998 Viability-Assessment of the Yucca Mountain site in Nevada. The Yucca Mountain site is being characterized to determine its suitability as the location of a permanent repository for disposing of spent nuclear fuel and high-level radioactive waste. The Board discusses the need to address key uncertainties that remain about the site, including the performance of the engineered and natural barriers. The Board addresses DOE's plans for reducing those uncertainties and suggests that consideration be given to alternative repository designs, including ventilated low-temperature designs that have the potential to reduce uncertainties and simplify the analytical bases for determining site suitably and for licensing. The Board also comments on DOE's total system performance assessment, the analytical tool that pulls together information on the performance of the repository system.

Report to the U.S. Congress and the Secretary of Energy
November 1998.

In this report, the Board presents its views on the direction of future scientific and technical research underway and planned by the U.S. Department of Energy as part of its program for characterizing a site at Yucca Mountain in Nevada as a potential repository for spent nuclear fuel and high-level radioactive waste. The Board discusses some of the remaining key scientific and technical uncertainties related to performance of a potential repository. The report addresses some of these uncertainties by examining information about the proposed repository system presented at Board meetings and other technical exchanges. The Board comments on some of the important connections between the site's natural properties and the current designs for the waste package and other engineered features of the repository.

Letter Report: Board Completes Review of Material on Hydrothermal Activity
July 24, 1998.

This letter and attachments present the Board's review of material related to Mr. Jerry Szymanski's hypothesis of ongoing, intermittent hydrothermal activity at Yucca Mountain and large earthquake-induced changes in the water table there. The report includes a cover letter, the Board's review, and the reports of the four consultants the Board contracted with to assist in the review.

1997 Findings and Recommendations
April 1998.

This report details the Board's technical and scientific evaluation in 1997 of U.S. Department of Energy (DOE) activities, including the development of DOE's viability assessment, due later this year; underground exploration of the candidate repository site at Yucca Mountain in Nevada; thermal testing underway at the site; what happens when radioactive waste reaches the water table beneath Yucca Mountain; spent nuclear fuel transportation; and using expert judgment. The Board makes four recommendations in the report concerning (1) the need for DOE to begin now to develop alternative design concepts for a repository, (2) the need for DOE to include estimates of the likely variation in doses for alternative candidate critical groups in its interim performance measure for Yucca Mountain, (3) the need for DOE to evaluate whether site-specific biosphere data is needed for a license application, and (4) the need for DOE to make full and effective use of formally elicited expert judgment.

Letter Report to the Secretary of Energy and the Congress
December 23, 1997.

This letter report addresses several key issues, including the U.S. Department of Energy's viability assessment of the Yucca Mountain site, design of the potential repository and waste package, the total system performance assessment, and the enhanced characterization of the repository block.

Report to the U.S. Congress and The Secretary of Energy: 1996 Findings and Recommendations
March 1997.

This report summarizes Board activities during calendar year 1996. Chapter 1 provides an overview of the U.S. Department of Energy's (DOE) high-level radioactive waste management program from the Board's perspective, including the viability assessment, program status, and progress in exploration and testing. Chapter 2 examines three technical issues—hydrology, radionuclide transport, and performance assessment, and provides conclusions and recommendations. Chapter 3 deals with the repository system, including underground operations, thermal loading, and engineered barriers. Also discussed are the repository layout, design alternatives, and construction planning. Chapter 4 provides an overview of recent Board activities, including an international exchange of information on repository programs, the Board's visit to the River Mountains tunnel, and a presentation to the Nuclear Regulatory Commission.

Nuclear Waste Management in the United States – The Board's Perspective
June 1996.

This document contains a talk by Board Chairman John Cantlon delivered at Topseal '96, an international conference on nuclear waste management and disposal. The conference was sponsored by the Swedish Nuclear Fuel and Waste Management Company (SKB) and the European Nuclear Society. The publication highlights Dr. Cantlon's views on the status of the U.S. repository program, including U.S. Department of Energy efforts to characterize the Yucca Mountain site and to develop a waste isolation strategy. The publication also describes legislative and regulatory changes under consideration at that time and the technical implications of those potential changes.

Report to the U.S. Congress and the Secretary of Energy: 1995 Findings and Recommendations
April 1996.

This report summarizes Board activities during calendar year 1995. Chapter 1 provides an overview of the U.S. Department of Energy's high-level radioactive waste management program, including highlights, current status, legislative issues, milestones, and Board recommendations. Chapter 2 reports on Board panel activities, and Chapter 3 provides information on new Board members, meetings attended, interactions with Congress and congressional staff, Board presentations to other organizations, interactions with foreign programs, and a review of the Board's report on spent nuclear fuel interim storage.

Disposal and Storage of Spent Nuclear Fuel – Finding the Right Balance
March 1996.

This special report caps more than two years of study and analysis by the Board into the issues surrounding interim storage of commercial spent nuclear fuel and the timing of developing a federal centralized storage facility. The Board suggests in the report that the U.S. Department of Energy should remain focused on permanent geologic disposal and the site investigations at Yucca Mountain in Nevada. Planning for a federal centralized spent nuclear fuel storage facility and the required transportation infrastructure should begin early, but actual construction of a facility should be delayed until after a site-suitability decision is made on the Yucca Mountain site.

Letter Report to the Secretary of Energy and the Congress
December 13, 1995.

This letter report discusses the U.S. Department of Energy's (DOE) progress in exploring the underground at Yucca Mountain with a tunnel boring machine, advances in developing a waste isolation strategy for the proposed repository, recent DOE work on engineered barrier design, and DOE activities related to repository performance assessment.

Report to the U.S. Congress and the Secretary of Energy: 1994 Findings and Recommendations
March 1995.

This report summarizes Board activities during calendar year 1994. It covers aspects of the U.S. Department of Energy's (DOE) Program Approach, the DOE's emerging waste isolation strategy, and the DOE's transportation program. It explores the Board's views on minimum exploratory requirements and thermal-loading issues for the repository. A chapter of the report focuses on the lessons learned on site assessment from high-level radioactive waste disposal projects around the world. Another chapter deals with volcanism and problem resolution. The Board also presents observations from its visit to Japan and the Japanese nuclear waste disposal program. Board findings and recommendations in the report center on structural geology and geoengineering, hydrogeology and geochemistry, the engineered barrier system, and risk and performance analysis.

Report to the U.S. Congress and the Secretary of Energy: January to December 1993
May 1994.

The report summarizes Board activities, primarily during 1993. In it, the Board reports on nuclear waste disposal programs in Belgium, France, and the United Kingdom; elaborates on the Board's understanding of the radiation protection standards being reviewed by the National Academy of Sciences; and, using "future climates" as an example, examines the U.S. Department of Energy's (DOE) approach to "resolving difficult issues." Recommendations center on the need for a systems approach in implementing DOE Office of Radioactive Waste Management programs, setting priorities among site-suitability activities, appropriate use of total system performance assessment and expert judgment, and the dynamics of the Yucca Mountain ecosystem.

Letter Report to Congress and the Secretary of Energy
February 1994.

The letter report restates a recommendation made in the Board's 1993 *Special Report* that an independent review of the Office of Civilian Radioactive Waste Management's management and organizational structure be initiated as soon as possible. The letter report adds two recommendations: sufficient and reliable funding should be assured for site characterization and performance assessment, whether the program budget remains level or is increased, and the U.S. Department of Energy's decision-making process on siting a Yucca Mountain repository should take into account the views of various stakeholders.

Underground Exploration and Testing at Yucca Mountain, A Report to Congress and the Secretary of Energy
October 1993.

This report focuses on the exploratory studies facility at Yucca Mountain in Nevada, including the conceptual design, planned exploration and testing, and excavation plans and schedules. In addition to a number of detailed recommendations, the Board makes three general recommendations. First, the Department of Energy (DOE) should develop a comprehensive strategy that integrates exploration and testing priorities with the design and excavation approach for the exploratory facility. Second, underground thermal testing should be resumed as soon as possible. Third, DOE should establish a geoengineering board with expertise in engineering, constructing, and managing large underground projects.

Special Report to Congress and the Secretary of Energy
March 1993.

This report discusses institutional and policy issues that potentially affect the technical and scientific credibility of the U.S. Department of Energy's (DOE) repository program. Three important issues are presented: first, the repository program is driven by unrealistic deadlines; second, the repository program lacks an integrated waste management plan; and third, program management needs to be improved. To address these issues, the Board makes the following recommendations: amend the current schedule to include realistic intermediate milestones; develop a comprehensive, well-integrated plan for overall management of all spent nuclear fuel and high-level defense waste from generation to disposal; and implement an independent evaluation of the organization and management of DOE's Office of Civilian Radioactive Waste Management. The Board notes that the recommendations should be implemented without slowing the progress of site-characterization activities at Yucca Mountain.

Sixth Report to the U.S. Congress and the U.S. Secretary of Energy
December 1992.

The report summarizes recent Board activities, congressional testimony, changes in Board makeup, and the effects of the Little Skull Mountain earthquake. Chapter 2 details panel activities and offers seven technical recommendations on the dangers of a schedule-driven program, including the need for top-level systems studies; consideration of the impact of defense high-level radioactive waste; the use of high capacity, self-shielded waste package designs; and the need for setting priorities among the numerous studies in the site-characterization plans. In Chapter 3, the Board offers candid insights to the high-level waste management program in five countries, specifically those issues that might be applicable to the U.S. program, including program size and cost, utility responsibilities, repository construction schedules, and alternative approaches to licensing. Appendix F provides background on the Finnish and Swiss programs.

Fifth Report to the U.S. Congress and the U.S. Secretary of Energy
June 1992.

The Board's fifth report focuses on thermal loading strategies in the United States and the importance and uncertainties of this crosscutting issue. The report discusses the Board's position on the technical implications of thermal loading for the U.S. spent nuclear fuel (SNF) and high-level radioactive waste (HLW) management system. The report also includes updates on Board and panel activities during the reporting period. The Board makes recommendations in the report to the U.S. Department of Energy (DOE) on the following subjects: the exploratory studies facility, repository design enhancements, repository sealing, seismic vulnerabilities (vibratory ground motion and fault displacement), DOE's approach to the engineered barrier system, and SNF and HLW transportation.

Fourth Report to the U.S. Congress and the U.S. Secretary of Energy
December 1991.

The report explores in depth and makes recommendations on the following technical areas: exploratory studies facility construction; testing priorities; rock mechanics; tectonic features and processes; volcanism; hydrogeology and geochemistry in the unsaturated zone; the engineered barrier system; regulations promulgated by the U.S. Environmental Protection Agency, the U.S. Nuclear Regulatory Commission, and the U.S. Department of Energy (DOE); the DOE performance assessment program; and the quality assurance program for the Yucca Mountain project.

Third Report to the U.S. Congress and the U.S. Secretary of Energy
May 1991.

The report describes Board activities and congressional testimony. Other topics include exploratory shaft facility design alternatives; repository design; risk-benefit analysis; waste package plans and funding; spent nuclear fuel corrosion; transportation and waste management systems; environmental program concerns; U.S. Department of Energy (DOE) task force studies on risk and performance assessment; federal quality assurance requirements for the repository program; and measuring, modeling, and applying radionuclide sorption data. The Board makes fifteen recommendations to DOE on these issues. Background information on the German and Swedish nuclear waste disposal programs is included in Appendix D of the report.

Second Report to the U.S. Congress and the U.S. Secretary of Energy
November 1990.

The Board's second report establishes a framework for discussing repository development and makes specific technical and scientific recommendations concerning tectonic features and processes, geoengineering considerations, the engineered barrier system, transportation and systems, environmental and public health issues, and risk and performance analysis. The report also offers concluding perspectives on progress made by the U.S. Department of Energy, the state of Nevada's role, the project's regulatory framework, the nuclear waste negotiator, other oversight agencies, and the Board's future plans.

First Report to the U.S. Congress and the U.S. Secretary of Energy
March 1990.

The first Board report sets the stage for the Board's evaluation of the U.S. Department of Energy's program to manage disposal of the nation's spent nuclear fuel (SNF) and high-level radioactive waste (HLW). The report briefly outlines the legislative history of the SNF and HLW management program, including its legal and regulatory requirements. The Board's evolution is described, along with its protocol, panel structure, and reporting requirements. The report identifies major technical and scientific issues the Board identified for further evaluation and highlights five cross-cutting issues.

Appendix D
Board Meetings: January 1, 2019 – December 31, 2021

Board Meetings: January 1, 2019 – December 31, 2021

April 24–25, 2019	**Spring 2019 Workshop** San Francisco, CA Recent Advances in Repository Science and Operations from International Underground Research Laboratory Collaborations
November 19, 2019	**Fall 2019 Board Meeting** Alexandria, VA DOE R&D Related to Packaging, Drying, and Dry Storage of Spent Nuclear Fuel
July 27–28, 2020	**Summer 2020 Board Virtual Meeting** DOE R&D Related to Disposal in Geologic Repository of Commercial Spent Nuclear Fuel in Dual-Purpose Canisters
December 2–3, 2020	**Fall 2020 Board Virtual Meeting** DOE Generic Disposal R&D Program and Priorities
May 12–13, 2021	**Spring 2021 Board Virtual Meeting** Advanced Nuclear Fuels and Accident Tolerant Fuels for Light Water Reactors and the Impact on Spent Nuclear Fuel Management and Disposal
August 24, 2021	**Summer 2021 Board Virtual Meeting** DOE Technology Development Related to Aluminum-Clad Spent Nuclear Fuel Packaging, Drying, and Dry Storage
November 3–4, 2021	**Fall 2021 Board Virtual Meeting** DOE R&D Activities Related to Geologic Disposal Safety Assessment Framework

Appendix E
Correspondence with the U.S. Department of Energy January 1, 2019 – December 31, 2021[16]

[16] For completeness, the following 2022 letters are in included in the appendix: the Board's January 2022 follow-up letter subsequent to the December 2021 Board meeting; DOE's April 2022 response to the Board's August 12, 2021, follow-up letter subsequent to the May 2021 Board meeting; and finally, DOE's June 2022 response to the Board's April 2021 report, *Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward*.

Correspondence with the U.S. Department of Energy January 1, 2019 – December 31, 2021

Letter from Chair Jean M. Bahr to Dr. Rita Baranwal, Assistant Secretary for Nuclear Energy, and Mr. William White, Senior Advisor for Environmental Management to the Under Secretary for Science; January 10, 2020.
Subject: Board comments on information presented at the November 2019 Board meeting.

Letter from Chair Jean M. Bahr to Mr. William White, Senior Advisor for Environmental Management to the Under Secretary for Science; January 10, 2020
Subject: Board request for more interaction between DOE Office of Environmental Management and the Board

Letter from Chair Jean M. Bahr to Dr. Rita Baranwal, Assistant Secretary for Nuclear Energy; January 11, 2021
Subject: Board comments on information presented at the July 2020 Board meeting.

Letter from Chair Jean M. Bahr to Jennifer Granholm, Secretary for Nuclear Energy; April 8, 2021
Subject: Board request for a meeting to discuss the Board's report on Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward

Letter from Chair Jean M. Bahr to Dr. Kathryn Huff, Assistant Secretary for Nuclear Energy; July 22, 2021
Subject: Board briefing on Board's role and Board's report on Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward

Letter from Chair Jean M. Bahr to Dr. Kathryn Huff, Assistant Secretary for Nuclear Energy; August 12, 2021
Subject: Board comments on information presented at the May 2021 Board meeting.

Letter from Chair Jean M. Bahr to Mr. William White, Senior Advisor for Environmental Management to the Under Secretary for Science; October 14, 2021
Subject: Board comments on information presented at the August 2021 Board meeting

Letter from Chair Jean M. Bahr to Dr. Kathryn Huff, Assistant Secretary for Nuclear Energy; December 30, 2021
Subject: Board comments on information presented at the December 2020 Board meeting.

Letter from Mr. William White, Senior Advisor for Environmental Management to the Under Secretary for Science; November 24, 2021
Subject: DOE response to October 14, 2021, Board letter.

Letter from Chair Jean M. Bahr to Dr. Kathryn Huff, Assistant Secretary for Nuclear Energy; January 7, 2022
Subject: Board comments on information presented at the November 2021 Board meeting.

Letter from Mr. Andrew Griffith, Acting Assistant Secretary for Nuclear Energy to Chair Jean M. Bahr; April 7, 2022
Subject: DOE response to August 12, 2021, Board letter.

Letter from Dr. Kathryn Huff, Assistant Secretary for Nuclear Energy, to Chair Jean M. Bahr; June 8, 2022
Subject: DOE response to April 2021 report on Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward.

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

January 10, 2020

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

Mr. William White
Senior Advisor for Environmental Management
to the Under Secretary for Science
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Dr. Baranwal and Mr. White:

On behalf of the U.S. Nuclear Waste Technical Review Board (Board), I want to thank you and your staff for supporting the Fall 2019 Board Meeting, which was held on November 19, 2019, in Alexandria, Virginia. The purpose of the meeting was to review research and development activities being sponsored by the Department of Energy (DOE) related to the dry-storage of commercial spent nuclear fuel (SNF) and DOE-managed SNF. The agenda and presentation materials for the meeting, as well as the meeting transcript and an archived version of the meeting webcast, are posted on the Board's website at: https://www.nwtrb.gov/meetings/past-meetings/fall-2019-board-meeting---november-19-2019.

Congress created the Board in the 1987 Nuclear Waste Policy Amendments Act (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 and to advise Congress and the Secretary on technical issues related to nuclear waste management. DOE activities to manage SNF, including packaging, drying, storing, and planning for transportation and disposal, have long been topics of Board review.

In recent years, relevant Board activities have included a 2014 public meeting on DOE plans for the packaging, transportation, and disposal of DOE-managed SNF and high-level radioactive waste (HLW). That public meeting provided information that formed a basis for the Board's 2017 report, *Management and Disposal of U.S. Department of Energy Spent Nuclear Fuel*. In the summer of 2018, the Board visited the Idaho National Laboratory (INL) and received briefings on a new research effort to study corrosion mechanisms affecting aluminum-clad SNF during drying and long-term dry storage. This research effort is one of the topics discussed at the Fall 2019 Board Meeting.

At its Fall 2019 meeting, the Board received opening presentations from senior managers in the DOE Office of Nuclear Energy (DOE-NE). The Board then heard from Pacific Northwest National Laboratory and Sandia National Laboratories researchers who are conducting thermal analyses of SNF dry cask storage systems, INL representatives who are working on programs related to the management of DOE SNF (with a focus on aluminum-clad SNF), and a representative of Sellafield, Ltd., in the United Kingdom (UK), where research is being conducted on the drying of UK SNF. More information about these presentations and the Board's observations and recommendations are noted in the enclosure to this letter.

A number of specific recommendations are made in the enclosure. Summaries of those specific recommendations are provided below.

Recommendation 1. The Board recommends that DOE give higher priority to evaluating how advanced nuclear fuels and accident tolerant fuels may impact later operations, including SNF packaging, transportation, and disposal in a geologic repository.

Recommendation 2. The Board recommends that DOE-NE pursue an increased understanding of the effect of moisture on SNF in dry storage, and continue its efforts to identify alternative methods of obtaining moisture measurements from inside SNF dry cask storage systems used by the nuclear industry and undertake similar efforts for the DOE Standard Canister.

Recommendation 3. The Board recommends that greater emphasis be placed on validating computer models before applying them to particular dry cask storage systems.

Recommendation 4. As DOE continues to develop and use computer models to predict SNF dry cask storage system parameters, the Board recommends that DOE ensure all assumptions and uncertainties be properly identified and accounted for, computer models be validated against data from real-world systems, fuel performance models be integrated within the multiphysics models, and enhanced coordination be achieved between model developers and experimentalists.

Recommendation 5. Regarding the DOE Standard Canister, the Board recommends that DOE engage early with the Nuclear Regulatory Commission (NRC) to ensure that the DOE Standard Canister project team is aware of all applicable regulatory requirements, including requirements for criticality safety and limiting hydrogen concentrations, and develop a firm path forward and schedule for completing development of the DOE Standard Canister and obtaining the necessary NRC approvals.

In addition to these recommendations, the Board makes the following observations.

1. *The Board observes that by continuing the High Burnup Demonstration Project (HDRP), even in light of less than ideal circumstances, and by exploring new solutions to project*

challenges, DOE-NE and the project team have obtained valuable results. For example, data collected on SNF temperatures have been used to improve SNF cask thermal-hydraulic modeling. The Board understands that the HDRP research team received the Secretary of Energy's Achievement Award for their work on this project and the Board congratulates the team for earning this award.

2. *The Board consistently observes that there are lessons to be learned from other countries that are not obvious unless one engages in some meaningful manner with researchers in these countries. At the Fall 2019 meeting, an example from the UK of a lesson to be learned was setting up an organizational structure with which to respond to challenges, as Sellafield Ltd. did in establishing an Innovation Team. This team is working on the concept of a Smart Package—an instrumented radioactive waste storage package that would include real-time monitoring of the conditions inside the package.*

The Board notes that the information on aluminum-clad DOE SNF presented at the Fall 2019 meeting was limited and provided insufficient opportunity for the Board to pursue areas of technical inquiry it wanted to pursue. Since the work is important and relevant to future DOE activities to package, dry, store, transport, and dispose of DOE-managed aluminum-clad SNF, the Board would like to have the opportunity to interact more directly with representatives of the DOE Office of Environmental Management (DOE-EM) and the research team being coordinated by Dr. Connolly. The Board will contact DOE-EM through separate correspondence to request additional interactions.

The Board would like to thank you again for the support of staff members within DOE-NE and DOE-EM during the planning and preparation of the Fall 2019 Board Meeting. The presentations and interactions during these meetings provide valuable information for the Board as it carries out its mission to review and evaluate DOE activities related to the management of SNF and HLW. We look forward to future productive interactions with you and your staff.

Sincerely,

{Signed by}

Jean M. Bahr
Chair

Enclosure

cc: Dr. William Boyle, DOE Office of Nuclear Energy
Ms. Betsy Connell, DOE Office of Environmental Management

Enclosure

Fall 2019 Board Meeting Summary, Observations, and Recommendations

This enclosure summarizes the contents of the presentations made at the Fall 2019 Board Meeting. Also presented are the Board's observations and recommendations that arise from the Fall 2019 meeting presentations and discussions, and from previously-reviewed written materials.

Department of Energy Office of Nuclear Energy (DOE-NE) Research and Development (R&D) Related to Advanced Fuels and Accident Tolerant Fuels. Dr. William Boyle, Acting Deputy Assistant Secretary for Spent Fuel and Waste Disposition in DOE-NE, provided opening remarks about the R&D efforts of his office, potential funding levels for the R&D work, and focus areas for future research. The Board is encouraged by the continued focus of Dr. Boyle and his office on the management of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) and their continuing support of important research that will allow the Department to better understand these waste streams.

Following his presentation, the Board asked Dr. Boyle about what planning is being done now to assess the potential impacts of new nuclear fuel designs, including accident tolerant fuels, on the back end of the fuel cycle, especially disposal in a geologic repository. Dr. Boyle expressed a position that new fuel designs being tested now in commercial power reactors are not substantially different from existing fuel designs, so there are no expected impacts on the back end of the fuel cycle. He also stated that the development and implementation of new fuel designs are initiatives of the private nuclear industry and are largely outside the scope of the activities of his office. Nonetheless, the Board pointed out that some of the newly proposed fuels include materials that are considerably different from those used in contemporary U.S. nuclear fuels. Examples of these materials are chromium coatings on zircaloy, uranium-silicide fuel material, and silicon-carbide cladding. The number and variety of these new materials raise questions about possible unintended consequences of their use, including their behavior after disposal in a geologic repository.

Recommendation 1. The Board recommends that DOE give higher priority to evaluating how advanced nuclear fuels and accident tolerant fuels may impact later operations, including SNF packaging, transportation, and disposal in a geologic repository.

High Burnup Demonstration Project (HDRP).[1] Mr. Ned Larson, DOE-NE, presented an overview of the R&D work sponsored by DOE-NE to understand the characteristics of, and the forces impacting the behavior of, high burnup[2] SNF during extended storage and transportation.

[1] The HDRP is also known by the names "High Burnup Dry Storage Cask Research and Development Project" and "High Burnup Data Project."

[2] Fuel burnup is a measure of the thermal energy generated in a nuclear reactor per unit of initial mass of nuclear fuel and is typically expressed in units of gigawatt-days per metric ton of uranium (GWd/MTU). In the United

One of the largest projects in this effort is the HDRP, in which 32 high burnup SNF assemblies were loaded into a Transnuclear (TN; now part of Orano) TN-32 cask, dried, and stored on the SNF dry-storage pad at the North Anna Nuclear Generation Station. The HDRP test plan calls for the cask to be transported, after storage for a period up to 10 years or possibly longer, to a facility that can open the cask and remove selected fuel rods. These rods would then undergo non-destructive and destructive examinations to compare their characteristics and performance to those of the HDRP sister rods[3] to determine the combined effects of drying, aging, and transportation. An important component of the project is the use of computer models to predict temperatures inside the HDRP cask, followed by a comparison of those predictions against temperatures measured inside the cask. Being able to predict the temperature of SNF is important since it influences the subsequent properties of the cladding relevant to storage, transportation, and disposal. Thermal modeling efforts are discussed in more detail in the next section. Mr. Larson summarized work completed to date on the HDRP and described two project challenges as noted below.

Mr. Larson stated that, during the course of the project, the HDRP research team encountered a number of unexpected events but made adjustments, as needed. In one example, the team found, through thermal model predictions, that the temperatures inside the HDRP cask would not be high enough to induce the kind of changes in the fuel cladding properties they wished to study (i.e., hydride reorientation in the fuel cladding). The team adjusted by heating some HDRP sister rods to 400°C using a furnace in a hot cell to try to induce hydride reorientation in the cladding so that the effects of hydride reorientation on cladding properties could be studied further. The results of this effort are not yet available but will be made known when the sister rod metallographic examinations are completed.

A second project challenge involved sampling the HDRP cask for moisture content. The research team had hoped to obtain gas samples from the HDRP cask after drying, in order to gain valuable information about cladding integrity and moisture levels remaining in the cask after drying. However, equipment and analysis problems prevented the team from obtaining reliable measurements of moisture concentrations. Mr. Larson stated that the research team is considering the options available for obtaining additional moisture samples from SNF storage casks. One option would be to move the HDRP cask to the CPP-603 facility at the Idaho National Laboratory (INL) before the end of the planned 10-year dry-storage period, in order to allow taking additional periodic gas samples.[4] Mr. Larson stated that a second option would be to work with the commercial nuclear industry to identify a to-be-loaded SNF cask from which gas samples could be obtained while the cask is still inside a radiologically-controlled facility. A decision about the preferred option had not been made at the time of the Board meeting.

States, nuclear fuel utilized beyond 45 GWd/MTU is defined by the Nuclear Regulatory Commission as high burnup SNF.

[3] Sister rods are high burnup SNF rods removed from SNF assemblies that are included in the HDRP cask or removed from SNF assemblies of the same type and operating history as SNF assemblies in the HDRP cask. The sister rods are being examined to determine their condition before drying, aging, and transportation.

[4] The Board recognizes that the terms of the Idaho Settlement Agreement may impact DOE's ability to transport SNF to the state of Idaho.

Obtaining moisture measurements from inside an SNF storage cask was a goal of the HDRP. The resulting data would help fill a knowledge gap related to the amount of moisture remaining in an SNF cask after drying and how that moisture may affect the condition of the SNF over time. In its November 2018 letter to DOE-NE,[5] the Board encouraged DOE to pursue alternatives for obtaining moisture measurements.

Recommendation 2. Consistent with its previous communication, the Board recommends that DOE-NE continue its efforts to identify alternative methods of obtaining moisture measurements from inside SNF dry cask storage systems, to include early shipment of the HDRP cask to the INL CPP-603 facility for gas sampling, and to work with the nuclear industry to identify one or more additional SNF dry cask storage systems that can be sampled for moisture content.

The Board commends DOE-NE and the HDRP research team for continuing the HDRP, even in light of less than ideal circumstances, described above, and for exploring new solutions to the challenges the project has faced. The Board notes that, in the same November 2018 letter mentioned above, the Board expressed a belief that continuing the HDRP was desirable, even though the maximum temperatures in the HDRP test cask did not reach the high levels desired. The Board also encourages the continued use of "blind" model predictions, which can then be compared against data collected during field or laboratory experiments, as a means for completing rigorous validation of the computer models.

Mr. Larson then discussed the results from the early phases of the sister rod destructive examinations. These examinations, which include cyclic bending tests, provide data regarding fuel and cladding characteristics and help analysts to understand how the fuel may perform during storage and normal conditions of transport. Of note, Mr. Larson stated that the destructive examinations being conducted at Oak Ridge National Laboratory (ORNL) are using segments of SNF rods that include the fuel inside the cladding (i.e., fueled cladding). In contrast, destructive examinations at PNNL and Argonne National Laboratory are being conducted on unfueled cladding segments. Comparing the results from the two laboratories will provide information on how much the fuel pellets contribute to the strength, or structural rigidity, of the fuel rod, as a result of the bond between the fuel pellets and the cladding. Understanding this is important since many destructive examinations have been completed using defueled samples of cladding, so the conclusions drawn from that work may not be directly applicable to SNF rods that contain fuel pellets.

During the question and answer period, Mr. Larson noted that the research completed to date includes testing consistent with normal conditions of transport but not accident conditions. He stated that DOE is considering adding new tests, such as drop tests of surrogate fuel assemblies, that can provide information about how the SNF may perform in hypothetical accident conditions. Mr. Larson invited the Board to meet with DOE personnel and laboratory analysts to review new data from the HDRP sister rods, once destructive examination tests are completed in 2020.

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[5] See the Board letter, Bahr to McGinnis, dated November 27, 2018, following the Fall 2018 Board meeting held in Albuquerque, New Mexico.

The Board endorses the DOE plan to continue pursuing additional testing that will provide information about the fuel-clad bonding and how the SNF will perform in accident conditions. The Board will continue to follow this work, and also appreciates the invitation to participate in a fact-finding meeting.

Mr. Larson's presentation concluded with a discussion of future plans for the HDRP, including transporting the HDRP cask to a hot-cell facility, removing SNF rods from the cask, and performing examinations of the SNF. He stated that the original plans for transporting the cask included a step of cutting the thermocouple cables and sealing the corresponding cask lid penetrations. However, DOE is now considering the possibility of leaving the thermocouple cables intact so that temperatures can be recorded while the cask is in a horizontal configuration, as it is being prepared for transport. Regarding a facility in which to open the HDRP cask, Mr. Larson explained that considerable work has been done to modify the CPP-603 facility at INL such that the facility can accept the HDRP cask, move the cask into the shielded portion of the facility, and remove selected SNF rods from the cask for transfer to a fuel examination facility. He noted that the modifications to CPP-603 make it suitable as a receipt facility for other SNF casks that are as large as (but no larger than) the TN-32 cask that is being utilized for the HDRP. Mr. Larson noted that DOE continues to consider options for HDRP SNF rod examinations, after the SNF rods are removed from the TN-32 cask. One option is to move the SNF rods to the Hot Fuel Examination Facility at INL.

The Board endorses DOE-NE's consideration of leaving the HDRP cask thermocouples intact to allow further temperature monitoring and commends DOE-NE for the proactive efforts to prepare the CPP-603 facility to accept the HDRP cask. The Board also commends DOE-NE for considering other useful missions for the facility now that it has been upgraded to allow handling of the HDRP cask.

Mr. Larson noted that the ORNL hot cells will be cleared out to make way for new activities when the HDRP sister rod examinations are complete. During the question and answer period, Mr. Larson clarified that sister rod segments that have not been examined will be saved for later testing, if needed. As noted in previous correspondence with DOE, the Board encourages DOE to retain the untested sister rod segments because they are valuable assets, and similar samples of high burnup SNF will be difficult and costly to obtain.

The Board observes that the HDRP has provided valuable information regarding the characteristics and behavior of high burnup SNF and this productive testing continues. Furthermore, DOE has sponsored significant work to adapt computer models, validated against the HDRP test data, that can be used to predict thermal-hydraulic conditions in the HDRP cask. However, the Board notes that the HDRP, including the TN-32 cask, is not representative of the typical SNF loaded in dry cask storage systems currently stored at nuclear power plant sites or the new SNF types that will likely be stored at nuclear power plant sites in the next few years. Some of the key differences are the following:

- The TN-32 cask is a bolted-lid cask, while approximately 90 percent of all dry cask storage systems loaded to date are welded canister-based systems.

- The TN-32 cask is a vertically oriented system, while approximately one-third of the dry cask storage systems loaded to date are horizontally oriented.
- The HDRP includes several types of pressurized water reactor SNF assemblies, but no boiling water reactor (BWR) SNF assemblies nor SNF assemblies with the types of materials used in accident tolerant fuels that are already being tested in commercial power reactors.

Given these specific features of the HDRP, it cannot be assumed that the computer modeling applicable to the HDRP will be applicable to other dry cask storage systems.

Recommendation 3. Consequently, the Board recommends that, before the computer models adapted for the HDRP cask are validated for application to other dry cask storage systems, additional testing be done to support model validation for these systems.

Thermal Analyses of SNF Dry Cask Storage Systems. Mr. David Richmond, PNNL, and Dr. Sam Durbin, SNL, presented information about DOE-sponsored research activities, including the HDRP, the Dry Cask Simulator at SNL, and computer model development focused on the prediction of temperatures in SNF dry cask storage systems. Extensive work was done in support of the HDRP effort, leading to substantial progress in validating the models against temperatures measured in the HDRP cask. Additionally, thermal-hydraulic models are being used to predict temperatures and gas flows in the Sandia Dry Cask Simulator, which includes a single surrogate BWR fuel assembly inside a mock storage cask. Testing and modeling have been completed using the Dry Cask Simulator in a vertical configuration. Testing has begun using the Dry Cask Simulator in a horizontal configuration and the results will be compared to predictions from existing thermal-hydraulic models.

Mr. Richmond displayed some of the modeling results for the HDRP cask, including mismatches between measured and predicted temperatures, and noted that the models typically over-predicted system temperatures. The research team attributed this over-prediction of temperatures to the use, in the models, of a design-specified uniform air gap between the SNF basket and the interior cask wall. In contrast, the actual loaded cask system had, in some places, direct contact between the SNF basket and the interior cask wall, causing greater conductive heat transfer and lower system temperatures.

Mr. Richmond also discussed an effort being coordinated by the Electric Power Research Institute (EPRI), through its Extended Storage Collaboration Program, to examine thermal modeling efforts for SNF dry cask storage systems. This effort, utilizing a Phenomena Identification and Ranking Table (PIRT) process, includes participation from EPRI, DOE, NRC, and the nuclear industry. This PIRT effort will consider the implications of the margins between the predicted cask system temperatures and the Nuclear Regulatory Commission (NRC) limit of 400°C for peak cladding temperature or the higher design basis temperature limits that are less than the NRC limit and which vary among storage systems. One key step in this process is identifying all parameters and phenomena that can affect SNF dry cask storage system temperatures and to assess the state of knowledge and importance of each parameter. Mr. Richmond described the process and displayed the set of parameters that the thermal PIRT team identified. The Board observes that the thermal PIRT process appears to include a thorough identification of the parameters and phenomena that affect SNF dry cask storage system temperature, and the Board looks forward to reviewing the results of this effort, which are expected in 2020.

Dr. Durbin described the Sandia Dry Cask Simulator used for studying temperature distributions and gas flows associated with a mock SNF dry cask storage system. The test system includes instrumentation to measure system temperatures and air flow rates. The simulator will be operated at four power levels (500, 1,000, 2,500, and 5,000 watts), with an internal pressure of 100 or 800 kilopascals, and a fill gas of helium or air.

Dr. Durbin also described thermal-hydraulic models (for predicting temperatures and gas flow rates) that were adapted for the simulator in a vertical configuration. He stated that the same models are being modified in order to predict temperatures and gas flow rates with the simulator in a horizontal configuration. As part of the overall test and modeling plan, Dr. Durbin stated that the computer modelers would be provided data sets including measured temperatures and air flow rates for two test runs conducted at 2500 watts. The modelers can use the data to calibrate their models and, then, they will be asked to predict the temperatures and gas flow rates for all other sets of test parameters. While using Dry Cask Simulator test data for computer model calibration may allow more accurate prediction of temperatures and gas flow rates in subsequent simulator tests, this approach does not ensure the models will be sufficiently flexible, or adaptable, for application to real-world dry cask storage systems, where such calibration data are not available.

The Board recognizes and commends DOE's work to develop modeling tools that can be used to predict SNF dry cask storage system performance. However, the Board believes DOE can do more to support and advance computer model development. The Board encourages DOE to identify which models perform well or poorly and also to develop a deeper understanding of the importance of various modeling aspects (e.g., numerical approximations and discretization, values assigned to material properties, boundary conditions, processes that are represented by the physics incorporated in the models) to good or poor model performance. Also, if several distinct models provide comparable matches to observations, the modelers and experimentalists should attempt to determine conditions for which the models might not yield comparable predictions. Then, they can design experiments to reproduce those conditions and determine which of the models better represents the system.

Recommendation 4. The Board recommends that DOE

a. *ensure current and new model development activities properly identify all assumptions and uncertainties and account for them to the extent possible,*

b. *ensure thermal models and multiphysics models (like the thermal-hydraulic models) are formally validated by collecting data from real-world systems and comparing the data with blind model predictions, wherever possible,*

c. *ensure computer models are used only for conducting analyses of systems for which model applicability is clearly shown,*

d. *promote the development and validation of broader multiphysics models that have the capability to predict fuel performance, such as cladding fracture behavior in accident conditions, and*

e. *promote greater coordination between model developers and experimentalists so that computer models and experiments are properly aligned.*

DOE Standard Canister[6] for SNF. Dr. Josh Jarrell, INL, presented information on the design, analysis, testing, and intended use of the DOE Standard Canister. Dr. Jarrell pointed out that the work he is conducting is funded by DOE-NE, but there is other work on the DOE Standard Canister being funded by the DOE Office of Environmental Management (DOE-EM). The DOE-EM work was not presented.

Dr. Jarrell noted that the DOE Standard Canister was originally designed by DOE in support of the Yucca Mountain license application as a multipurpose (storage, transport, and disposal) canister for DOE-managed SNF.[7] Because of the large variety and range of sizes of DOE-managed SNF, the DOE Standard Canister was designed to be available in two diameters (0.46 and 0.61 meters [18 and 24 inches]) and two lengths (3.05 and 4.57 meters [10 and 15 feet]). Although DOE completed some R&D on the Standard Canister in support of the Yucca Mountain license application, that work was not finished and no application was submitted to the NRC for approval to use the canister to transport SNF.

Dr. Jarrell stated that DOE continues to pursue development of the DOE Standard Canister and has identified the canister as an option for dry-storage of Advanced Test Reactor SNF at INL. Ongoing work includes evaluations of operations to load, dry, seal, and inspect DOE Standard Canisters in the CPP-603 facility at INL. Dr. Jarrell also noted that DOE continues to evaluate neutron absorber materials that can be used in the fabrication of canister components for criticality safety purposes. Dr. Jarrell stated that this work has shown that the use of new variations of borated stainless steels will allow the DOE Standard Canister to meet all criticality safety requirements.

The Board is encouraged by DOE's continuing work to develop the DOE Standard Canister but notes that there is currently a relatively low level of effort and funding devoted to this activity and there is no schedule for completing it. Several important design features of the DOE Standard Canister are yet to be finalized and operations such as drying and inspection need to be more fully developed. Regarding these latter points, the Board notes that it transmitted a report to DOE in 2017,[8] which recommended 1) development of an improved technical basis for the proposed procedures for drying DOE SNF before it is packaged in multi-purpose canisters; and 2) development of the capability for measuring and monitoring the conditions of the SNF in new DOE storage systems, such as the DOE standardized canister.

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[6] In previous work, including DOE's License Application for the Yucca Mountain Project, the name of this canister was the DOE SNF Standardized Canister.

[7] The DOE Standard Canister is distinct from the TAD [transportation, aging, and disposal] Canister that was designed by DOE to hold commercial SNF and was included in the Yucca Mountain license application.

[8] See *Management and Disposal of U.S. Department of Energy Spent Nuclear Fuel*, December 2017, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

Recommendation 5. Consistent with the Board's previous recommendations and based on the current state of the DOE Standard Canister, the Board recommends that DOE

a. determine the amount of moisture that can remain in a loaded DOE Standard Canister after drying without adversely affecting the SNF in the canister,

b. develop methods to monitor the conditions inside the DOE Standard Canister after it is loaded and sealed shut,

c. work with EPRI and others in the nuclear industry to apply newly developed remotely-operated techniques for inspecting the exterior surface of loaded DOE Standard Canisters,

d. engage early with the NRC to ensure that the DOE Standard Canister project team is aware of all applicable regulatory requirements, including requirements for criticality safety and hydrogen gas concentrations, and

e. develop a firm path forward and schedule for completing development of the DOE Standard Canister and obtaining the necessary NRC approvals.

DOE-EM Research on Aluminum-clad SNF. Dr. Mike Connolly, INL, presented an overview of DOE-EM-sponsored research on the long-term dry storage of aluminum-clad SNF. Dr. Connolly is coordinating a team of researchers, comprising six sub-teams working on distinct research tasks, all of which are of interest to the Board. However, the Board was informed by DOE-EM management that Dr. Connolly would only provide one presentation at the meeting, giving an overview of the program.

Dr. Connolly described the types and sources of aluminum-clad SNF in the DOE inventory and discussed corrosion mechanisms that can lead to the formation of aluminum-oxide, -hydroxide, and -oxyhydroxide layers on the surface of the fuel. These corrosion layers can retain water, even after drying operations, and this water can then be a source of radiolytically-generated gases, such as hydrogen and oxygen. The DOE-EM research project is examining all stages of these corrosion and gas generation processes. The research includes characterization of aluminum-clad SNF, laboratory experiments on corrosion and gas generation, and computer model development with an aim of predicting the behavior of aluminum-clad SNF during drying and dry storage. All six research tasks within the program are ongoing and early results have just been published within the past year.

Dr. Connolly noted that one particularly challenging aspect of this research is the scope of the corrosion and the reactions resulting in the generation of gases. A full description of gas generation following the corrosion of aluminum is characterized by 115 chemical reactions involving 40 chemical species. In order to make the laboratory research and modeling manageable and timely, the research team conducted sensitivity studies to eliminate the less-significant reactions and species, and reduced the problem to 22 reactions, involving eight chemical species.

The Board considers research on aluminum-clad SNF to be important and encourages DOE's continued support of the program being managed by Dr. Connolly. However, the Board urges that the research teams should review and confirm the results of their efforts carefully, prior to eliminating any chemical reactions and chemical species from further research, recognizing that elimination of many reactions and species may collectively impact predictions. The Board asked Dr. Connolly about the progress in developing a model to predict the behavior of aluminum-clad SNF during drying and dry storage, including progress in validating the models against experimental data. Although Dr. Connolly's presentation did not include comparisons of model predictions against experimental results, he stated that those comparisons are included in the research reports he listed in the reference section of his presentation.

The Board notes that the information presented by Dr. Connolly was limited and provided insufficient opportunity for the Board to pursue areas of technical inquiry it wanted to pursue, particularly the technical basis for drying aluminum-clad DOE SNF, as noted above and in the Board's 2017 report.[9] Since the work is important and relevant to future DOE activities to package, dry, store, transport, and dispose of DOE-managed aluminum-clad SNF, the Board would like to have the opportunity to interact more directly with representatives of DOE-EM and the research team being coordinated by Dr. Connolly. The Board will contact DOE-EM through separate correspondence to request additional interactions.

Research on the Drying and Storage of SNF in the United Kingdom. Dr. Paul Standring, Sellafield Ltd. (UK), provided an overview of SNF managed in the UK, the condition and status of aluminum-clad SNF, and SNF dry storage experience in the UK. He then discussed, in more detail, the research related to Magnox SNF [nuclear reactor fuel with MAGnesium, Non-OXidizing cladding; a cladding composed of magnesium and a small amount of aluminum and other metals] and aluminum-clad SNF.

Dr. Standring pointed out that Magnox SNF is currently reprocessed in a facility at the Sellafield site, but the facility is more than 50 years old, operating beyond its design lifetime, and could be taken out of service at any time. As a back-up plan, Sellafield has sponsored work to develop the "Magnox contingency," which is a plan to package Magnox fuel into a new design of canister, dry it, and place it into dry storage. Dr. Standring described the research being undertaken to support the plan, including the need to address the generation of hydrogen gas, both from corrosion and from the radiolytic dissociation of water, and the formation of uranium hydride, which is pyrophoric in air. The research team found that, after drying the Magnox SNF, hydrogen gas pressures will not reach levels that challenge the design specification of the canister. However, if damaged fuel is present, uranium hydride formation may eventually exceed the limits for handling the SNF in an air atmosphere. Therefore, the current plan is to package, dry, and store undamaged fuel only. For the storage of damaged Magnox SNF, Dr. Standring stated that one possible solution is a newly-designed Self Shielded Box, that is vented (through a filtered vent) to mitigate the hazards associated with the formation of uranium hydride.

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[9] See *Management and Disposal of U.S. Department of Energy Spent Nuclear Fuel*, December 2017, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

Dr. Standring stated that the UK manages only a small quantity of aluminum-clad SNF, but said that this SNF will need to be transferred from pool storage to dry storage. Based on an evaluation of alternatives, the best option for managing this fuel would be to include it in the Magnox contingency campaign, if it proceeds. If that option is not implemented for Magnox SNF, then another option, such as the Self Shielded Box, will have to be considered. In a panel discussion at the end of the meeting, Dr. Standring noted that Sellafield has established an "Innovation Team" to look for solutions to waste management challenges such as these. One example of the results of the work of this team is the concept of a "Smart Package" for waste storage that would be instrumented to provide real-time information about the conditions inside the package.

The Board was pleased to hear the insights provided by Dr. Standring and to learn about the SNF management program in the UK. The Board suggests that DOE should take note of the lessons learned in other countries related to the management of aluminum-clad SNF and consider adopting new initiatives such as establishing an Innovation Team and developing an instrumented package like the Smart Package concept being considered in the UK for storage of radioactive wastes.

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

January 10, 2020

Mr. William White
Senior Advisor for Environmental Management
to the Under Secretary for Science
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Mr. White:

I am writing to request that we establish a framework for more regular interaction between the DOE Office of Environmental Management (DOE-EM) and the Nuclear Waste Technical Review Board (Board). This would significantly assist the Board in its review of DOE-EM activities related to the management and disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW).

The Board was created by Congress in the 1987 Nuclear Waste Policy Amendments Act (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 and to advise Congress and the Secretary on technical issues related to managing SNF and HLW. In line with this role, the Board has long had an interest in DOE activities related to packaging, drying and storing SNF, as well as planning for transportation and disposal.

To address certain aspects of these issues, the Board held a public meeting in Alexandria, VA, on November 19, 2019. While DOE-EM is undertaking a broad range of research activities related to the management of aluminum-clad SNF and is funding work on development of the DOE Standard Canister, the Board is concerned that DOE-EM elected to participate in the meeting in a limited fashion, supporting only one overview presentation on DOE-EM activities related to aluminum-clad SNF and no presentation on DOE-EM work related to the DOE Standard Canister. The Board suggests that more regular interaction with DOE-EM at a senior management level would help us better plan for DOE-EM participation in future Board meetings.

The Board's staff holds meetings with the staff of the DOE Office of Nuclear Energy (DOE-NE) periodically, to discuss DOE-NE activities and coordinate and plan future Board meetings. I suggest such staff-to-staff meetings would be good models to use for setting up similar interactions between the Board and DOE-EM. I would be pleased to discuss this by telephone or meet with you in Washington, D.C., at a mutually agreeable time, to develop a strategy for enhanced interactions between the Board and DOE-EM more generally.

I would appreciate your consideration of this matter and I look forward to your response. I also look forward to future productive interactions with you and your staff.

Sincerely,

{Signed by}

Jean M. Bahr
Chair

cc: Todd Shrader, Principal Deputy Assistant Secretary, DOE-EM

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

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.

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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 inthe 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

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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]

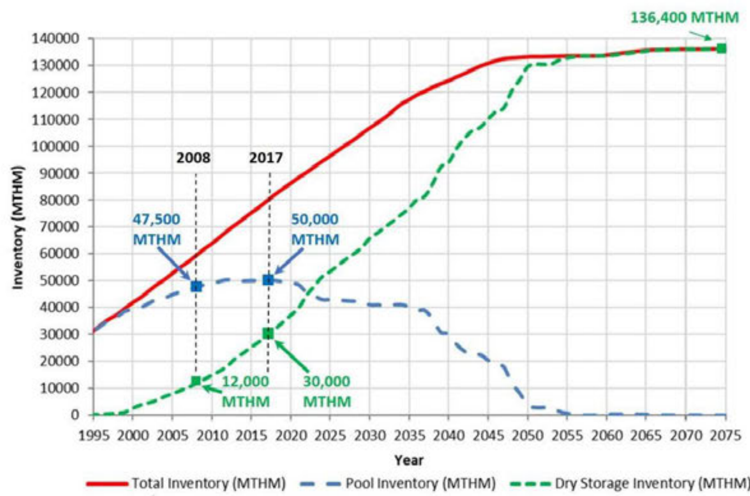

Figure A-1. Projected Inventory of Commercial Spent Nuclear Fuel in Storage.
Note: Figure taken from Freeze et al. (2019; Fig. 1-5) and revised for clarity. The projections of inventory with time developed by Vinson and Metzger (2017) and used by Freeze et al. (2019) assumed: (i) 93 of the 99 reactors 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.

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[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.

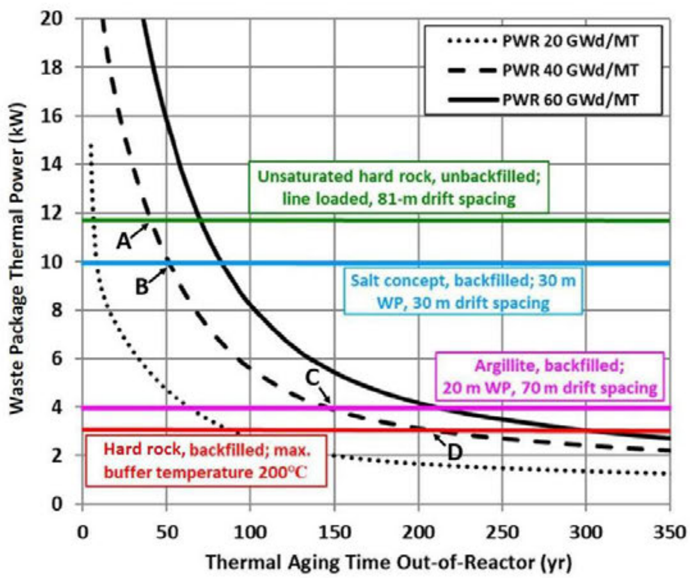

Figure A-2. Thermal Power Versus Age for a Waste Package Containing a Dual-Purpose Canister with 32 Assemblies of Pressurized Water Reactor Spent Nuclear Fuel.

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.

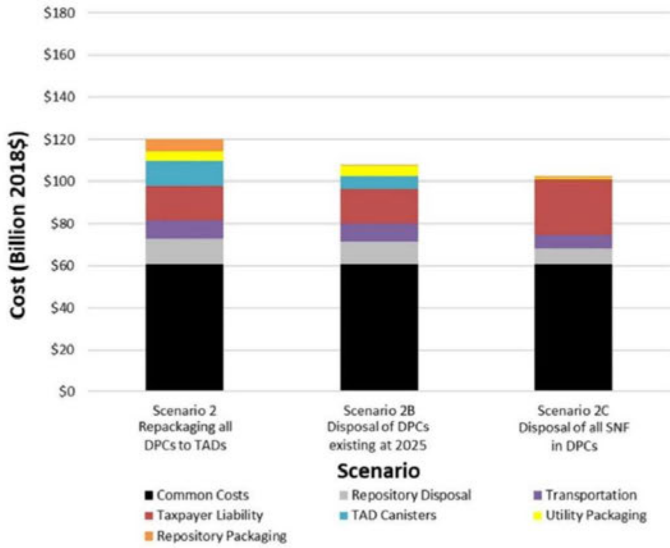

Figure A-3. Comparison of estimated costs for different DPC disposal variants for the scenario when the repository begins disposal in 2031.
Modified from Figure ES-3 in Freeze et al. (2019). Scenario 2 includes loading of TADs at utilities starting in 2025 and repackaging of SNF from DPCs (loaded until 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.

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[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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UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
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April 8, 2021

The Honorable Jennifer Granholm
Secretary
U.S. Department of Energy
Washington, DC. 20585
(By electronic mail)

Dear Secretary Granholm,

I am writing to request a meeting with you to discuss a report that is about to be released by the U.S. Nuclear Waste Technical Review Board. The report is addressed to you and to Congress and, in accordance with our normal practice, the meeting would allow myself and other Board members to brief you and/or the Deputy Secretary on the recommendations in the report, prior to our releasing it publicly. We would be pleased to also brief the Acting Assistant Secretaries of the Office of Nuclear Energy and the Office of Environmental Management at the same time or in a separate meeting.

The report synthesizes the experience gained by the current Board members during our nearly decade-long experience of reviewing DOE activities related to the development and implementation of the nation's program for management and disposal of spent nuclear fuel and high-level radioactive waste. The report includes six overarching recommendations and a number of associated action items the Board members believe it is important for DOE to take, in order to implement those recommendations.

The Board was created by Congress in the 1987 Nuclear Waste Policy Amendments Act (NWPAA) to:

> "…evaluate the technical and scientific validity of activities undertaken by the Secretary [of Energy] after the date of the enactment of the Nuclear Waste Policy Amendments Act of 1987, including (1) site characterization activities; and (2) activities relating to the packaging or transportation of high-level radioactive waste or spent nuclear fuel."

The NWPAA requires the Board to report its findings, conclusions, and recommendations to you and to Congress. The legislative history of the NWPAA records that the Board cannot compel DOE to accept its recommendations but indicates that DOE should accept the Board's recommendations or state its reasons for not doing so.

We plan to offer briefings on the report to members of Congress, their staffs, and representatives of Congressional Committees during April, and to release the report by the end of the month. If we can arrange a meeting with you within the next few weeks, we will schedule those briefings, and release of the report, for after we have briefed you. Please let me know when it will be possible to arrange a meeting for the Board to brief you on the report. Thank you.

Sincerely,

{signed by}

Jean Bahr
Chair

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
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July 22, 2021

Dr. Kathryn Huff
Acting Assistant Secretary
U.S. Department of Energy
Office of Nuclear Energy
1000 Independence Avenue, SW
Washington, DC 20585
VIA EMAIL

Dear Dr. Huff,

Thank you for meeting with us, and other members of the Board and staff, on Tuesday last week, July 13, 2021, and congratulations again on your appointment to the position of Principal Deputy Assistant Secretary and Acting Assistant Secretary for the DOE Office of Nuclear Energy (DOE-NE). It was a pleasure to meet with you in your new capacity and to discuss both the Board's role in reviewing DOE activities related to the management of spent nuclear fuel (SNF) and high-level radioactive waste (HLW), and the Board's report titled "Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward."

In discussing the Board's activities, we indicated that the legislative history of the Nuclear Waste Policy Amendments Act of 1987 (NWPAA) indicates that, in response to recommendations from the Board, "it is assumed that the Department will heed those views or clearly state its reasons for disagreeing". We were pleased that you indicated you intend to follow this guidance and respond to letters and reports that contain Board recommendations.

The Board's role is defined in the NWPAA as evaluating the "technical and scientific validity" of activities undertaken by DOE to develop and implement the nation's program for management and disposal of SNF and HLW. In doing so, the Board identifies the appropriate activities and decisions that it should review. However, as we discussed in our meeting, the Board would be pleased to receive suggestions or requests from DOE regarding R&D programs, or other activities within the Board's mandate, it would be helpful to DOE for the Board to review. We believe it would be in the interests of all stakeholders for the Board to undertake reviews that offer the most benefit for the development and implementation of the waste management program.

Once again, we would like to thank you for your time, and the time of the DOE-NE staff who participated in the meeting. We believe it was a most constructive meeting and look forward to holding additional meetings with you and your staff to discuss the Board's future reviews of DOE-NE activities. We do hope you can find the time to participate in the Board's public meetings.

Sincerely,

{Signed by}

Jean M. Bahr, Chair

{Signed by}

Paul J. Turinsky, Deputy Chair

cc:
Dr. K. Petry, DOE-NE
Dr. W. Boyle, DOE-NE
Mr. A Richards, DOE-NE

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
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August 12, 2021

Dr. Kathryn D. Huff
Acting Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, D.C. 20585

Dear Dr. Huff:

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 Spring 2021 Meeting, which was held virtually on May 12–13, 2021. 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 advanced nuclear fuels for light water reactors (LWRs), including accident tolerant fuels (ANF/ATF), and the impact of these fuels on spent nuclear fuel (SNF) management and disposal. This letter presents the Board's observations, findings, and recommendations to DOE 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/spring-2021-board-virtual-meeting---may-12-13-2021. 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 virtually on April 26, 2021. This fact-finding meeting enabled the Board to prepare for the Spring 2021 public meeting.

Background

Since the 2011 Fukushima Daiichi nuclear accident in Japan, there has been significant R&D in several countries to enhance the accident tolerance of reactor fuels. In 2012, Congress directed DOE to give priority to developing ATFs.[1] Pursuant to the Congressional mandate, DOE-NE has been supporting R&D with nuclear fuel vendors to give priority to developing "enhanced fuels and cladding for light water reactors to improve safety in the event of accidents in the reactor or spent fuel pools." Concurrently, the U.S. Nuclear Regulatory Commission (NRC) has been working to ensure that the existing regulatory framework will support the licensing of ATFs in current commercial LWRs. The state-of-the-art in ATFs has progressed from research reactor irradiation campaigns for characterizing new fuels and new cladding materials, to demonstrations

[1] See Consolidated Appropriations Act, 2012, Conference Report 112-75.

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of full-scale lead test assemblies in commercial nuclear reactors, and post irradiation examinations of the first batch of discharged ATFs at DOE national laboratory hot cell facilities.

Near-term ATFs are envisioned to be licensed for use in the current commercial fleet of LWRs in the U.S. in the next 5 to 10 years. The ANF/ATF comprise a diverse class of fuel materials and claddings, including ceramic claddings, metallic fuels, and some innovative fuels that are designed to operate to higher burnups and to utilize higher enrichments of uranium-235. Background information on the fuel designs is provided in the Appendix to this letter and are included in the public meeting presentation materials.

Although DOE has made significant progress in the development of ANF/ATF, there has been less effort focused on planning for the management and disposal of the resulting SNF. To address these issues, the Board planned its Spring 2021 public meeting to hear from DOE, national laboratories, and the nuclear industry in the U.S. and to gain insights from experts from some other countries (Switzerland, Sweden, and United Kingdom) about some of their development activities for ANF/ATF but ultimately focusing on the plans for management and disposal of the resulting SNF in those countries.

Public Meeting

DOE-NE Office of Nuclear Fuel Cycle and Supply Chain and Idaho National Laboratory
Mr. Bill McCaughey (DOE-NE) and Dr. Dan Wachs (Idaho National Laboratory [INL]) provided an overview of the DOE-supported, industry-led ATF R&D activities from 2012 to present. Mr. McCaughey recognized the ATF program as one of DOE-NE's highest priorities with strong government support of the program and hundreds of participants. Mr. McCaughey stated that the two guiding principles of the Congressional mandate to develop ATFs were that the technology supports the existing LWR fleet and that the technology be developed as quickly as possible.

The technical presentation was given by Dr. Wachs and covered design specifications and safety attributes of the fuel and cladding materials for candidate ATF designs. The R&D is led by commercial fuel vendors Westinghouse, General Electric/Global Nuclear Fuel (GE/GNF), and Framatome. The near-term ATFs include chromium-based coatings on zirconium alloy claddings and chromium-doped uranium dioxide (UO_2) fuel and, in the longer-term, iron-based claddings like iron-chromium-aluminum (FeCrAl), ceramic composite claddings like silicon carbide (SiC) and other high density fuels like uranium nitride (UN). More background information on ATFs is provided in the Appendix.

Dr. Wachs described the on-going irradiation testing of ATF specimens in the INL Advanced Test Reactor for NRC fuel qualification and licensing, and testing the response of specimens when subjected to accident conditions in the Transient Reactor Test Facility. Dr. Wachs also described the irradiation of full-scale lead test assemblies in eight commercial LWRs and the plan for subsequent post irradiation examination work (see Appendix, Figure A1). Dr. Wachs stated that international collaborations also support the U.S. ATF R&D through partnerships with other countries that enable DOE to access their facilities. The three main fuel vendors also have their networks around the world.

Lightbridge Corporation

Dr. Aaron Totemeier (Lightbridge) described Lightbridge's metallic fuel technology and helical fuel rod design. Lightbridge Fuel is a type of ANF being developed for existing and future LWRs. Unlike traditional LWR UO_2 fuel rods, comprised of stacked UO_2 pellets in cylindrical zirconium alloy cladding, Lightbridge Fuel is an innovative fuel design with a helical (twisted) rod geometry formed from a metallic alloy of uranium and zirconium, with a metallurgically bonded zirconium-niobium cladding. Dr. Totemeier stated that Lightbridge Fuel offers several increased safety benefits over traditional zirconium alloy-clad UO_2 fuel (e.g., higher thermal conductivities, lower fuel operating temperatures, etc.) and is envisioned to be developed with enrichments of uranium-235 higher than that in current LWR fuels, such as high assay low-enriched uranium (HALEU).[2] Currently, Lightbridge Fuel is considered a longer-term ANF technology and is supported in part by DOE to partner with INL for Advanced Test Reactor irradiation testing and with Pacific Northwest National Laboratory (PNNL) on fuel casting techniques for fabricating metallic fuel. According to Dr. Totemeier, the SNF management implications of Lightbridge Fuel are not currently expected to present any "showstoppers," and Lightbridge has plans to explore SNF management topics in the future.

U.S. Nuclear Regulatory Commission

Ms. Marilyn Diaz and Dr. John Wise described the NRC ATF Project Plan,[3] the purpose of which is to guide the NRC staff to ensure that the necessary regulatory processes and knowledge will be in place to consider applications for the use of ATFs in commercial reactors. ATF designs that have been given higher priority in the Project Plan are chromium-coated zirconium alloy claddings, FeCrAl cladding, and doped fuel pellets. The Project Plan considers mainly ATF qualification and reactor operational issues but also considers storage and transportation of the resulting SNF. Ms. Diaz provided a high-level overview of the activities in the Project Plan, which includes identification of critical paths for required regulatory actions and for conducting research on ATFs through technical assessments, confirmatory code development, and expert elicitations.[4]

One of the new paradigms of the Project Plan is to conduct NRC activities in parallel with nuclear industry development efforts in order to build NRC staff expertise early. Ms. Diaz also stated that the NRC has proactively communicated early and often with stakeholders on regulatory activities through public meetings, reports, and regular, formal interactions relating to licensing considerations for ATFs. Ms. Diaz noted that the NRC will update the Project Plan in Fall 2021.

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[2] High assay low-enriched uranium (HALEU) based fuel has a uranium-235 assay greater than 5% but less than 20%. The current commercial fleet of LWRs relies on low-enriched uranium which is enriched to less than 5% uranium-235.

[3] *Project Plan to Prepare the U.S. Nuclear Regulatory Commission for Efficient and Effective Licensing of Accident Tolerant Fuels*. ML19301B166, Version 1.1. U.S. Nuclear Regulatory Commission. October 2019.

[4] The NRC uses an expert elicitation process called the Phenomena Identification and Ranking Table (PIRT) process.

Dr. John Wise highlighted technical aspects of new ATF designs that will be important to consider when licensing them for fabrication, fresh fuel transportation, reactor operations, and management of the resulting SNF. Dr. Wise noted that key characteristics of ATF designs to be considered when evaluating SNF transportation and storage are criticality safety and cladding performance. An initial study conducted by PNNL for NRC on the impact of ATF cladding designs[5] (chromium-coated zirconium alloy cladding and FeCrAl cladding) on storage and transportation revealed no significant issues. However, Dr. Wise stated that there are limited data available on the mechanical and thermal properties and fatigue lifetimes of new cladding designs. The missing relevant data will need to be obtained by the fuel vendors to support computer model development and NRC evaluation of the ATF designs. Regarding evaluation of SNF disposal, the NRC staff has no current plans on that topic, but Dr. Wise stated that the NRC will consider potential disposal implications as ATF technologies advance.

DOE-NE Office of Spent Fuel and Waste Disposition and Sandia National Laboratories
Dr. William Boyle (DOE-NE) and Dr. Sylvia Saltzstein (Sandia National Laboratories [SNL]) discussed preliminary considerations for the potential impacts of ANF/ATF on SNF management and disposal. In the opening remarks for DOE, Dr. Boyle stated that DOE will follow the terms of the Standard Contracts that are in place between DOE and the nuclear utilities, and that DOE will do any testing and modeling of the SNF that is needed to support disposal of the SNF.

Dr. Sylvia Saltzstein summarized the results of a high-level "gap analysis" report[6] prepared by SNL with input from Oak Ridge National Laboratory (ORNL), Argonne National Laboratory, and PNNL. The report identifies information needs (gaps) that, when met, will support a thorough evaluation of the impacts of ATFs on SNF storage and transportation. Dr. Saltzstein pointed out that, since no post irradiation examination of ATFs has yet been completed, there are many gaps. The technical gaps for ATFs were grouped into the same priority groupings (called tiers) that SNL had identified in previous gap analyses for high burnup SNF (which involves information on standard UO_2 fuel with zirconium alloy cladding utilized to high burnup). The top three tiers are:

Tier 1	Thermal profiles in SNF dry cask storage systems, stress profiles in SNF assemblies and cladding, and welded canister-atmospheric corrosion.
Tier 2	Measuring the efficiency of drying SNF in dry cask storage systems.
Tier 3	External monitoring of SNF dry cask storage systems, hydrogen effects in SNF cladding, consequences of SNF canister failure, and fuel transfer options.

For the purposes of the gap analysis, the proposed fuels investigated are categorized as:

- doped fuel pellets (chromia and chromia/alumina dopants)
- modified current (coated zirconium alloy) and new claddings (FeCrAl, SiC, etc.)
- fuels with higher density than uranium dioxide to facilitate higher burnup and higher power while reducing fuel temperature:

[5] *Spent Fuel Storage and Transportation of Accident Tolerant Fuel Concepts; Cr-Coated Zirconium Alloy and FeCrAl Cladding*, PNNL-30451, September 2020.

[6] *High Level Gap Analysis for Accident Tolerant and Advanced Fuels for Storage and Transportation*. SAND2021-4732, Revision 6. Albuquerque, New Mexico: Sandia National Laboratories. April 2021.

- uranium metals (including Mo or Pu/Zr alloys, etc.)
- uranium nitrides
- uranium silicides
- fuel (UO_2-based or other) with enrichment of 5 to 20% to increase burnup, cycle length, and power
  - HALEU

The general conclusion of the ATF gap analysis, according to Dr. Saltzstein, is that for LWR fuel in a traditional pellet-in-rod design, the information needs can be met by examining the new ATF SNF in the existing facilities and test equipment used to examine the zirconium alloy-clad "sibling pins" in DOE's High Burnup Dry Storage Cask Research and Development Project (HDRP).[7] Non-traditional fuels (e.g., TRISO fuels) will require alternate testing plans to be developed. Dr. Saltzstein stated that updates to the ATF gap analysis report are expected to become integrated into the gap analysis process that covers the broad range of SNF DOE expects to accept eventually from the nuclear utilities.

ANF/ATF Development and Approval Process and Plans for SNF Management in Other Countries

Switzerland

Dr. Stefano Caruso (Kernkraftwerk Gösgen, [KKG]) highlighted some of the Swiss ATF R&D activities and collaborations, the license application process and various assessments for approving new fuels in Switzerland, and outlined the Swiss strategy for management of SNF. Switzerland is considering ATF candidates that are similar to those in the U.S. and in some cases working with the same fuel vendors. The Swiss ATF candidates[8] include chromium-coated zirconium alloy claddings and chromium- and aluminum-doped UO_2 fuel in the near-term. Alternative claddings will be developed in the long-term like SiC composites and iron-based alloys to replace conventional zirconium alloy claddings (see Appendix for more information on U.S. ATF candidates). KKG has several collaborations with Framatome involving chromium-coated zirconium alloy cladding development including manufacturing, irradiation, and post irradiation examination activities. Dr. Caruso described the IMAGO (Irradiation of Materials for Accident-tolerant fuels in the Gösgen reactor) R&D program to verify the behavior of ATF concepts in representative pressurized water reactor conditions. In the GOCHROM R&D program, which is a follow-up program to the IMAGO R&D program, test assemblies have completed two irradiation cycles with full-length fuel rods of chromium-coated M5 (lead test rods with Framatome's zirconium alloy based cladding) inserted in the Gösgen reactor; these included traditional and doped UO_2 fuel.

Prior to use in a commercial nuclear reactor, new nuclear fuel designs in Switzerland must be approved by ENSI (Swiss Federal Nuclear Safety Inspectorate; like the U.S. NRC) after consideration of all aspects of the safety of the new fuel design and the related in-core

[7] The High Burnup Dry Storage Cask Research and Development Project (HDRP) is a project, cosponsored by DOE and the Electric Power Research Institute, to study the effects of long-term dry storage and transportation on high burnup SNF. The project includes the testing of mechanical properties of 25 high burnup SNF rods ("sister rods" or "sibling pins") to establish a baseline prior to storage and transportation. The sister rods include fuel with Zircaloy-4, low-tin Zircaloy-4, ZIRLO®, or M5® cladding.

[8] Dr. Caruso noted that these were some examples and not intended to be a comprehensive list of all of the Swiss ATF R&D.

performance. The approval process includes irradiation of lead test assemblies that include the new fuel design, in-pool inspections of the fuel, and detailed post irradiation examination of the fuel. The Gösgen nuclear power plant supports many of these activities.

The ENSI approval process for a new fuel design includes an evaluation of the safety of the fuel during all phases of the fuel life cycle, including fuel performance in the reactor, during storage and transportation, during pre-disposal operations (e.g., encapsulation), and during the post-closure period. As the implementor of the radioactive waste disposal program in Switzerland, Nagra [the National Cooperative for the Disposal of Radioactive Waste] is involved in the process to evaluate the performance of new fuel designs in pre-disposal and disposal scenarios.

Dr. Caruso discussed the characteristics of new fuel designs that are important during transportation, storage, and disposal. Fuel assembly and cladding integrity (as affected by cladding oxidation, burnup levels, hydride reorientation, etc.) and radiation shielding are key features considered when evaluating the fuel for transportation, storage, and pre-disposal operations (e.g., encapsulation). For post-closure safety, no credit is taken for cladding integrity, but other fuel characteristics, such as burnup credit (for criticality safety), the potential rate of radionuclide release, and the decay heat of the fuel are important factors that are taken into account.

To evaluate SNF performance, KKG is also participating in several international activities. KKG, Nagra, and Framatome have a joint program that is evaluating the long-term aging of fuel assembly structural components by simulation of the aging process during dry storage; Dr. Caruso noted that this is an important pre-disposal activity for Nagra.

Sweden

Dr. Anders Sjöland (SKB [Svensk Kärnbränslehantering AB]) described the Swedish nuclear industry, the types of ATFs being developed in Sweden, and the Swedish approach for management of SNF resulting from ANF/ATF. SKB is owned by the Swedish utilities and its mission is to manage and dispose of nuclear waste in Sweden. Like many other nations, Sweden's leading ATF candidates include coated zirconium alloys and chromium-doped UO_2 fuels in the near-term. Longer-term candidates include higher enriched (fuel enrichments of 5 to 6% uranium-235) UO_2 fuels and FeCrAl and SiC composite claddings.

In contrast to the United States, all fuels proposed for Swedish nuclear power plants have to be approved in advance by SKB and the Swedish regulator to ensure that the resulting SNF is compatible with the waste management program, including transportation, intermediate wet storage, encapsulation, and disposal. Approval of new nuclear fuel is typically a nine-month process, and involves formal decision making meetings. New nuclear fuel designs are reviewed to ensure that the resulting SNF will meet certain acceptance criteria, including dimension and weight limits, criticality safety requirements, radiation levels, and mechanical integrity.

According to Dr. Sjöland, SKB and the regulator can refuse to allow utilities to load a new fuel type if it has not been demonstrated to meet the transportation, storage and disposal requirements, or if the resulting SNF will result in significant increases in the cost of the waste management program or require changes to the current waste management infrastructure. The fuel also has to have a low dissolution rate in water over a long period, which is considered a major test for acceptability for disposal. Accordingly, the doped UO_2 fuels have already been approved for use in Swedish reactors. Regarding the possibility of using more advanced ATF designs, Dr. Sjöland noted that there is a limitation in Sweden that nuclear fuel must have a UO_2 fuel matrix, and no other fuel matrix is accepted.

United Kingdom (U.K.)

Mr. Dave Goddard and Mr. David Hambley (both from National Nuclear Laboratory [NNL]) summarized ATF R&D in the U.K., described the U.K. approach to licensing new fuels, and explained the decision making required prior to the loading of new fuel designs in existing reactors. Mr. Dave Goddard provided technical details on some of the current ATF R&D at NNL, including claddings and high density fuels that are similar to the U.S. ATF candidate designs. The ATF designs include chromium-coated zirconium alloy cladding and other coatings on zirconium alloy claddings, SiC composite claddings, and iron-based claddings. New fuel matrix materials include doped UO_2, composite fuel, fuels with higher thermal conductivity, fuels with higher enrichments, and high density fuels. NNL engages in several international collaborations to develop ATFs including irradiation and non-destructive post irradiation examination at the Massachusetts Institute of Technology reactor facilities, burst tests at ORNL, quench tests at Karlsruhe Institute of Technology in Germany, and participation in the Nuclear Energy Agency-Framework for Irradiation Experiments international fuel and materials testing program. Mr. Goddard described the Advanced Fuel Cycle Program in UK in which two of the areas of focus (one in future fuels and one in recycling of fuels from future reactors) are being led by NNL, and he noted how bringing the two focus areas together helped ensure the right decision-making. Mr. Goddard stated that, for the near-term ATF concepts such as coated zirconium alloy claddings, commercial deployment is not expected to be limited by waste management considerations. However, longer-term advanced claddings or high density fuels will require substantially more R&D, including research on the implications for SNF storage, transport, and disposal. He further indicated that testing of irradiated fuels will be necessary, under conditions to simulate storage and disposal.

Mr. David Hambley discussed the U.K. national policy to transition from a closed fuel cycle to an open fuel cycle and the U.K. process for managing SNF. He described the roles of the utilities and the developer of the waste management program, Radioactive Waste Management (RWM), in preparing for the introduction of new fuel designs. Mr. Hambley stated that the U.K. regulatory process requires demonstration of fuel lifecycle management prior to new reactor builds and before a new fuel design can be used in U.K. nuclear power plants. Disposability of new fuels is a consideration by regulators and environmental agencies, but it is not a part of the formal licensing process. According to Mr. Hambley, the disposability assessment process is a "confidence-building measure" by the applicant to show that materials can be packaged in a manner that is compliant with the geologic disposal facility design assumptions and provides a route to adapt the geologic disposal facility concept or design, if required. Another consideration that is not a part of the formal licensing process is the generic design assessment process. This process is a way of providing fuel vendors and reactor designers the confidence that a design can be licensed before production or construction, respectively, are started. Mr. Hambley noted that this helps RWM to avoid future potential liabilities.

A panel session discussion followed the technical information sessions. The purpose of the panel discussion was to identify the main implications of ANF/ATF on SNF management and disposal based on the materials presented during the two days of the public meeting. The panelists were also asked about R&D activities that would help countries interested in ANF/ATF designs for their LWRs understand the implications of such a change. The panelists then also shared their views on opportunities for international collaboration in planning for SNF management of ANF/ATF. Finally, the panelists discussed the kinds of regulatory changes related to SNF management that needed to be implemented to support the use of ANF/ATF. The panel discussion helped to highlight the importance of early stakeholder engagement and creating a discussion with a broader community (that includes implementors, regulators, and utilities) to support the introduction of the use of new fuel types. Discussions also ensued on the kinds of early R&D activities that would help prepare countries that are interested in ATF (which oftentimes involves interest in developing the same types of fuels and claddings) and preparing to manage and dispose of the resulting SNF.

Board Findings, Conclusions, and Recommendations

After discussing and examining the information presented at the fact finding meeting and the public meeting, the Board has derived several findings, conclusions, and recommendations as noted below.

Findings and Conclusions:

- Certain other countries developing ATFs have taken waste management issues (disposability, cost, fuel matrix composition, etc.) into account when approving new fuel designs for use in nuclear reactors. In contrast, in the United States there appears to be little, if any, consideration of waste management issues during the development of new ANF/ATF.

- Pursuant to the Congressional direction to improve the safety of LWR fuel technology for existing reactors in the event of accidents, development of ANF/ATF is one of DOE-NE's highest priority R&D programs. The R&D is conducted at various national laboratories and is led by commercial fuel vendors. However, the Board notes that the current coordination and level of integration on R&D activities among the two involved DOE-NE offices responsible for ANF/ATF development (the Office of Nuclear Fuel Cycle and Supply Chain) and spent ANF/ATF disposition (the Office of Spent Fuel and Waste Disposition) appear to be limited, and only preliminary considerations have been made regarding plans for storage and transportation of the SNF that will result from the use of ANF/ATF.

- DOE is working with organizations in other countries (e.g., the Nuclear Energy Agency, the Institut de Radioprotection et de Sûreté Nucléaire, and the Japan Atomic Energy Agency) on a variety of topics related to ATFs. The Board commends DOE for funding this work and helping to facilitate collaborative research with international partners, but the Board notes that collaborative international research on SNF management including disposal of ANF/ATF is also warranted.

- Since the 2011 Fukushima Daiichi accident, early stakeholder and general public engagement on advancements in nuclear technology have had an impact on public trust in nuclear energy. The Board observes that, in some other countries, the same considerations for early stakeholder and public engagement in ATF development occur in all parts of the fuel cycle. This early engagement provides additional confidence in the acceptability of a new fuel design for current waste management infrastructure and is considered a part of successful implementation of the new fuels. Within the DOE-funded ATF program, there is currently only limited information available to the public regarding the impacts of the new fuels on the various stages of the fuel cycle.

- The scope of the high-level "gap analysis" report (SNL 2021) on managing SNF resulting from the use of ANF/ATF is limited to storage and transportation. The Board notes that relevant fuel vendor data and results, international lessons learned, and preliminary disposal considerations for ATF and other advanced fuels would enhance the next update of the gap analysis report.
  - Sweden, for instance, considers fuel matrix dissolution rate in a repository environment an important consideration for waste management planning when it is reviewing new, proposed ANF/ATF.

- DOE's current SNF post-irradiation examination plans are limited to testing specimens that are like the zirconium alloy-clad "sibling pins" in DOE's HDRP and will be tested in the same facilities. Some of the other proposed ATF claddings include very different materials compared to zirconium alloy or coated zirconium alloy ATF claddings, paired with different fuel forms, and could include fuel designs with higher enrichments of uranium. Thus, ANF/ATF may require different approaches and facilities.

- DOE's investment in ATF and its commitment to support fuel vendors is substantial; thus, DOE may be able to leverage that support to obtain some of the fuel performance data it needs from the vendors to prioritize R&D programs and to optimize the entire fuel cycle, including disposal.
  - Characterization data obtained from irradiated ATF specimens and the specimens themselves could be shared among DOE offices, including the Office of Spent Fuel and Waste Disposition.
  - The high-level gap analysis report on ATF storage and transportation (SNL 2021) was prepared without access to or the opportunity to consider relevant and important fuel vendor data, including the potential impacts of using higher enrichments nuclear fuels that can achieve higher burnups. Higher enrichments and higher burnups, among other SNF characteristics, can significantly affect how SNF performs during storage, transportation, and disposal.

Board Recommendations:

1. *The Board recommends that the DOE Office of Spent Fuel and Waste Disposition coordinate and integrate in an ongoing fashion with the DOE Office of Nuclear Fuel Cycle and Supply Chain on preparing for the storage, transportation, and disposal of SNF resulting from deploying ANF/ATF in existing LWRs. Steps that can be taken include, but are not limited to, forming collaborative working groups, sharing laboratory*

facilities and equipment, and sharing irradiated fuel specimens and fuel characterization data.

2. *The Board recommends that the next update to DOE's gap analysis report for SNF management be expanded in scope beyond storage and transportation to include disposal of SNF resulting from the use of ANF/ATF.*

3. *The Board recommends that DOE-NE work to improve its access to fuel characterization data obtained during DOE-sponsored ANF/ATF development programs. Some of these data are important for assessing and closing the knowledge gaps related to ANF/ATF storage, transportation, and disposal.*

4. *The Board recommends that DOE evaluate the approaches used and experiences gained in other countries regarding early consideration of the potential impacts of new ANF/ATF designs on SNF storage, transportation, and disposal. Based on the lessons learned in other countries, DOE should implement mechanisms to provide feedback to ANF/ATF development work that accounts for the impact of these new fuels on SNF management and disposal. The feedback process can also be used to prioritize SNF management research and development.*

5. *The Board recommends that DOE increase the accessibility of ATF information to the general public in the interest of clearly demonstrating openness, facilitating public engagement, factoring in public concerns in planned R&D, and avoiding the perception that there may be unexplored or unresolved issues (including issues affecting SNF management and disposal) related to the introduction of the new fuel designs.*

The Board thanks DOE 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

This Appendix provides further information about the types of advanced nuclear fuels (ANF) including accident tolerant fuels (ATF) within the scope of the public meeting. The ANF/ATF included in the discussions can be divided into two groups: "near-term" fuels and "longer-term" ATFs, which include claddings and fuel designs. Near-term ANF/ATF generally include chromium-coated and ARMOR-coated zirconium alloy claddings and doped UO_2 fuels (i.e., the UO_2 fuel matrix includes additives to improve the performance of fuel during irradiation). A doped UO_2 fuel has a higher density than traditional UO_2 fuel. In these fuels, sintering additives of chromium and aluminum (as in the doped UO_2 pellets) are typically incorporated to help form a denser fuel matrix that improves fuel performance and helps extend core cycle length (OECD 2018).

In contrast, longer-term ATF designs will require more R&D and potential, additional regulatory changes to support commercial operation. Longer-term ATF cladding materials include iron-chromium-aluminum (FeCrAl) and silicon carbide (SiC) composite claddings, that will replace zirconium alloy claddings and are envisioned to be paired with doped or other high density fuels. Longer-term fuel matrix designs aim to achieve higher fuel density, make use of higher enrichments of uranium-235, and achieve higher burnups. Although ATFs with FeCrAl cladding were among the first to be tested in commercial nuclear reactors (see Figure A1), licensing of the FeCrAl cladding concept has fallen behind that of the other near-term ATF concepts.

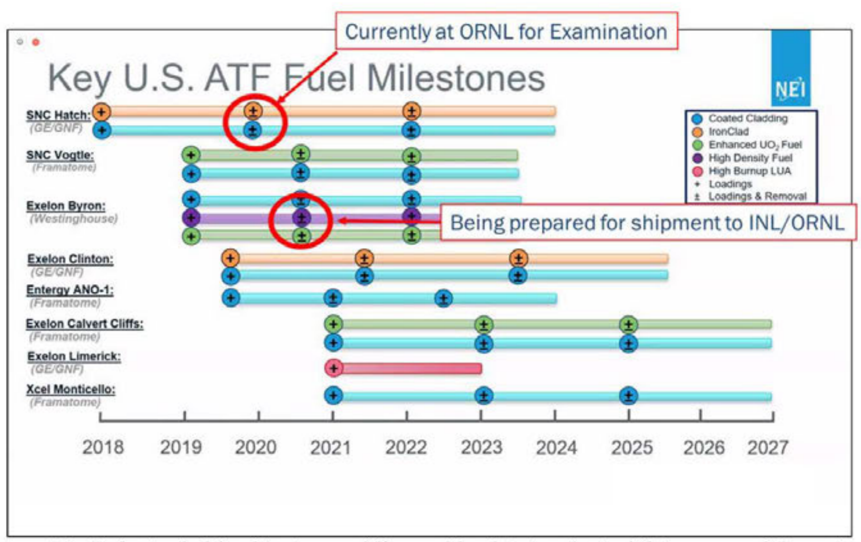

Figure A1. Industry-led lead test assemblies and lead test rods at eight commercial reactors for full-scale irradiation testing of ATFs. (Original image source: Nuclear Energy Institute, 2021, modified and adopted from Dan Wach's presentation, May 12, 2021, NWTRB Spring 2021 Meeting, https://www.nwtrb.gov/docs/default-source/meetings/2021/may/wachs.pdf?sfvrsn=4; Acronyms: SNC is Southern Nuclear Company; ANO is Arkansas Nuclear One; LUA is lead use assembly).

Therefore, the Board considers the FeCrAl cladding concept to be grouped among the longer-term ANF/ATF designs. Other longer-term fuel matrix compositions like uranium nitride (UN) are being actively considered by the fuel vendors; uranium silicides were once considered a part of the DOE ATF program but are no longer considered an ATF candidate due to compatibility issues with LWR water chemistry.

Figure A1 was presented by Idaho National Laboratories (modified from original source: NEI 2021) in its presentations. The candidate ATF fuels (see Figure A1, legend) and the status of loadings and removals of lead test assemblies (commercial irradiation testing) are shown. The ATF design concepts being tested include chromium and other coatings on zirconium alloy cladding, FeCrAl cladding, chromium and aluminum doped UO_2, and other fuel loadings that are intended to be utilized to higher burnups. The left side of Figure A1 indicates the eight commercial reactors that are involved in the full-scale testing demonstrations; the fuel vendor name appears in parentheses. The ATF fuel loadings (+) and removals (-) are indicated in the figure. The graphic further indicates that two sets of lead test assemblies have completed their irradiation cycles and have been discharged for shipment and post irradiation examinations at national laboratories.

Another longer-term fuel design is the Lightbridge Fuel design which is a private venture with some on-going DOE national laboratory support, such as GAIN [Gateway for Accelerated Innovation in Nuclear] vouchers that give recipients access to DOE's national laboratory facilities for research. Lightbridge has been award GAIN vouchers to support initial irradiation testing and fuel fabrication for their fuel. Lightbridge Fuel is a uranium-zirconium alloy helical rod with a metallurgically bonded zirconium-niobium cladding. Many of these new fuel designs, including Lightbridge Fuel, use uranium enrichments[9] of between 5% and 20% uranium-235 and will achieve higher burnups than conventional fuel designs. This can improve fuel efficiency and cost savings during reactor operations.

References:

OECD. 2018. *State-of-the-Art Report on Light Water Reactor Accident-Tolerant Fuels*. NEA No. 7317. Paris, France: Nuclear Energy Agency. Organization for Economic Co-Operation and Development. October.

SNL. 2021. *High Level Gap Analysis for Accident Tolerant and Advanced Fuels for Storage and Transportation.* SAND2021-4732, Revision 6. Albuquerque, New Mexico: Sandia National Laboratories. April 2021.

[9] Note the current U.S. LWR fleet uses low enriched uranium, i.e. uranium with an assay below 5% uranium-235. DOE is funding the development of a commercial domestic HALEU capability. See "What is High-Assay Low-Enriched Uranium (HALEU)," https://www.energy.gov/ne/articles/what-high-assay-low-enriched-uranium-haleu, April 7, 2020 (last visited 6/9/2021).

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

October 14, 2021

Mr. William (Ike) White
Acting Assistant Secretary for Environmental Management
U.S. Department of Energy
1000 Independence Ave., SW
Washington, D.C. 20585

Dear Mr. White:

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 Summer 2021 public meeting, held virtually on August 24, 2021. The purpose of the meeting was to review information on the U.S. Department of Energy (DOE) technology development activities related to aluminum-clad spent nuclear fuel (ASNF) packaging, drying, and dry storage. This letter presents the Board's findings and conclusions 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-2021-virtual-board-meeting---august-24-2021. The meeting transcript and an archived recording of the webcast also are posted on the same web page.

As you know, the DOE Office of Environmental Management (DOE-EM) manages ASNF primarily at the Idaho National Laboratory (INL) and at the Savannah River Site in South Carolina. Since 2017, DOE has been supporting technology development work to study extended dry storage of ASNF, including corrosion of aluminum cladding, radiolytic gas generation, and drying processes to remove residual water from the cladding corrosion layers (also called oxide layers or oxyhydroxide layers). INL manages the integrated technology development program for DOE. The Board commends DOE for sponsoring this research.

Public Meeting

U.S. DOE Support of Research on ASNF Packaging, Drying and Dry Storage. Mr. Mark Senderling and Dr. John Shultz, DOE-EM, described the DOE support for ASNF research, through the DOE-EM technology development program. In 2017, the DOE Spent Nuclear Fuel Working Group issued a report that identified technical data needs related to ASNF dry storage.[1] DOE-EM provided funding for research to meet the data needs, and progress has been made in achieving a better understanding of ANSF packaging, drying, and extended dry storage. Dr. Shultz stated that DOE has prioritized safety and efficiency in these activities. Dr. Shultz also

[1] DOE Spent Nuclear Fuel Working Group Report, *Aluminum-Clad Spent Nuclear Fuel: Technical Considerations and Challenges for Extended (>50 Years) Dry Storage*, DOE/ID RPT #1575, June 2017.

described the organization of the technology development program and noted that the ASNF work is a congressionally-directed activity, funded at $5M per year.

The Board notes that DOE incorporated recommendations from the Board's 2017 report on DOE-managed SNF, as well as recommendations from DOE's Spent Nuclear Fuel Working Group report, to provide the framework for its research. The Board suggests that DOE continue to provide resources (personnel, facility access, etc.) for follow-on research as the technology development program progresses.

Review of the Research Program on ASNF Packaging, Drying, and Dry Storage. Dr. Josh Jarrell, INL, provided an update on the technology development program and its progress since 2017. In the 2017 Spent Nuclear Fuel Working Group report, DOE identified five main technical data needs for ASNF extended dry storage. In response, INL designed a research program with six main research tasks and an Instrumented Lid Project for sensor development. Among the six research tasks, Dr. Jarrell indicated that Task 1 (behavior and chemistry of hydrated oxide layers on ASNF) and Task 4 (performance of Advanced Test Reactor ASNF in existing dry storage systems) are complete. Tasks 2, 3, 5, and 6 are continuing and are discussed in more detail in later sections of this letter.

Dr. Jarrell offered preliminary conclusions based on the research completed to date. He stated that ASNF, including high dose-rate SNF from the Advanced Test Reactor, in vented dry storage at INL is safe for continued, extended dry storage (> 50 years) without corrosion degradation challenges. He also stated that ASNF from L Basin at the Savannah River Site can be safely placed in sealed canisters for dry storage pending ultimate disposal. To provide more confidence in the research results, INL arranged for Pacific Northwest National Laboratory (PNNL) to conduct an independent review of Tasks 2 and 3 and offer suggestions for improvement.

The Board commends DOE and INL for enabling the independent peer review by PNNL. The Board encourages INL to further evaluate whether Advanced Test Reactor fuel bounds all other ASNF types, especially with regard to the cumulative dose that is expected over a 50-year storage period.

Drying of ASNF Surrogates (part of Task 5) and Scale-up Radiolysis Testing of ANSF in L Basin at the Savannah River Site (part of Task 6). Ms. Rebecca Smith, INL, discussed research to study the drying of ASNF surrogates. This research was a collaborative effort, including INL, Savannah River National Laboratory (SRNL), Holtec International, and the University of South Carolina. The testing utilized an engineering-scale drying vessel, and experiments were developed to dry lab-grown surrogate materials using either forced helium dehydration or vacuum drying. Results from Task 5 indicate significant progress in understanding the removal of residual water from hydrated oxide layers. Forced helium dehydration drying is significantly more effective than vacuum drying at the removal of water that is chemically bound to the oxide layers. Future work will be focused on providing more experimental data that can be used to benchmark predictive process models (see Task 3).

Dr. Anna d'Entremont, SRNL, described radiolysis testing of ASNF surrogates and reactor-exposed aluminum cladding samples in a mini-canister environment. The test apparatus allows

2

on-line monitoring and data acquisition that can be used to evaluate the impact of drying and help benchmark predictive models. Results indicate that elevated temperature drying removes more water, thereby reducing subsequent radiolytic gas generation. SRNL plans additional drying tests using different irradiated cladding specimens to gather more data on hydrogen gas generation.

The Board commends DOE and INL for collaborating with industry and universities while conducting the ASNF research. The Board also commends DOE and the national laboratories for their progress on developing experiments to perform drying tests to better understand the different drying processes and removal of residual water. The Board encourages DOE to continue these experiments, which can generate useful data to inform predictive models and to validate results obtained from surrogate materials.

Radiolytic Gas Generation due to Aluminum-clad SNF Corrosion Layers (part of Task 2). Dr. Greg Horne, INL, discussed laboratory testing designed to measure radiolytic hydrogen gas generation from the water retained in ASNF corrosion layers. The testing examined hydrogen gas generation as a function of absorbed gamma dose, corrosion layer composition, gaseous environment, relative humidity, and temperature. Results indicated that hydrogen gas generation increases with temperature and relative humidity and is more pronounced in argon or nitrogen atmospheres (compared to helium atmospheres). Future work includes investigations of how corrosion layer surface compositions change with absorbed dose upon reaching steady state and what effect alloy composition has on hydrogen gas production.

The Board suggests that DOE explore more fully the maximum expected dose for ASNF in the DOE inventory to ensure the testing is bounding. The Board also suggests that DOE conduct a more detailed evaluation of the fate of oxygen that is produced during radiolysis of water in sealed SNF canisters to provide support for assumptions in modeling and simulations. The Board encourages DOE to support additional surface characterization of surrogate sample materials prior to future drying tests.

Modeling and Simulation Results for ASNF in DOE Standard Canisters (part of Task 3). Dr. Alex Abboud, INL, described computer modeling efforts focused on predicting the behavior of ASNF in sealed dry storage canisters for up to 50 years. Key parameters to be predicted are hydrogen and oxygen gas concentrations and internal canister pressure. Several different scenarios have been modeled, including canisters loaded with different types of ASNF, different oxide layers on the cladding, and different quantities of air in-leakage. The INL model includes a 3D computational fluid dynamics code one-way coupled with a chemistry code that predicts chemical species evolution, including gas generation due to radiolysis. Early model predictions for hydrogen concentrations were compared to the experimental results of Tasks 1 and 2 and shown to be in reasonable agreement. In most scenarios modeled, hydrogen was predicted to accumulate to concentrations above 4%, but oxygen is assumed to be irreversibly scavenged, so no flammable gas mixture is predicted. The maximum predicted pressure inside a canister was 2.6 atmospheres (compared to a canister limit of 34 atmospheres).

The Board encourages INL to implement a well-documented verification and validation process for its modeling software. The Board also suggests that INL work to include formal uncertainty quantification in its modeling efforts to improve confidence in model predictions, since decisions related to safely storing ASNF for an extended time period will be based mainly upon these model predictions.

Development of Wireless Sensors for Dry-Storage of ASNF (Instrumented Lid Project). Dr. Evans Kitcher, INL, presented details of the Instrumented Lid Project to develop wireless sensors for use in vented ASNF canisters that are stored in the INL CPP-603 facility. These vented canisters, holding primarily Advanced Test Reactor SNF, are different than the proposed, sealed DOE Standard Canister. Wireless sensors would provide real-time monitoring of temperature, relative humidity, and hydrogen concentration inside the canister. Dr. Kitcher noted that INL is partnering with Idaho State University and Westinghouse to develop the sensors and fabricate the needed components.

The Board notes that this development work has many parallels with work sponsored by the DOE Office of Nuclear Energy (DOE-NE) to develop remote sensor technology applicable to canisters holding commercial SNF. The Board suggests that DOE-EM coordinate with DOE-NE and the Electric Power Research Institute on the development of wireless sensors for SNF canisters.

Future activities related to ASNF. As an extension of the work leading to dry storage of ASNF, the Board encourages DOE to consider the following:

- Ensure that the Nuclear Regulatory Commission transportation requirements are considered when planning follow-on research on ASNF and in advancing the design of the DOE Standard Canister for DOE-managed SNF.
- Evaluate the amount of residual water that may remain in an ASNF canister after drying and evaluate the potential consequences of that water (e.g., corrosion, creation of flammable gas mixtures, and pressure buildup).
- Continue to develop the wireless sensor technology and to look for other applications (e.g., use in waste disposal environments), while also paying close attention to cybersecurity precautions.

The Board thanks you and your staff members for assisting with the organization of the Summer 2021 Board Meeting. The Board also thanks researchers from the national laboratories for preparing and giving detailed technical presentations. The Board staff will be contacting representatives of DOE-EM and the laboratories with follow-up questions. The Board looks forward to continuing its 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

UNITED STATES
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December 30, 2021

Dr. Kathryn Huff
Principal Deputy Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Dr. Huff:

On behalf of the U.S. Nuclear Waste Technical Review Board (Board), I want to thank you and your staff, and the staff from the national laboratories, for supporting the Board's Fall 2020 Meeting. In this virtual meeting, held on December 2–3, 2020, the Board reviewed information on the U.S. Department of Energy Office of Nuclear Energy's (DOE-NE) non-site-specific disposal research program. This letter presents the Board's findings, conclusions, and recommendations resulting from the meeting. The agenda and meeting presentation materials are on the Board's website at: https://www.nwtrb.gov/meetings/past-meetings/fall-2020-board-virtual-meeting----december-2-3-2020. A meeting transcript is also available there. The agenda and presentation materials from a virtual fact-finding meeting on November 4–5, 2020 are on the same web page. This fact-finding meeting enabled the Board to prepare for the December 2020 public meeting.

Congress created the Board in the 1987 Nuclear Waste Policy Amendments Act (Public Law 100-203) to evaluate the technical and scientific validity of activities undertaken by the Secretary of Energy to manage and dispose of the nation's spent nuclear fuel (SNF) and high-level radioactive waste (HLW) and to advise Congress and the Secretary on technical issues related to nuclear waste management. For this meeting, the Board focused on DOE's non-site-specific disposal research and development (R&D) program that has the goals of:

- Providing a sound technical basis for multiple viable disposal options in the United States.
- Increasing confidence in the robustness of generic disposal concepts.
- Developing the science and engineering tools needed to support disposal concept implementation.[1]

[1] This letter uses the term "disposal concept" as defined by DOE to refer to geologic disposal in a repository in either crystalline, salt, or argillite host rock. These are three types of host rocks that other nations are investigating for geologic disposal of SNF and HLW. Likewise, DOE uses the term "disposal option" to refer to the collection of specific repository features including engineered barriers, such as backfill, the type of disposal waste package, such as a dual-purpose (storage and transportation) canister, which could be disposed of without repackaging stored SNF,

DOE's program examines disposal options in crystalline, salt, and argillite host rocks.

The Fall 2020 meeting on disposal research builds on information gathered during several previous Board reviews. In 2014, the Board reviewed DOE's salt disposal R&D activities[2] and made several recommendations to DOE.[3] In 2019, the Board reviewed recent advances in repository science and operations from international underground research laboratory (URL) collaborations.[4] That information formed the basis for the Board's 2020 report entitled *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*.[5] At its Summer 2020 meeting, the Board reviewed DOE's R&D on geologic disposal of commercial SNF in dual-purpose canisters.[6]

At its Fall 2020 meeting, the Board received an opening presentation from Mr. Tim Gunter (DOE-NE) that summarized DOE's non-site-specific disposal research program. The Board then heard several presentations from researchers at Sandia National Laboratories. These presentations described the program's technical direction and R&D activities related to crystalline, salt, and argillite host rock. Speakers from the IGD-TP (Implementing Geological Disposal of radioactive waste Technology Platform) group[7] and the United Kingdom's Radioactive Waste Management described their disposal research strategies. Sandia National Laboratories and Lawrence Berkeley National Laboratory staff described prioritization of cross-cutting R&D activities. One presentation described an unsaturated alluvium reference case, disposal of dual-purpose canisters (DPCs), and the Geologic Disposal Safety Assessment (GDSA) framework.[8] Another presentation addressed the engineered barrier system (EBS) and the HotBENT experiment in Switzerland. The final presentation addressed DOE's prioritization of its international activities and DOE's Disposal Research R&D 5-Year Plan. The Board's findings, conclusions, and recommendations are summarized immediately below. The enclosure to this letter provides more information on the presentations and the Board's findings, conclusions, and recommendations, as well a listing of several areas on which the Board plans to follow-up.

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and waste emplacement geometry (vertical or horizontal with respect to the orientation of emplacement tunnels) that comprise a disposal option.

[2] https://www.nwtrb.gov/meetings/past-meetings/spring-2014-board-meeting

[3] https://www.nwtrb.gov/docs/default-source/correspondence/rce025.pdf?sfvrsn=11

[4] https://www.nwtrb.gov/meetings/past-meetings/spring-2019-workshop-april-24-25-2019

[5] https://www.nwtrb.gov/docs/default-source/reports/nwtrb-url-report.pdf?sfvrsn=9

[6] https://www.nwtrb.gov/meetings/past-meetings/summer-2020-board-meeting

[7] The IGD-TP group is dedicated to initiating and carrying out European strategic initiatives to facilitate the stepwise implementation of safe, deep geological disposal of spent fuel, high-level waste and other long-lived radioactive waste. It aims to address the remaining scientific, technological and social challenges, and support European waste management programs.

[8] DOE uses the term "reference case" to refer to a specific modeling case that DOE analyzes using the GDSA framework to assess a disposal option.

Board Findings, Conclusions, and Recommendations

After discussing and examining the information presented at the fact-finding meeting and the public meeting, the Board has derived several findings, conclusions, and recommendations as noted below. Summary findings and conclusions follow. The enclosure documents the many specific findings that are the basis of the summary findings.

Summary Findings and Conclusions

Board Findings

- Other countries in an early radioactive waste management and disposal program stage have identified challenges to ensuring and carrying out an acceptable early-stage R&D program. Successful repository implementation needs a legal framework that clearly describes the roles of the implementer, regulator, and society. Procedures for conducting the site selection and implementing the repository program must be accepted by all these parties. Success requires a long-term political commitment.

- In general, other countries believe, based on their experiences, that the major challenges for repository implementation are not primarily technical, but rather, involve fully addressing the societal concerns and challenges, including taking account of societal perspectives as well as technical objectives in developing the technical research to be conducted.

- Other countries are considering the development of repositories in crystalline rock, salt, and argillite that use host-rock-specific repository designs. DOE collaborated with these countries and took account of information and experience from their programs in developing and rapidly advancing its R&D program.

- DOE can increase its chance of success by benefitting from lessons learned by other countries and organizations like the IGD-TP group, such as the need to clearly communicate why a disposal option should be considered safe.

- Overall, DOE has made good progress toward developing the technical bases and the tools to support the evaluation of multiple disposal options. Regular program planning, prioritization of R&D activities, and integration among its program elements and other countries are occurring. DOE has taken the initiative to develop a knowledge management program.[9] Through the HotBENT experiment, DOE has advanced its understanding of coupled thermal-hydrologic-mechanical-chemical processes in the EBS at high temperatures in crystalline and argillite host rocks. DOE has adopted advanced mathematical methods used in their performance assessment calculations that have reduced the computational time by a factor of 35 thus allowing for more robust and detailed analysis of performance and uncertainties therein.

[9] Knowledge management is the process of creating, sharing, using, and managing the knowledge and information of an organization. It refers to a multidisciplinary approach to achieve organizational objectives by making the best use of knowledge.

- DOE can advance its program by:
    - Fostering stakeholder engagement, consistently and clearly explaining to stakeholders the various disposal options, and better defining the safety functions of the engineered barriers and geologic setting for each disposal option.
    - Improving how it sets priorities and by further developing the GDSA framework.
    - Addressing processes that will occur upon instantaneous dissolution of DOE SNF.
    - Addressing the effects of clay layers that are expected in bedded salt formations.
    - Using natural analogue information that can inform understanding of the performance of bentonite and argillite at high temperatures over long periods.

Board Recommendations

The enclosure includes nine specific recommendations that are reproduced here.

Recommendation 1. The Board recommends that DOE use a well-developed technology maturity scoring method as one of the factors in setting R&D priorities.

Recommendation 2. The Board recommends that DOE assess the need for and scope of new technical siting guidelines for a repository for each of its potential disposal concepts (e.g., disposal in an argillite host rock).

Recommendation 3. The Board recommends that, when DOE is developing models for disposal options, there should be more focus on how the experimental data that are needed to set values of modeling parameters will be acquired.

Recommendation 4. Because DOE-NE models all DOE SNF as instantaneously dissolving once a waste package is breached in a repository, the Board recommends that DOE-NE include all processes within the repository that would occur upon instantaneous dissolution of DOE SNF, such as gas generation from the dissolution of uranium metal, in the GDSA framework or provide a technical basis that demonstrates those processes would not adversely impact engineered barriers and overall system performance.

Recommendation 5. DOE should assess whether it needs to develop reference cases and identify supporting R&D for disposal options in domal salts and brittle argillites and, if DOE decides these are not needed, provide a rationale for the decision.

Recommendation 6. The Board recommends that DOE's testing and models address the effects of clay layers in bedded salt formations and their impact on salt repository performance.

Recommendation 7. The Board recommends that DOE consider natural analogues in its strategic planning and determine whether a natural analogue exists that could be used to evaluate the consequences of aging of bentonite and argillite at high temperatures over longer periods than those possible in laboratory or underground research experiments.

Recommendation 8. The Board recommends that DOE become a member of the IGD-TP organization and focus on lessons learned, mainly societal information sharing, communication, and ways of building public confidence and trust, from countries that have advanced their repository programs beyond concept evaluation.

Recommendation 9. The Board recommends that DOE make clear and effective communication of its disposal options, and their associated barriers, barrier functions, and supporting technical bases, an integral part of its disposal R&D program. DOE should use a communication approach that is informed by stakeholder input and can consistently describe in verbal and graphic forms the claims, argument and evidence supporting the disposal option. These should include pre-disposal management activities such as any repackaging or storage that are required prior to disposal.

The Board would like to thank you again for the support of DOE-NE staff members during the Board's planning and preparation for the Fall 2020 Board Meeting. The presentations and interactions during these meetings provide valuable information for the Board as it carries out its mission to review and evaluate DOE activities related to the management and disposal of SNF and HLW. We look forward to future productive interactions with you and your staff.

Sincerely,

{Signed by}

Jean M. Bahr
Chair

Enclosure

cc: Dr. Kimberly Petry, DOE-NE
Dr. William Boyle, DOE-NE
Mr. Timothy Gunter, DOE-NE

Enclosure

Fall 2020 Board Meeting Summary, Findings, and Recommendations

As a complement to the letter, this enclosure summarizes the contents of the presentations made at the Fall 2020 Board Meeting. Interlaced with the presentation summaries are the Board's findings and recommendations that arose from the Fall 2020 meeting presentations and discussions, and from previously reviewed written materials. The topics that were addressed are underlined, **the findings are noted in bolded text** *and the recommendations in italics.*

U.S. Department of Energy (DOE) Disposal Research Program: Program Overview, Purpose, Scope, and Goals. Mr. Timothy Gunter, Program Manager for Disposal Research in the Office of Spent Fuel and Waste Science and Technology of DOE's Office of Nuclear Energy (DOE-NE), summarized DOE's non-site-specific disposal research program. Mr. Gunter described the program's mission and purpose and a disposal research program conceptual timeline (Figure E-1). During his talk, Mr. Gunter described how DOE sets priorities for research and development (R&D) activities. The program's goals include developing a sound technical basis for multiple U.S. disposal options and developing the science and engineering tools needed to evaluate disposal concepts. The program uses international experience and develops the U.S. program capabilities by collaborating with other international programs. The R&D program focuses on disposal in salt, crystalline, and argillite host rocks and addresses disposal of dual-purpose canisters (DPCs).

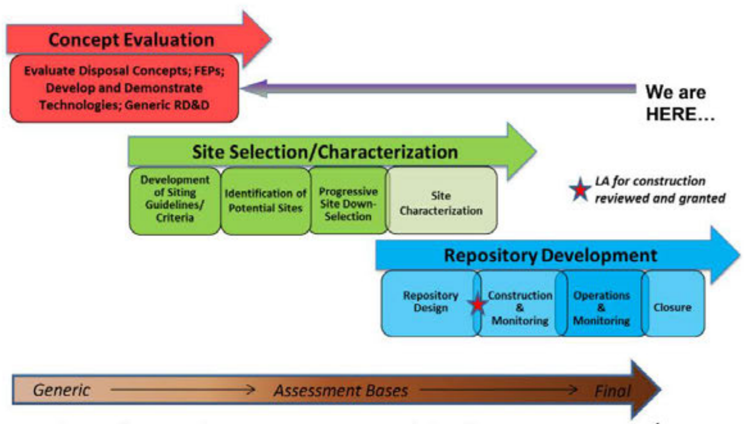

Figure E-1. Disposal research program conceptual timeline (Gunter 2020).[1]

The Board is encouraged by DOE's continued focus and R&D progress on developing generic options for managing spent nuclear fuel (SNF) and high-level radioactive waste (HLW) disposal. DOE deserves credit for enabling national laboratory staff to engage with

[1] Gunter, T.C., 2020, *Disposal Research Program: Program Overview, Purpose, Scope and Goals*, https://www.nwtrb.gov/docs/default-source/meetings/2020/december/2_gunter.pdf?sfvrsn=4.

international programs, and for supporting multi-year experiments in underground research laboratories (URLs) that help propel the program.

Mr. Gunter described factors that affect setting priorities for program activities. **Applying a form of technology maturity scoring, such as Technology Readiness Levels, which DOE uses to assess the maturity of technologies needed in design projects,[2] or Scientific Readiness Levels™, which the United Kingdom (UK) disposal program uses, can be beneficial.** These techniques could inform DOE about the maturity of its disposal options and further focus the R&D program.

Recommendation 1. The Board recommends that DOE use a well-developed technology maturity scoring method as one of the factors in setting R&D priorities.

Mr. Gunter indicated that development of siting guidelines and criteria for selecting potential repository sites follows concept evaluation (Figure E-1). He did not address the decades-old siting guidelines[3] and whether these guidelines are appropriate for use with DOE's disposal options, including potential higher temperature designs associated with the disposal of DPCs, or would need to be updated before being used to guide the current R&D program. **Site selection criteria are important to understanding what questions have to be answered, and in turn, that could help define what DOE R&D priorities should be.**

Recommendation 2. The Board recommends that DOE assess the need for and scope of new technical siting guidelines for a repository for each of its potential disposal concepts (e.g., disposal in an argillite host rock).

Technical Approach and Prioritization of Activities. Dr. David Sassani, Sandia National Laboratories (SNL), addressed the planning and prioritization efforts for the disposal R&D program. He described the 2012 Roadmap, and the priorities and results in the roadmap. Dr. Sassani also presented the evaluation bases, major findings, gaps, and defined focus areas for the 2019 Roadmap Update.

The purpose for the 2012 Roadmap was to set priorities systematically for the disposal R&D program. The 2012 Roadmap effort used repository safety functions, such as containment and limiting release of radionuclides, and features, events, and processes to identify R&D issues. To set priorities for each issue, DOE determined the issue's importance to safety and state-of-art-knowledge level. DOE assessed these metrics at four points in time along the conceptual timeline (Figure E-1). To plan work, disposal R&D program staff then combined results for individual issues into higher-level topic areas. Example topic areas are design concept development, generic disposal system modeling, knowledge management, and URLs. Dr. Sassani said that by around 2017, the disposal R&D program had addressed many of the 2012 Roadmap priorities but had identified some additional R&D gaps. These gaps included waste package degradation and the engineered barrier system (EBS) chemical environment resulting

[2] https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-09-admchg1/@@images/file.

[3] "10 CFR 960—General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories," 49 *Federal Register* 47,752, December 6, 1984.

from coupled thermal-hydrologic-chemical processes. Both the disposal program progress and the gaps suggested that it was appropriate to re-evaluate the disposal R&D program priorities which led to the 2019 roadmap effort.

The 2019 Roadmap Update efforts set priorities for the R&D of a mature program. The 2019 effort did not use barrier functions and separate decision points as part of setting priorities. DOE and national laboratory staff assessed existing activities, identified research gaps (gap activities), and then assigned priorities for all R&D activities. For the update, for each R&D activity, the large staff team developed the importance to safety and state-of-art-knowledge level ratings and justifications. The team assessed these factors for each host rock and cross-cutting activity groups such as DPC, EBS, performance assessment, and international activities. The team used consensus evaluations of the importance to the safety case values and the state-of-art-levels for each activity to decide an overall low-medium-high R&D priority score. Based on the score, the team assigned a priority ranking to each activity. For example, a high priority R&D activity had to have both high importance to the safety case and fundamental gaps in method or fundamental data needs, or both.

The Board's findings and recommendation on DOE's technical approach and prioritization of activities, presented here, are based on Dr. Sassani's presentation and on subsequent presentations provided by national laboratory staff. **A prioritization process that focuses on safety functions, such as used in the 2012 Roadmap, is helpful to identify significant gaps and to communicate how disposal options will work.** Such an approach defines the functions of each barrier[4] and the degree to which each barrier must perform its functions. If DOE decides to dispose of SNF in DPCs, temperatures in the near field of a repository could reach up to 200 °C, which is 100 °C higher than the temperature limits used by other countries. Higher temperatures will affect the performance of engineered barriers including the SNF, waste package, and bentonite buffer. DOE has not identified consistently the information it needs to support barrier performance in higher temperature alternatives.[5] The Board is interested in learning more from DOE on how barrier functions and expected performance would differ at these higher temperatures. **DOE needs to specify modeling requirements and how it will get the data to set modeling parameter values.**

Recommendation 3. The Board recommends that, when DOE is developing models for disposal options, there should be more focus on how the experimental data that are needed to set values of modeling parameters will be acquired.

The Board would like to better understand the effort and time DOE needs to address each of the high priority activities, how DOE tracks the completion status of high priority activities, and when all high priority activities will be completed.

[4] A barrier may be a geologic feature, an engineered structure, a canister, a waste form with physical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around the waste, provided that the material substantially delays movement of water or radionuclides.

[5] DOE's activity descriptions related to the high temperature alternatives use different temperatures (150, 200, and 250 °C) to describe the high temperature alternatives and for which information is needed to close individual R&D activities (See the 2019 Roadmap Update, *DOE SFWST Campaign R&D Roadmap Update Rev.1.*, https://www.osti.gov/servlets/purl/1559571).

DOE has used relevant international data sets and approaches for modeling the flow and transport processes in the far-field of the different host rocks, and for modeling parts of the EBS and the near-field.[6] During the Board questioning, Dr. Sassani said that modeling efforts to incorporate the biosphere into its overall performance assessment framework, known as the Geologic Disposal Safety Assessment (GDSA) framework, are at an early stage. Like its far-field modeling efforts, DOE could use international biosphere data sets and modeling approaches to its advantage.

Host Rock Presentations. Presentations on crystalline, salt, and argillite host rocks addressed disposal options and R&D activities. Based on those presentations, the Board provides findings and recommendations on the overall generic host rock R&D effort. The Board's evaluation of each host rock R&D activities follows the Board's overall comments.

DOE uses one or more reference cases for each host rock type. Multiple reference cases for each host rock reflect alternatives with different waste package capacity and orientation. For example, one crystalline rock reference case uses a vertical waste package that contains 4 pressurized water reactor (PWR) commercial SNF assemblies whereas another crystalline rock reference case uses a horizontal waste package containing 12 PWR assemblies.

DPCs can contain up to 37 PWR assemblies and most commercial SNF in dry storage is in DPCs. A reference case that uses waste packages that contain fewer SNF assemblies than the smallest DPCs, which contain 24 PWR assemblies, implies repackaging of stored SNF into the smaller waste package.[7] Repackaging would need to occur before emplacing the waste in a repository. DOE would need to store existing DPCs many decades to hundreds of years before the DPCs could be as cool as 4 or 12 PWR assembly-containing waste packages.

In describing disposal options for a repository in a crystalline host rock or argillite host, DOE should have explained that repackaging of DPCs or storage of DPCs many decades to hundreds of years prior to emplacement may be required depending on disposal option details, which DOE has done previously.[8] **The Board positively notes Dr. Kris Kuhlman's, SNL, presentation on salt R&D.** Dr. Kuhlman presented the best account of how a host rock contributes to safety functions. Dr. Kuhlman also described the repository attributes for safe disposal and addressed the duration of pre-disposal storage. **The Board finds that consistently describing the disposal options, including pre-disposal waste management activities such as repackaging or storage, is important, especially as DOE moves forward with its consent-based siting process that would be used to identify sites to store the nation's spent nuclear fuel.**

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[6] See *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*, January 2020, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

[7] See *Letter from Chair Jean M. Bahr to the Honorable Rita Baranwal, Assistant Secretary for DOE-NE; January 11, 2021*, related to disposal of commercial SNF contained in DPCs in a geologic repository. https://www.nwtrb.gov/docs/default-source/correspondence/jmb026.pdf?sfvrsn=8.

[8] Hardin, E., 2020, *Technical Basis for Engineering Feasibility and Thermal Management*, https://www.nwtrb.gov/docs/default-source/meetings/2020/july/3_hardin_technical-basis-for-engineering-feasibility-and-thermal-management.pdf?sfvrsn=4.

The disposal R&D program is not adequately addressing DOE SNF. DOE is currently required to dispose of this waste in a repository. DOE SNF dissolution can be different than that expected for commercial SNF[9] or metallic waste packages. For example, uranium-metal SNF rapidly reacts in water lacking dissolved oxygen and produces hydrogen that could adversely affect the engineered barriers. Understanding gas generation and migration is a key issue in the assessment of repository performance.[10] Water lacking dissolved oxygen persists in crystalline rocks at repository depths. DOE models all DOE SNF assuming instantaneous dissolution of the waste once a waste package is breached and water enters. DOE does not address gas generation that would occur with dissolution of uranium-metal DOE SNF, which is the dominant type of DOE SNF on a mass basis.

Recommendation 4. Because DOE-NE models all DOE SNF as instantaneously dissolving once a waste package is breached in a repository, the Board recommends that DOE-NE include all processes within a repository that would occur upon instantaneous dissolution of DOE SNF, such as gas generation from the dissolution of uranium metal, in the GDSA framework or provide a technical basis that demonstrates those processes would not adversely impact engineered barriers and overall system performance.

DOE has not evaluated the full range of expected conditions for salt and argillite. DOE is focusing its salt R&D on horizontally bedded salt formations. The stress orientation in these formations leads to rapid mechanical deformation and closure of the bedded salt drifts. In contrast, in domal salt formations rapid closure of emplacement drifts does not occur in the dome flanks. For example, the Morsleben, Germany, deep repository for low and intermediate level radioactive waste is in the flanks of a domal salt deposit. Large underground galleries (on the order of 100's of feet long and 10's of feet wide and high) remain open and do not have significant mechanical closure issues. This could be an advantage during repository operations but a disadvantage during post-closure when deformation imparts self-sealing attributes. The domal salt disposal concept (open galleries) is different from the bedded salt idea considered by DOE. The United States contains both bedded salt and domal salt formations. DOE is not assessing disposal in domal salt.

DOE is focusing on self-sealing argillites and is not examining brittle argillites. These types of rock have different mechanical and hydrologic properties. DOE's argillite R&D does not address the range of mechanical and hydrologic properties of U.S. argillites.

Recommendation 5. DOE should assess if it needs reference cases and supporting R&D for domal salts and brittle argillites and, if DOE decides these are not needed, provide a rationale for the decision.

Crystalline Host Rock: Disposal Concepts and Research & Development Activities. Dr. Yifeng Wang, SNL, described characteristics of crystalline rocks and disposal concepts. For the crystalline host rock, DOE has only studied waste packages for SNF containing 4 and 12 PWR

[9] See *Management and Disposal of U.S. Department of Energy Spent Nuclear Fuel*, December 2017, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

[10] Rutqvist, J., 2019, *Gas Migration in Clay-Based Materials – International Collaboration Activities as Part of the DECOVALEX Project*, https://www.nwtrb.gov/docs/default-source/meetings/2019/april/rutqvist-gas.pdf?sfvrsn=6.

assemblies. Dr. Wang described technical gaps and priorities and process model development and integration. He outlined future activities for the crystalline host rock R&D. One DOE focus is better characterization and understanding of fractured rock, fluid flow, and radionuclide transport. The second DOE focus is designing an effective EBS for waste isolation. Dr. Wang described recent efforts to assess using lead/lead-alloy as a corrosion-resistant outer layer packaging material. The Board notes that DOE also looked at these materials as part of the design options review in the Yucca Mountain, Nevada, repository program.

Dr. Wang described the fuel matrix degradation model that is used for commercial SNF. DOE will use this SNF degradation model for all reference cases in all host rock types. Dr. Wang described ambient temperature three-electrode electrochemical cell experiments. DOE uses the experimental results to assess and parameterize the model. Dr. Wang described the status of process models and total system integration. Dr. Wang explained that DOE is addressing how higher temperatures affect the backfill and seals portion of the EBS and host rocks but not how it will affect the degradation of commercial SNF. **DOE will need to validate the commercial fuel matrix degradation model at temperatures greater than ambient unless it can be demonstrated that waste packages are unlikely to fail before the temperature of the repository returns to ambient conditions.**

Disposal in crystalline host rocks relies heavily on the EBS for containment and isolation. The material used for sealing the EBS has different attributes than the host rock. There are differences in the thermal, hydrologic, chemical (composition), and mechanical properties between bentonite and other clay-based materials and host rocks. Seal materials are mechanically weaker than crystalline rocks by design to allow plastic deformation and have lower hydraulic conductivity compared to fractured crystalline rock, in which the degree of fracturing controls the hydraulic conductivity. Moreover, transport of radionuclides away from the EBS is mainly by water flow in rock fractures as opposed to transport through intact rock. **Understanding processes at the interfaces between these materials is important.** Processes in the near field disturbed zone[11] are also important. DOE has made good progress in understanding and modeling the interface between metallic waste packages and the sealing material.

<u>Salt Host Rock: Disposal Concepts and Research & Development Activities</u>. Dr. Kris Kuhlman, SNL, updated the Board's understanding of DOE's salt-related disposal R&D. He described well the characteristics of horizontal bedded salt and DOE's safety strategy and disposal options. Dr. Kuhlman addressed the susceptibility of a salt repository to climate change. He described how the characteristics of salt, such as brine corrosion of instrumentation, challenges its characterization and monitoring. Dr. Kuhlman stressed why using underground experiments, such as the Brine Availability Test in Salt (BATS), can address those limits. He described how DOE applied high priority R&D to advance coupled processes knowledge and modeling. Dr. Kuhlman explained that understanding coupled thermal-hydrologic-mechanical-chemical processes was necessary to assess a salt repository's performance.

[11] The excavation of shafts and tunnels in a waste repository and decay heat from the emplaced waste will cause a disturbance to the surrounding rock mass with possible alterations to rock mass stability and hydraulic properties. The properties and extent of the disturbed zone must be considered in the design of a repository and in the assessment of its long-term safety.

In 2014, the Board held a public meeting on DOE's salt-related disposal R&D. The Board provided recommendations to DOE in a letter.[12] The Board recommended that DOE better address the effects of clay layers that occur in bedded salt formations. The clay layers can affect the amount of fluid, heat transport, and significantly impact mechanical performance of "intact" salt. The Board noted that quickened plastic flow because of heat-producing waste was possible. The Board noted these factors are potential disadvantages for a salt repository during the operational phase. The Board recommended that "attention be given to these factors in order to ensure a balanced evaluation of the performance of salt as a medium for a geologic repository." In 2014, the Board also recommended that DOE include possible entry of water from sources external to the salt body in a performance assessment of a salt repository.

DOE's current salt R&D tasks do not adequately address clay layers. The BATS experiment does not test the effects of clay layers because of its location away from clay layers. The detailed models DOE is developing to address coupled thermal-hydrologic-mechanical-chemical processes do not address the effects of clay layers.

Recommendation 6. The Board recommends that DOE's testing and models address the effects of clay layers in bedded salt formations and their impact on salt repository performance.

Argillite Host Rock: Disposal Concepts and Research & Development Activities. Dr. Carlos Jové Colón, SNL, described argillaceous rock characteristics and DOE's repository concept and post-closure safety strategy. Dr. Jové Colón described the waste forms and EBS, which includes cement and backfill, and seals such as bentonite. DOE's analyses have addressed different waste package arrangements, such as in-drift axial emplacement and horizontal emplacement boreholes that extend perpendicular to the drift axis. DOE has completed analyses for packages that contain 4, 12, and 21 to 37 PWR SNF assemblies. DOE used a 4-kW waste package thermal power limit for packages containing between 21 to 37 PWR assemblies to limit degradation of a protective buffer or backfill. Dr. Jové Colón described high priority R&D and briefly addressed a higher temperature reference case.

Dr. Jové Colón presented ordinary Portland cement and cement plug/liner degradation as high priority R&D topics. DOE's assignment of high priority means fundamental gaps in a method or a need for fundamental data exists, and the topic has a high importance to the safety case.[13] This seems inconsistent with the broad knowledge base for understanding and modeling ordinary Portland cement and cement plug/liner degradation. For example, the Nuclear Energy Agency has completed specific radioactive waste-related studies on these topics.[14]

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[12] See *Letter from Chairman Rodney C. Ewing to Dr. Peter B. Lyons, Assistant Secretary for DOE-NE, and Mr. David Huizenga, Senior Advisor for Environmental Management; June 4, 2014,* on R&D activities related to salt as a geologic medium for disposing of SNF and HLW. https://www.nwtrb.gov/docs/default-source/correspondence/rce025.pdf?sfvrsn=11.

[13] See the 2019 Roadmap Update, *DOE SFWST Campaign R&D Roadmap Update Rev.1.*, https://www.osti.gov/servlets/purl/1559571.

[14] NEA. 2012. *Cementitious Materials in Safety Cases for Radioactive Waste: Role, Evolution and Interactions.* NEA/RWM/R(2012)3/REV. https://www.oecd-nea.org/upload/docs/application/pdf/2020-01/rwm-r2012-3.pdf.

While the Board commends DOE for developing a higher temperature argillite disposal case, it remains concerned that DOE has not obtained a technical basis for assessing the performance of bentonite over longer periods than can be assessed in laboratory or underground experiments, such as HotBENT. A robust disposal R&D program uses an iterative process with laboratory experiments, modeling, and field observations.[15] The Board noted a robust program includes URL and natural analogue studies to address field observations and that natural analogues may help address longer timescales than can be addressed in URL experiments.[16] For example, the thermal effect induced by the Morrón de Mateo volcanic dome, Spain, on the adjacent bentonitised tuffaceous beds has been studied as a natural analogue of the thermal behavior of the bentonite-engineered barrier of a geologic repository.[17] It may be possible to find another analogue that reflects more closely the conditions expected for a higher temperature argillite disposal case.

Later in the meeting, Dr. Birkholzer's presentation on international disposal research activities did not address any efforts with the international natural analogue community, such as through participation in the Natural Analogue Working Group. Neither the 5-year R&D plan[18] or 2019 Roadmap update includes any current or future tasks related to natural analogues.

Recommendation 7. The Board recommends that DOE consider natural analogues in its strategic planning and determine whether a natural analogue exists that could be used to evaluate the consequences of aging of bentonite and argillite at high temperatures over longer periods than those possible in laboratory or underground research experiments.

Geologic Disposal Research Strategies from Abroad: Examples from IGD-TP (Implementing Geological Disposal of radioactive waste Technology Platform) and the United Kingdom (UK). Dr. Irina Gaus, IGD-TP chair, and Dr. Lucy Bailey, Radioactive Waste Management (RWM), UK, presented their organization's disposal research strategies. Dr. Gaus also presented IGD-TP member views, based on their experience in national programs, of the relationship between early program development stages, site selection, and R&D programs.

IGD-TP sets up and carries out European efforts to facilitate the stepwise implementation of safe deep geological disposal of SNF, HLW, and other long-lived radioactive waste. IGD-TP does not limit membership to European organizations and DOE is not a member. IGD-TP serves as a forum to discuss research, development, and demonstration (RD&D) issues and priorities. IGD-TP members share RD&D information and results. Members also share information and

[15] See *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*, January 2020, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

[16] See *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*, January 2020, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

[17] Pérez del Villar, L., et al, 2005, "Thermochemically induced transformations in Al-smectites: A Spanish natural analogue of the bentonite barrier behaviour in a radwaste disposal," *Applied Geochemistry*, volume 20, issue 12, pages 2252-2282.

[18] See *SFWST Disposal Research R&D 5-Year Plan*, July 31, 2020, SAND2020-9053 R, Sandia National Laboratories, Albuquerque, New Mexico.

experience on RD&D planning and management. IGD-TP coordinates RD&D on topics of shared interest between programs and groups of organizations. Dr. Gaus described the benefits from IGD-TP participation. These benefits include competence building, joint work and use of resources, joint work on strategies, and knowledge transfer. Dr. Gaus encouraged DOE's participation in the IGD-TP.

Dr. Gaus described the results of her elicitation of some repository implementors that focused on obtaining their lessons learned on generic disposal RD&D programs and the transition to siting a repository.[19] IGD-TP implementors from Belgium, Germany, the Netherlands, Spain, Hungary, UK, and Switzerland took part in the elicitation. These countries are at the same early repository development phase as DOE. Dr. Gaus presented their lessons learned on disposal RD&D programs and the transition to siting a repository as a series of key observations.

To ensure and carry out an adequate RD&D program at an early stage, Dr. Gaus stated:

> "Successful repository implementation needs the legal framework with the roles of each party clearly described (implementer, regulator, society), how to implement the repository program and conduct the site selection needs to be set out and accepted by all parties, and a long-term political commitment is required."

These factors are integral to a satisfactory early-stage RD&D program like DOE's. The European implementors noted:

> "While RD&D is an important part of the repository program, it is widely felt that the challenges for repository implementation do not lie in the technical aspects (although optimization will always remain a driver), but rather in the success of mastering the societal challenges."

The Board concurs with the European implementors that mastering societal challenges is crucial.[20]

Dr. Gaus discussed lessons learned related to social and economic RD&D developments and identifying who deals with these. Not considering these issues, Dr. Gaus said, can adversely impact program success. To stress the importance of societal aspects, Dr. Gaus presented the recently completed results of the Netherlands' safety case. That safety case found that the host rock, including geotechnical properties and long-term evolution, was the most important consideration and "integrating societal aspects into technical research" was the next most important consideration.

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[19] Dr. Gaus collected this information to support the Board's meeting and her effort, documented in her presentation, demonstrates how valuable the IGD-TP could be to DOE and the U.S. efforts to dispose of SNF and HLW in a geologic repository.

[20] See *Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward*, April 2021, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

Dr. Gaus ended the presentation by listing the challenges of early-stage programs, many of which DOE is facing. As the Board noted in its Six Recommendations Report,[21] DOE is facing a loss of knowledge because of the suspension of the Yucca Mountain program and attrition due to workforce aging. DOE must find the balance between a narrowly focused R&D program and a broad enough program to cover all disposal options. Dr. Gaus noted that a good safety case focuses the RD&D program and helps to address the challenge of maintaining program agility and long-term collaborations with academia.[22] **Clearly explaining the disposal options and better defining the safety functions of the barriers and their technical bases for each option will help focus DOE's R&D program.**

Based on the information Dr. Gaus provided, the Board notes the importance of having a strong implementor defining the R&D needs. The lack of an active, near autonomous implementor, which is the case for DOE,[23] challenges the R&D program and the process for setting priorities.

The Board believes that DOE would benefit from working with organizations, such as IGD-TP, whose members are currently demonstrating proposed repository operations in URLs and surface facilities or constructing a geological repository, and with countries who have advanced to or beyond the progress of DOE's non-site-specific disposal R&D program.

Recommendation 8. The Board recommends that DOE become a member of the IGD-TP organization and focus on lessons learned, mainly societal information sharing, communication, and ways of building public confidence and trust, from countries that have advanced their repository programs beyond concept evaluation.

Dr. Bailey stressed that during the early stage of the UK siting process, the UK's RWM focuses on building and communicating its understanding of the safety of the repository. RWM builds confidence in the safety of the geologic repository by developing an understanding of how the barriers perform and change through time. RWM focuses on the barrier's safety roles and the features, events, and processes that affect the safety roles. RWM also focuses on developing an understanding of radionuclide release and transport to the accessible environment and the effects of engineering design. RWM's strategy includes expected operations, including construction, and hazard identification and mitigation. The final part of the RWM strategy is understanding the transport of the waste to the disposal site. RWM uses Scientific Readiness Levels™, which are like Technology Readiness Levels, to assess its level of understanding of the safety of the repository. RWM also uses Scientific Readiness Levels™ as a measure of progress and to

[21] See *Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward*, April 2021, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

[22] Unlike in the United States, where national laboratories conduct most of the disposal R&D, European nuclear waste disposal implementers rely on academic collaborations for much of their RD&D support.

[23] The Board observes that DOE is in this position because two of the three factors [legal framework with the roles of each party clearly described (implementer, regulator, society), how to implement the repository program and conduct the site selection needs to be set out and accepted by all parties, and a long-term political commitment] needed to ensure and execute an adequate RD&D program are uncertain or missing in the US. How to implement the repository program and conduct the site selection has not been set out and accepted by all parties and a long-term political commitment is still required.

decide what understanding can reasonably be obtained at the generic stage of a repository program.

Dr. Bailey described the regulatory basis for communicating the UK safety case. That regulatory approach uses a claims, arguments, and evidence approach. Dr. Bailey described the importance of this communication to the success of a disposal program. Dr. Bailey also introduced RWM's tool for seeing "claims to be made against the regulatory requirements, arguments that explain how those claims will be met, and evidence to support the arguments." **The claims, arguments, and evidence approach may make it easier for a non-technical audience to understand the disposal options, and their associated barriers, barrier functions, and supporting technical bases.**

RWM uses the ViSI (Visualization of System Information) tool as a digital safety case.[24] The tool identifies claims, arguments, and evidence in a tree-like diagram. RWM uses that diagram not only to communicate with stakeholders but also to identify research gaps. The Board suggests that a visualization tool, such as ViSI, could be an important means for DOE to communicate its disposal options, and their associated barriers, barrier functions, and supporting technical bases and manage its R&D portfolio. This could help address a limitation of the disposal R&D presentations at this meeting from DOE that, in general, did not provide consistent links between the field, laboratory, and modeling work. Presenting those links through a visualization tool such as ViSI would have helped communicate the work's relationship to disposal options, and their associated barriers, barrier functions, and supporting technical bases.

While highlighting the importance of communication, Dr. Bailey stated that

> "Our safety cases [are] really only as powerful as our ability to communicate it. … Building understanding is the most important focus for research during early siting. Communicating that understanding to all stakeholders is vital if we're going to build trust. … Information remains just information until it is integrated, until it's linked, until we put pieces of the jigsaw together, until we identify how or what that actually means."

The Board finds her statements compelling. Public engagement, which requires transparency, openness, and two-way communication with the public, in geologic disposal programs is one of the core principles of nuclear waste management programs.[25] It is important to have a clear explanation of each disposal option, including the safety functions of the barriers and their technical bases, to integrate the team of researchers and engage the public towards gaining an understanding where individual research projects fit into supporting a disposal option.

Recommendation 9. The Board recommends that DOE make clear and effective communication of its disposal options, and their associated barriers, barrier functions, and supporting technical

[24] Hall, O., and L. Gray, 2021, *ViSI: RWM's Digital Safety Case Management Tool*, https://www.research-support-office-gdf.ac.uk/wp-content/uploads/sites/244/2021/09/12.-ViSI_RWM-Safety-Case-Management-Tool-Introduction.pdf.

[25] See *Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward*, April 2021, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

bases, an integral part of its disposal R&D program. DOE should use a communication approach that is informed by stakeholder input and can consistently describe in verbal and graphic forms the claims, argument and evidence supporting the disposal option. These should include pre-disposal management activities such as any repackaging or storage that are required prior to disposal.

Both Drs. Gaus and Bailey stressed the importance of repository programs developing and preserving links to academic institutions. Dr. Bailey described RWM's research support office. That office seeks to develop a long-term strategic relationship with UK universities. The office is better aligning academic research that addresses RWM's needs with a stronger university delivery-focus. The office seeks increased sharing with world-class cutting-edge science and "increased contextual understanding and enhanced advocacy within a respected and influential stakeholder group." RWM is aiming for a better coordinated community of RWM funded researchers and is developing the next generation of researchers. RWM seeks a "sustained and enhanced multi-disciplinary capability through collaborative long-term relationships." By reviewing European academic engagement models, DOE might identify possible improvements to its university support programs.

<u>Prioritization of Cross-Cutting Research and Development Activities: Unsaturated Alluvium Reference Case, Disposal of Dual-Purpose Canisters, and Geologic Disposal Safety Assessment</u>. Dr. Emily Stein, SNL, defined the GDSA framework and its role in DOE's safety assessment process. She also presented an unsaturated alluvium case. DOE developed that reference case to provide understanding on a few key subjects, such as coupled thermal-hydrologic-chemical processes in hydrologically unsaturated environments, for inclusion in the GDSA framework.

On the previous day, Dr. Sassani mentioned that a key objective for assessing safety is to provide the basis for planning and setting technical work priorities. Dr. Stein identified the GDSA framework as DOE's safety assessment computational platform. She stressed the GDSA framework's role in assessing what RD&D DOE should do in the next stage of program development. DOE's Disposal Research R&D 5-Year Plan states that this software framework will provide DOE with "robust, sophisticated simulation and analysis tools that will support site selection, site characterization, and licensing for the nation's next deep geologic disposal facility."[26] Dr. Sassani indicated that DOE has not developed the GDSA framework enough to apply it to repository post-closure safety analyses that can inform decision making or prioritize the R&D activities. Dr. Sassani stated that developing that capability is on DOE's near-term agenda.

Dr. Stein addressed the advanced non-linear solvers considered in the GDSA framework. She described the Newton Trust Region Dogleg Cauchy approach[27] the program had developed that has reduced computational time by a factor of 35. **The Board commends the staff who developed this approach.** It was an important contribution to reducing the computational

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[26] See *SFWST Disposal Research R&D 5-Year Plan*, July 31, 2020, SAND2020-9053 R, Sandia National Laboratories, Albuquerque, New Mexico.

[27] The Newton Trust Region Dogleg Cauchy approach combines two separate algorithms (Newton Trust Region and Dogleg Cauchy) for time stepping (iteration methods) that minimize the residual of a multidimensional function.

burden in computationally intensive analyses such as repository performance assessments thus enabling more detailed modeling of repository performance.

The Board notes other opportunities for reducing computational time. Adding a very complex model to capture some more detail of the physics of a process would add computational burden. Understanding the ability of models having varying levels of detail to predict system performance can tell DOE whether it actually needs to routinely use a more complex model, or a simpler model will suffice for the intended application.

Dr. Stein noted the need to further develop both the source term, EBS evolution, and biosphere models. She stated that much development work remains on temperature-dependent and material-specific corrosion models. Dr. Stein also outlined DOE's plans to develop models for temperature-dependent reactions and coupled thermal-hydrological-mechanical evolution of the near field. She noted that DOE plans to incorporate mechanistic approaches into the GDSA framework. These approaches will be computationally intensive. The Board recognizes that in the future DOE will need to develop the capability to address other scenarios[28] such as a human intrusion scenario. So far DOE has focused on a nominal scenario.

Prioritization of Cross-Cutting Research and Development Activities: Engineered Barrier System Overview and the HotBENT Experiment at the Grimsel Test Site. Dr. Ed Matteo, SNL, presented a review of EBS-related R&D. Dr. LianGe Zheng, Lawrence Berkeley National Laboratory (LBNL), presented an update on the HotBENT experiment. Dr. Matteo explained that understanding the behavior of cement and bentonite are EBS R&D priorities and identified how international efforts such as the Cement Task in the EBS Task Force, which is a group led by Sweden's implementer, support their efforts. To address knowledge gaps, DOE has focused on repository seals integrity and processes at material interfaces. Dr. Matteo described that coupled processes remain a knowledge gap. Dr. Matteo explained they focused on increasing understanding of mineralogic changes and permeability evolution in seals and liners and better understanding of mineralogic changes at the buffer and waste package interface.

Focusing on filling the knowledge gaps associated with processes at the buffer and waste package interface is important and DOE's progress is encouraging. The Board recognizes DOE's strong international involvement with many of the R&D priority tasks. DOE's participation in the EBS Task Force program and its leadership on the high temperature bentonite experiment are important.

Dr. Zheng had previously described the HotBENT experiment to the Board at its April 2019 workshop on URLs.[29] The HotBENT experiment is being conducted at the Grimsel Test Site, a

[28] A scenario is a well-defined, connected sequence of features, events, and processes that can be thought of as an outline of a possible future condition of the proposed repository system. Scenarios can be undisturbed, in which case the performance would be the expected, or nominal, behavior for the system. Scenarios can also be disturbed, if altered by disruptive events such as human intrusion or natural phenomena such as volcanism or nuclear criticality.

[29] Zheng, L., 2019, *DOE's Engineered Barrier Integrity Activities: Understanding EBS Coupled Processes and Mineral Alterations at High Temperatures: From FEBEX-DP to HotBENT*, https://www.nwtrb.gov/docs/default-source/meetings/2019/april/zheng.pdf?sfvrsn=6.

URL in Switzerland. The experiment focuses on understanding the effects of high-temperatures (>150 °C) on bentonite-based buffers. The Board previously recommended[30] that DOE increase its focus on underground laboratory experiments to assess the extent to which coupled processes occur and whether DOE needs to develop new constitutive models to model accurately the longer-term underground HotBENT test.

Dr. Zheng updated the Board on the HotBENT experiment and supporting laboratory and modeling work. DOE is supporting high temperature bentonite column experiments, the Grimsel field scale test, and a modeling platform. Dr. Zheng explained the column experiment results showed hydration, clay swelling, heating dehydration, and mineral formation. Dr. Zheng described the field scale test's design, timeline, installation, and instrumentation. Dr. Zheng also described the objective of the HotBENT modeling platform. The modeling platform enables the experiment to inform the modeling and the modeling to inform the experiment. As Dr. Zheng explained, the modeling platform will speed up data analysis and model updates for system understanding and decision support. Dr. Zheng stated that pre-experiment scoping modeling helped to design the field experiment. Dr. Zheng explained that blind comparisons will be part of a model "validation" exercise. He explained that multiple modeling teams will use alternative conceptual models to analyze uncertainties.

The Board commends DOE for their initiative in co-developing the HotBENT experiment. DOE's commitment to a lengthy experiment is important and noteworthy. HotBENT is a good example of international collaboration and use of URLs. The Board notes that DOE sees an important role for the multiple modeling teams to analyze conceptual uncertainties. **However, it is still not clear whether there was enough pre-experiment modeling, employing distinct conceptual models, to identify what data DOE needs to collect to help it discriminate among the models.** DOE will need to develop a well-thought-out experimental matrix for "validation" of the models.

Prioritization of International Activities and Moving Forward: Disposal Research R&D 5-Year Plan. Dr. Jens Birkholzer, LBNL, presented an overview of the prioritization of international activities. Dr. David Sassani, SNL, described the Disposal Research R&D 5-Year Plan.[31] Dr. Birkholzer described how active collaboration with international programs is a central and fully integrated part of DOE's disposal research program. He stressed that DOE is now playing a more active role in defining international research efforts. DOE's leadership in developing the HotBENT experiment and chairing the current phase of the DECOVALEX project is noteworthy. The Board notes DOE's active leadership can play a major role in aligning future international efforts with the U.S. disposal R&D program strategic goals. In response to a Board question, Dr. Birkholzer noted that DOE's international collaborations have focused on conducting R&D. He pointed out that joining IGD-TP would be valuable for the lessons learned, especially if the U.S. disposal program moves forward into the site selection stage (Figure E-1).

[30] See *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*, January 2020, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

[31] See *SFWST Disposal Research R&D 5-Year Plan*, July 31, 2020, SAND2020-9053 R, Sandia National Laboratories, Albuquerque, New Mexico.

Dr. Sassani described challenges to program planning and DOE's efforts that led to its Disposal Research R&D 5-Year Plan. DOE's planning challenges included addressing a wide range of geologic disposal concepts with limited resources, defining the most important R&D activities, and defining how much generic R&D is enough. DOE also had to decide how best to use the vast international experience and integrate cross-cutting topics in its planning. Both the 2012 Roadmap and the 2019 Roadmap Update served as forerunners to the Disposal Research R&D 5-Year Plan.

Dr. Sassani addressed the purpose and structure and R&D priorities of the Disposal Research R&D 5-Year Plan. He described an integration example from fiscal year 2021 planning efforts. The plan serves as a strategic guide to the work within the disposal research R&D technical areas (for example, argillite R&D). The plan provides thrust topics in each disposal research technical area. The plan presents near-term (1-to 2-years' timeframe) and longer-term (3-to 5-years' timeframe) thrust topics. The longer-term topics provide a vision of where the R&D is heading assuming no major program changes. DOE will update the Disposal Research R&D 5-year Plan yearly to present short-term progress and the bases for changed priorities.

The Disposal Research R&D 5-Year Plan is a major advance in DOE's planning and setting priorities. The Board notes that DOE added "Technical Support for Underground Research Laboratory Activities" as a new disposal research technical area. DOE is also looking to use the Yucca Mountain, Nevada, Exploratory Studies Facility tunnel for R&D on passive monitoring techniques. **DOE's efforts are one step towards addressing the Board's recommendation for development of U.S.-based URLs.**[32] DOE's intent to develop best practices and technologies for site selection through international collaboration, such as described by Dr. Gaus for the IGD-TP, is important.

DOE identified back in 2017 knowledge management as a crucial issue to address. **DOE's knowledge management efforts are commendable.** Dr. Sassani said that DOE plans to put more effort into knowledge management. He stated they intend to expand their efforts to storage and transportation, and the Board encourages those efforts.

The Board looks forward to future productive interactions with DOE and supporting national laboratory staff on several topics including:

- How DOE is determining R&D priorities and assessing the maturity of disposal options. The Board would like to better understand the effort and time DOE needs to address each of the high priority activities, how DOE tracks the completion status of high priority activities, and when all high priority activities are planned for completion.
- How barrier functions and expected performance would differ in higher temperature disposal options.
- A further understanding of DOE's Portland cement and cement plug/liner degradation activities.

[32] See *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*, January 2020, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

The Board looks forward to future updates of the Disposal Research R&D 5-Year Plan. The Board anticipates that future updates will indicate how DOE will address management of new fuels such as accident tolerant fuel, high-assay low-enriched uranium fuels, other advanced fuels, and existing DOE SNF.

Department of Energy
Washington, DC 20585

November 24, 2021

Dr. Jean M. Bahr
Chair, Nuclear Waste Technical Review Board
2300 Clarendon Boulevard, Suite 1300
Arlington, Virginia 22201-3367

Dear Dr. Bahr:

I appreciate the time that the Nuclear Waste Technical Review Board (NWTRB) took to review the U.S. Department of Energy (DOE) information on technology development (TD) activities related to aluminum-clad spent nuclear fuel (ASNF) packaging, drying, and dry storage during the NWTRB public meeting, held virtually on August 24, 2021. The DOE Office of Environmental Management manages ASNF primarily at the Idaho National Laboratory (INL) and at the Savannah River Site (SRS). Since 2017, DOE has supported technology development to study extended dry storage of ASNF, including corrosion of aluminum cladding, radiolytic gas generation, and drying processes to remove residual water from the cladding corrosion layers.

The NWTRB commended DOE for sponsorship of this research and noted that DOE incorporated recommendations from the NWTRB's 2017 report on DOE-managed SNF to help guide the work. As suggested by NWTRB, DOE continues to provide resources (personnel, facility access, etc.) for follow-on research as the technology development program progresses.

Thank you for your positive comments on our ASNF TD program. We share a strong commitment to manage ASNF in a manner that is protective of human health and the environment, cost-effective, and achievable. I can assure you that DOE remains committed to supporting this important research.

If you have any questions, please contact me or Ms. Aimee Witteman, Deputy Assistant Secretary for Intergovernmental Affairs, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

William I. White
Senior Advisor for Environmental Management

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
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January 7, 2022

Dr. Kathryn Huff
Principal Deputy Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Dr. Huff:

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 2021 Fall Meeting, which was held virtually on November 3–4, 2021. The purpose of the meeting was to review information on the U.S. Department of Energy, Office of Nuclear Energy (DOE-NE) research and development (R&D) activities related to the Geologic Disposal Safety Assessment (GDSA) Framework. This letter presents the Board's observations, findings, and recommendations resulting from the meeting. The agenda, presentation materials, and an archived recording of the webcast for the meeting are posted on the Board's website at https://www.nwtrb.gov/meetings/past-meetings/fall-2021-virtual-board-meeting---november-3-4-2021. A meeting transcript is also available there.

The Board also thanks the staff from DOE and the national laboratories for supporting a technical fact-finding meeting, which was held virtually on October 13–14, 2021. This fact-finding meeting enabled the Board to prepare for the November 2021 public meeting.

Background

Over the past several years, DOE has been developing a modeling capability for evaluating the post-closure performance of potential repositories for spent nuclear fuel (SNF) and high-level radioactive waste (HLW). According to DOE, the suite of computational models and codes called the GDSA Framework is part of its efforts to develop a sound technical basis for evaluating geologic disposal in the United States in different host rocks and different disposal options.[1] The Board sees DOE's efforts as having the capability to address several recommendations the Board made in its Six Recommendations Report,[2] issued in April 2021,

[1] DOE uses the term "disposal option" to refer to the collection of specific repository features including engineered barriers, such as buffer or backfill, the type of disposal waste package, and the waste emplacement geometry (vertical or horizontal with respect to the orientation of emplacement tunnels).

[2] NWTRB. 2021. *Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward.* Arlington, Virginia: U.S. Nuclear Waste Technical Review Board. April.

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namely, to anticipate the required high-performance computing and data management infrastructure required for a multi-decade waste management program and to facilitate application of iterative and adaptive approaches to development of a geologic repository. The Board's meeting examined DOE's R&D activities related to the GDSA Framework. Although DOE presentations in previous Board meetings have touched upon some aspects of the GDSA Framework and the Board has commented on those in Board reports or letters to DOE,[3,4] the November 2021 meeting was an opportunity for the Board to conduct a high-level review focused on DOE's GDSA efforts.

At the meeting, the Board received a brief update from William Boyle (DOE-NE) on DOE's Spent Fuel and Waste Disposition Program. Alisa Trunzo (DOE-NE) then described DOE's current efforts on a consent-based approach to siting a federal interim storage facility for SNF, and also summarized the work DOE-NE has been conducting to prepare for an integrated waste management system. Ms. Trunzo stated that DOE is committed to a consent-based approach to siting a federal interim storage facility that fully embraces principles of openness, transparency, public engagement, equity, environmental justice, and broad participation including that of historically underrepresented groups and communities. She noted also that DOE is incorporating expertise in the social sciences and resources from the national laboratory system to help move the program forward. She stated that DOE is funding an integrated research project for up to three years and $3 million for a university-led team to perform research that will inform how DOE implements a consent-based siting process. Further, she noted that DOE's approach is aligned with the recommendations in the Board's Six Recommendations Report for how to move the nation's nuclear waste management program forward.

The Board then heard several presentations from the national laboratory researchers who are conducting the work for DOE. These presentations included an overview of R&D activities related to developing the GDSA Framework and descriptions of several GDSA Framework components, including the multiphase flow and reactive transport code PFLOTRAN, the uncertainty quantification and sensitivity analysis code DAKOTA, the discrete fracture network model dfnWorks, the Fuel Matrix Degradation Model for commercial SNF, and a biosphere model. Other presentations by national laboratory researchers described the uncertainty and sensitivity analysis tools being applied in the GDSA Framework, the application of the GDSA Framework to generic repository reference cases in bedded salt, shale, and crystalline host rocks, and a case study in integrating insight and experience from the international community into geologic disposal safety assessments.

The Board also heard a presentation by two U.S. Nuclear Regulatory Commission (NRC) staff members and another by a representative from the Radioactive Waste Management organization in the United Kingdom (U.K.). The NRC staff members discussed their

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[3] NWTRB. 2020. *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program.* Arlington, Virginia: U.S. Nuclear Waste Technical Review Board. January.

[4] Bahr, J.M. 2021. Board letter to Dr. Kathryn Huff with comments from December 2020 Board meeting (December 30, 2021). https://www.nwtrb.gov/docs/default-source/correspondence/jmb028.pdf?sfvrsn=4. (Accessed January 6, 2022)

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perspectives on developing and applying performance assessment computer codes based on their collective experiences in these activities at the NRC and their participation in international programs. The U.K. representative described the development of environmental safety case models that will support geologic disposal of the U.K.'s radioactive waste.

Board Observations, Findings, and Recommendations

After discussing and examining the information presented at the fact-finding meeting and the public meeting, the Board has several observations, findings, and recommendations on DOE's program and GDSA R&D activities, which are provided below. The Board notes that all the meeting presentations were well done and addressed the questions the Board posed in the meeting agenda. A positive aspect of the meeting was hearing from a variety of staff and researchers, which the Board understands is important to DOE's efforts on knowledge management and human capacity building.

DOE's Consent-Based Process for an Interim Storage Facility

The Board commends DOE for starting a new effort on consent-based siting of an interim storage facility[5] and for recognizing the crucial importance of effective risk communication, full public engagement, and inclusiveness in the siting process. The Board supports DOE's commitment to transparency, openness, and effectively engaging stakeholders, including historically underrepresented communities, in any consent-based siting process. The Board is pleased DOE noted that its path forward for a consent-based siting process is well-aligned with the recommendations in the Board's Six Recommendations Report.

The Board also commends DOE for its plan to support its future risk communication efforts with social science expertise. At the same time, the Board observes that a great deal of relevant knowledge and expertise on risk communication, public engagement, and inclusiveness may be found in other fields, including behavioral science and the public health sciences. The Board notes that including these other fields would provide DOE a significantly broader and stronger knowledge base upon which to draw insights and expertise. Further, the Board supports DOE funding of a university-led team to conduct research on consent-based siting as the Board believes universities are well equipped to conduct multidisciplinary research that includes experts in the social and behavioral sciences, public health, and other relevant fields, and may enhance public confidence in DOE's efforts to improve risk communication.

At the meeting, in response to a Board member comment, the DOE representative stated that DOE is open to learning from experiences in other countries on the consent-based process for siting nuclear waste facilities. The Board notes that experiences in other countries, such as Sweden, Switzerland, and Canada, suggest that effective risk communication, public engagement, and inclusiveness in the siting process can be central to the success of any siting effort. The Board is encouraged by DOE's willingness to consider international experience. Although no two countries are identical, valuable insights can be gained by reviewing siting

[5] On December 1, 2021, DOE issued a Request for Information in the *Federal Register* (Vol. 86, No. 228) to collect comments and opinions about using a consent-based siting process to identify sites to consolidate and temporarily store the nation's SNF.

experiences elsewhere.[6] The Board notes that as DOE further develops its strategy for communication, engagement, and inclusiveness, it would be beneficial to systematically review key lessons that have been learned from siting processes in other nations. Ideally, this should include not only a review of literature on siting experiences in other countries, but direct interaction with government agencies, stakeholder organizations, and community groups that have been part of siting processes. The Board looks forward to hearing more in the future about DOE activities in this area.

Although DOE's current effort is focused on siting an interim storage facility, the Board notes that DOE previously worked on a consent-based process for both storage and disposal facilities for SNF and HLW.[7,8] The Board observes that strategies for effective communication, public engagement, and inclusiveness that DOE applies or develops in its current effort could be applicable to a future siting of a geologic repository for SNF and HLW.

The Board also observes that there may be lessons that could be learned from the challenges that arose with the proposal in 2016 to conduct a deep borehole experiment in Rugby, North Dakota. The Board noted in its Six Recommendations Report that this proposal encountered difficulties partly due to a lack of sufficient transparency and early engagement with the public. The Board suggests that as a follow-on to that project, DOE could do a detailed analysis of how the project was developed and the strategies for public engagement identified, and produce a candid "lessons learned" document that might be used for future consent-based siting and stakeholder engagement activities.

DOE's GDSA R&D Activities

The Board commends DOE for its R&D activities related to developing and enhancing its geologic disposal safety assessment capability. The Board notes that DOE is using state-of-the-art models, modeling approaches, and methods of analysis to develop and expand the GDSA Framework. There is a focused and excellent effort on uncertainty quantification and sensitivity analysis, which the Board believes can help increase the overall confidence in the results generated using the GDSA Framework. The Board also notes that DOE is actively applying lessons learned from the Waste Isolation Pilot Plant and Yucca Mountain projects, the international community, and publicly available sources.

- *The Board finds that DOE has a technically valid approach to developing its geologic disposal safety assessment capability that will enable it to evaluate the post-closure*

[6] NWTRB. 2015. *Designing a Process for Selecting a Site for a Deep-Mined, Geologic Repository for High-Level Radioactive Waste and Spent Nuclear Fuel: A Detailed Analysis*. Arlington, Virginia: U.S. Nuclear Waste Technical Review Board. January.

[7] DOE. 2016. *Designing a Consent-based Siting Process. Summary of Public Input Final Report*. December. https://www.energy.gov/sites/prod/files/2016/12/f34/Summary%20of%20Public%20Input%20Report%20FINAL.pdf. (Accessed January 6, 2022)

[8] DOE. 2017. *Draft Consent-Based Siting Process for Consolidated Storage and Disposal Facilities for Spent Nuclear Fuel and High-Level Radioactive Waste*. January. https://www.energy.gov/sites/prod/files/2017/01/f34/Draft%20Consent-Based%20Siting%20Process%20and%20Siting%20Considerations.pdf. (Accessed January 6, 2022)

performance of potential SNF and HLW repositories in different host rocks and with different disposal options. DOE is competently carrying out the development of the GDSA Framework and is making great progress in this effort while recognizing some of the challenges.

The Board encourages DOE to continue its GDSA Framework development efforts.

The Board notes that the GDSA Framework can be applied at various stages of the repository program, including site selection and evaluation, assessment of disposal options, and, eventually, to support a license application to construct a geologic repository. The repository performance modeling requirements will evolve as the repository program progresses through its various stages. The performance assessment models and codes should also evolve and improve as the repository program progresses — simpler during the early stages and later becoming more complex as more features, events, and processes are considered and advances in models and codes are made. Hence, the iterative nature of performance assessment code development. The Board believes that continued improvements in the GDSA Framework can be facilitated by applying it systematically to a broad suite of reference cases to begin exploration of the needed changes to the framework, to understand better the performance of the total system and that of the various engineered and natural barriers, and to assess the various disposal options. For example, a set of simulations for a crystalline host rock can evaluate what disposal options can lead to poor, mid-range, and good repository performance. The disposal options considered could explore various waste package designs, near-field configurations, far-field configurations, and biosphere assumptions. The Board acknowledges that DOE is currently using the GDSA Framework to simulate the performance of a small set of generic reference cases, but believes a strategy and intended outcome of the simulations need to be clearly defined and the GDSA Framework systematically applied.

- *The Board finds that DOE needs to more clearly define and articulate the near-term goals and applications of the GDSA Framework in order to better prioritize what needs to be incorporated into the software framework at different stages of the repository program.*

  The Board recommends that DOE define a clear strategy and intended outcome for the use of the GDSA Framework in the near term and systematically apply it to a broad suite of reference cases.

The Board notes that an important component of repository performance assessments, as well as evaluation of different disposal options, is the performance modeling and evaluation of engineered barriers, including waste forms, waste packages, and buffer materials. Performance assessment codes need to have a robust capability to assess the performance of engineered barriers, particularly for disposal options that are likely to rely heavily on those barriers. The GDSA Framework currently has limited capability to represent engineered barriers, such as fuel cladding and waste package materials, and to model their degradation. This limits DOE's ability to assess different disposal options, to determine engineered barrier importance, and to prioritize its R&D portfolio related to engineered barrier performance. The Board notes DOE indicated that it plans to improve the representation of the evolution of buffer and backfill behavior and waste package degradation in its numerical models.

- *The Board finds that the GDSA Framework currently does not have an adequate capability to assess the performance of engineered barriers, which may be necessary for evaluating engineered barrier capability and different disposal options.*

  The Board recommends that DOE expedite the development of the GDSA Framework such that it has sufficient capability to assess the performance of different engineered barriers. This capability is needed to assess different disposal options and to apply the GDSA Framework systematically to a broad suite of reference cases. The Board notes that in developing this capability, DOE also needs to take account of near-field processes that could affect the performance of engineered barriers.

The Board notes that there is great value in independent assessments, evaluations, and critiques of major code systems such as the GDSA Framework. The Board acknowledges that components of DOE R&D activities related to the GDSA Framework, such as modeling and laboratory work, are being peer-reviewed as part of journal and conference publication processes, as well as by technical experts in the national laboratories and entities such as the NWTRB. However, the Board believes that input from a broader set of stakeholders, including the public and regulators, on the development of the GDSA Framework can help improve the transparency of the processes being modeled (e.g., assumptions, conceptual models) and the modeling results. This improved transparency can be in the form of a clearer and simpler display of results and an ability to show how different components of a multibarrier system contribute to long-term safety. Transparency is important when interacting with stakeholders at all stages of the repository program, and is particularly important when interacting with regulators during the implementer's preparation of and the regulator's review of a license application to construct a repository. The NRC speakers at the meeting stated that stakeholder engagement was an important component of NRC's development of its performance assessment capability.

- *The Board finds that the development of the GDSA Framework can be improved by peer reviews by a broader spectrum of stakeholders.*

  The Board recommends that DOE solicit input on the development of the GDSA Framework from a broader spectrum of stakeholders, including the public and the regulator.

The Board observes that, although DOE has applied its own quality assurance (QA) program, the GDSA Framework, PFLOTRAN, and DAKOTA codes have not been developed under a Nuclear Quality Assurance (NQA-1)[9] or equivalent QA program. Yet this will be an important requirement for any future submission of a license to the NRC for repository construction. The Board believes that qualifying the computer codes using an acceptable QA program will be more costly, challenging, and time consuming the longer the implementation of the QA program is delayed. The Board notes that it would be appropriate for DOE to start an assessment of what needs to be done to have all the components of the GDSA Framework NQA-1 qualified (or equivalent). Moreover, it appears to the Board that the capabilities of the DAKOTA code are not being utilized in model calibration to determine the values and associated uncertainties of parameters that appear in various models. If that is the case, the Board notes it would be useful

[9] ASME NQA-1-2019, "Quality Assurance Requirements for Nuclear Facility Applications," American Society of Mechanical Engineers, New York, NY.

for the GDSA Framework team, including the process model developers, to work with the DAKOTA code team to identify how the DAKOTA capabilities can be used in model calibration.

Thank you again, on behalf of the Board, for the participation of DOE-NE staff and technical experts from the national laboratories at our November meeting. We look forward to continuing our ongoing review of DOE's technical activities related to managing and disposing of SNF and HLW.

Sincerely,

{Signed by}

Jean M. Bahr
Chair

cc: Dr. Kimberly Petry, DOE-NE
Dr. William Boyle, DOE-NE
Mr. Timothy Gunter, DOE-NE

Department of Energy
Washington, DC 20585

April 7, 2022

Dr. Jean M. Bahr
Chair
Nuclear Waste Technical Review Board
2300 Clarendon Boulevard
Suite 1300
Arlington, Virginia 22201

Dear Dr. Bahr,

We appreciate your letter dated August 12, 2021, which presented observations, comments, and recommendations on the Board's Spring 2021 Meeting held on May 12-13, 2021. The Department of Energy (DOE) understands the Board's position in the letter where five recommendations were made. Enclosed is the Department's response to the five recommendations that were presented in the letter.

DOE appreciates the Board's input to our program and looks forward to continued input and insight from the Board on this topic as the testing progresses. If you have any questions, please feel free to contact Dr. Kimberly Petry, Acting Deputy Assistant Secretary for Spent Fuel and Waste Disposition, Office of Nuclear Energy at Kimberly.Petry@nuclear.energy.gov.

Sincerely,

Andrew Griffith
Acting Assistant Secretary
for Nuclear Energy

Enclosure

Department of Energy, Office of Nuclear Energy (DOE-NE) Response to Nuclear Waste Technical Review Board (NWTRB) Comments and Recommendations on Advanced Nuclear Fuels (ANF) and Accident Tolerant Fuels (ATF)
Spring 2021 NWTRB Meeting

Recommendation #1:
The Board recommends that the DOE Office of Spent Fuel and Waste Disposition coordinate and integrate in an ongoing fashion with the Office of Nuclear Fuel Cycle and Supply Chain on preparing for storage, transportation, and disposal of SNF resulting from deploying ANF/ATF in existing LWRs. Steps that can be taken include but are not limited to forming collaborative working groups, sharing laboratory facilities and equipment, and sharing irradiated fuel specimens and fuel characterization data.

DOE-NE Office of Nuclear Fuel Cycle and Supply Chain and DOE-NE Office of Spent Fuel and Waste Disposition will continue to cooperate and collaborate in sharing data, plans, laboratories, equipment, and ANF/ATF samples. In addition, DOE-NE has working relationships with the Electric Power Research Institute (EPRI), the Nuclear Regulatory Commission (NRC), the Extended Storage Collaboration Program (ESCP), international programs and industry. The relationships, sharing, integration and cooperation between all the groups and organizations are similar to those that were established for the High Burnup Demonstration and have proved to be very effective over the years. DOE-NE will continue to effectively use that model and processes for ANF/ATF issues now and in the future. In light of the Board's recommendation, however, DOE-NE will look for opportunities to further enhance coordination and integration between the Office of Nuclear Fuel Cycle and Supply Chain and the Office of Spent Fuel and Waste Disposition.

Recommendation #2:
The Board recommends that the next update to DOE's gap analysis report for SNF management be expanded in scope beyond storage and transportation to include disposal of SNF resulting from the use of ANF/ATF.

The national labs have begun work on a report that will continue the analysis of the evolving ANF/ATF technologies and potential waste streams from ANF/ATF reactor fuel cycles which includes disposal analyses. This report will pull from work on the disposal, storage, and transportation gap analyses and should address the substance of the Board's recommendation. R&D work on spent ANF/ATF is continuing for disposal, storage, and transportation, but because the test plans for these activities are changing and adapting at different schedules, the documents for disposal are better left separate from the documents for storage and transportation, for now. As more data and information become available in the future, DOE-NE may consider greater integration among those documents.

Recommendation #3:
The Board recommends that DOE-NE work to improve its access to fuel characterization data obtained during DOE-sponsored ANF/ATF development programs. Some of these data are important for assessing and closing the knowledge gaps related to ANF/ATF storage, transportation, and disposal.

The two DOE-NE offices are working closely on ANF/ATF issues, and they currently collaborate and share data that are available. The current non-disclosure agreements (NDAs) with private industry on proprietary data must be maintained. All data allowed by the NDAs that are currently available and needed for assessing and closing the knowledge gaps are shared. Once there is access to ANF/ATF at relevant burnups, DOE-NE will be able to test and model the behavior of the fuel in storage, transportation, and disposal conditions. This will allow DOE-NE to close any knowledge gaps that exist which should address the substance of the Board's recommendation.

Recommendation #4

The Board recommends that DOE evaluate the approaches used and experiences gained in other countries regarding early consideration of the potential impacts of new ANF/ATF designs on SNF storage, transportation, and disposal. Based on the lessons learned in other countries, DOE should implement mechanisms to provide feedback to ANF/ATF development work that accounts for the impact of these fuels on SNF management and disposal. The feedback process can also be used to prioritize SNF management research and development.

DOE-NE is involved in multiple international collaborations for storage, transportation, and disposal through the International Atomic Energy Agency, the Nuclear Energy Agency, the European Commission, EPRI's Extended Storage Collaboration Program (ESCP), the International Nuclear Energy Research Initiative (I-NERI), and other multi-national cooperation initiatives. Other countries also participate and share in these organizations. The purpose of each of these collaborations is to share data, information, and knowledge for the purpose of enabling more informed decisions. In line with the Board's recommendation, DOE-NE will continue to proactively and holistically evaluate modifications to the ANF/ATF with consideration given to international approaches and experiences.

Recommendation #5:

The Board recommends that DOE increase the accessibility of ATF information to the general public in the interest of clearly demonstrating openness, facilitating public engagement, factoring in public concerns in planned R&D, and avoiding the perception that there may be unexplored or unresolved issues (including issues affecting SNF management and disposal) related to the introduction of the new fuel designs.

DOE-NE Office of Spent Fuel and Waste Disposition plans, data, and reports are publicly available via the Office of Scientific and Technical Information (OSTI) and the DOE-NE website. Reports are sent to the NRC, EPRI, NWTRB, fuel vendors, utilities, and cask vendors prior to release so they can review them. The work is also presented in public conferences and papers published in peer-reviewed journals where anyone from the public can review and understand what has been and is being done. DOE-NE believes that segments of the public with interest in nuclear issues have full access to all relevant data. In light of the Board's recommendation, DOE-NE will look for opportunities to further enhance this access.

Department of Energy
Washington, DC 20585

June 8, 2022

Dr. Jean M. Bahr
Chair
Nuclear Waste Technical Review Board
2300 Clarendon Boulevard, Suite 1300
Arlington, Virginia 22201

Dear Dr. Bahr:

The U.S. Department of Energy (DOE) appreciates your April 2021 report to the Congress of the United States and the Secretary of Energy which provided the Board members' synthesis of their reviews of DOE's activities related to the management and disposal of spent nuclear fuel and high-level radioactive waste.

The report provides six overarching recommendations (and 27 associated action items) in several areas, including the design and effective operation of an integrated nuclear waste management program, guidance on creating a more effective and rigorous science and engineering program, and building public trust and international engagement to foster success. The Board stated that the "progress the nation is making in developing its waste management capability, as well as public and stakeholder acceptance, could be improved with regard to both timeliness and effectiveness by adopting these recommendations as core principles of the nuclear waste management program." DOE agrees with the Board that some of the action items identified require contributions from entities that are beyond DOE's control and require both authorization and appropriations by Congress.

Enclosed are DOE's responses to the six recommendations and associated action items. In general, there are existing activities in progress that address many of the Board's actions items. However, there are additional actions that could be taken and will be considered for future implementation. These are identified as "Relevant Existing Activities" and "Potential Future Actions" in the Enclosure.

DOE appreciates the Board's input to our program and looks forward to continued input and insight from the Board on DOE's activities related to the management and disposal of spent nuclear fuel and high-level radioactive waste. If you have any questions, please feel free to contact me or Kimberly Petry, Deputy Assistant Secretary for Spent Fuel and Waste Disposition, at (301) 903-5685.

Sincerely,

Kathryn Huff

Dr. Kathryn Huff
Assistant Secretary
for Nuclear Energy

Enclosure

Department of Energy (DOE) Response to the Nuclear Waste Technical Review Board (NWTRB) Report to the U.S. Congress and the Secretary of Energy

"Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward" (April 2021)

The DOE's responses to the six recommendations and associated action items are listed below. In general, there are many DOE activities that were already in progress that address the Board's action items. However, there are additional actions that will be considered for future implementation that may more fully address the action items. These are identified as "Relevant Existing Activities" and "Potential Future Actions" in the response below.

1) **NWTRB Recommendation #1: Ensure an Integrated Organizational Approach**
   a) ***NWTRB Recommended Action Item 1a**: Foster broader sharing of information among DOE offices, national laboratories, and contractors (e.g., university researchers supported by Nuclear Energy University Program grants).*
      i) Relevant Existing Activities:
         - Multiple laboratories work together to develop the Integrated Priorities List (IPL), as well as to coordinate program management and execution.
         - Work packages that involve contributions from multiple laboratories have monthly status meetings with contributing labs to enable effective integration of activities across the laboratories.
         - Technical Research & Development (R&D) projects are actively integrated across national laboratories and other DOE offices, with applicable developments and results presented at numerous domestic and international conferences each year.
         - Weekly meetings are held to discuss management integration.
         - Dozens of publicly available milestones/reports are published each year. Additionally, internal-use-only work is also shared as appropriate within controlled groups. Public reports are available from either the DOE website or the DOE Office of Scientific and Technical Information (OSTI) database. In addition, The DOE Office of Spent Fuel and Waste Disposition (SFWD) milestone reports are archived in Sharepoint databases (public and non-public reports) within the Sandia National Laboratories (SNL) External Collaboration Network (ECN) accessible to SFWD staff and external individuals with an account.
      ii) Potential Future Actions
         - Expand tools such as the Used Nuclear Fuel – Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) [1], incorporating the latest GC-859 information in the Unified Database (UDB) and the Next Generation System

[1] UNF-ST&DARDS = Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System

Analysis Model (NGSAM) to include other DOE-managed spent fuel and high-level waste.[2]

- Establish an outward-facing document archive in FY2022; the archive could be similar to CURIE[3].
- Expand the SFWD seminar series to include broader audiences.

b) ***NWTRB Recommended Action Item 1b:*** *Further enhance integration of R&D programs executed by DOE's Office of Environmental Management (DOE-EM), Office of Nuclear Energy (DOE-NE), and other DOE offices* to optimize collaboration, minimize duplication, and maximize the effectiveness of the effort.

i) Relevant Existing Activities:

- Integration of scientific R&D occurs regularly within and across the National Laboratories through execution of collaborative projects. For example, Oak Ridge National Laboratory (ORNL), Argonne National Laboratory (ANL), Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (SNL) collaborated to provide input to ARPA-E [4] for its workshop on advanced reactors in December 2020. ARPA-E has hosted additional coordination events (including workshops, industry days, meetings), where national labs, NE, EM, and the National Nuclear Security Administration (NNSA) have been invited to comment on program development and areas of technical and programmatic coordination.
- Staff from multiple laboratories support a range of programs for several DOE energy and science offices. The knowledge and experience gained in those programs can be leveraged to support SFWD objectives.
- The Disposal Research International Activities Program collaborates actively with science-based R&D disposal programs around the world.
- SFWD engages in direct communication with the other DOE-NE offices as well as with the DOE's Office of Environmental Management (DOE-EM), e.g., through DOE's Spent Nuclear Fuel Working Group, to discuss or collaborate on a variety of topics including:
    - Considerations for advanced fuels/reactors
    - Potential changes to High-Level Waste (HLW) glass compositions
    - Development and maintenance of DOE O 460.2B [5]
    - Operation of the National Transportation Stakeholders Forum (NTSF), primarily through conferences and webinars
    - Standard Canister design work

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[2] These tools are currently used by NE to better understand the spent fuel component of the integrated waste management system.

[3] CURIE = Centralized Used-Fuel Resource for Information Exchange. CURIE is an information-sharing website, accessible to federal and laboratory partners, as well as other stakeholders that provides usable, collaborative document and data access. CURIE helps users find resources, upload documents, and work more efficiently.

[4] ARPA-E = Advanced Research Projects Agency - Energy

[5] DOE O 460.2B = DOE Transportation Order for Departmental Materials Transportation & Packaging Management

- The Hanford Lead Canister Project[6]
- The DOE Spent Nuclear Fuel (SNF) Packaging Demonstration

- Under the auspices of the DOE Spent Nuclear Fuel Working Group (SNFWG), DOE is integrating development of packaging and processing technologies not only to address aging SNF and SNF facilities but also to facilitate a seamless transition from DOE-regulated SNF management to an NRC-regulated nuclear waste management environment
- SFWD is contributing to development of fully remote Cold Spray Coating (CSC), Friction Stir Processing (FSP), and Friction Stir Welding (FSW) for small diameter standardized canisters which could be used on DOE Standard Canisters, and which could also be slightly modified to include Multi-Canister Overpacks (MCOs). The specific use cases are being considered are part of the DOE SNF Packaging Demonstration.
- SFWD collaborates with Energy Information Administration (EIA) on the Nuclear Fuel Data Survey Form GC-859 data collection process.
- SFWD has been expanding the Next Generation Systems Analysis Model (NGSAM) to be able to explicitly model individual assemblies of non-commercial SNF.

ii) Potential Future Actions

- In FY2022, SFWD will enhance collaboration with the DOE Office of Nuclear Fuel Cycle and Supply Chain (NE-4) and the DOE Office for Reactor Fleet and Advanced Reactor Deployment (NE-5) to address SNF and HLW waste management challenges from advanced reactors.
- Opportunities exist for additional integration through collaborations on subsurface characterization and modeling efforts. Specific opportunities include projects that utilize underground research labs (URLs) across the world.

c) ***NWTRB Recommended Action Item 1c:*** *Find ways to work with utilities, cask vendors, fuel manufacturers, and others in the nuclear industry in an ongoing manner, to more effectively develop and implement the nuclear waste management program.*

i) Relevant Existing Activities:

- The SFWD Program actively collaborates with nuclear industry organizations including utilities, cask manufacturers, fuel vendors, and others (e.g., Orano (formerly Transnuclear Inc.), Dominion Energy Virginia, Orano (formerly AREVA), Framatome (formerly AREVA), Westinghouse, NAC International, the Electric Power Research Institute (EPRI), and the Nuclear Energy Institute (NEI). The SFWD Program also coordinates with the U.S. Nuclear Regulatory Commission (NRC) and international nuclear agencies on a variety of research activities related to storage, transportation, or disposal of SNF. Examples include:

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[6] This collaborative project seeks to transfer Cs/Sr capsules from the Waste Encapsulation and Storage Facility (WESF) into dry storage.

- The Canister Deposition Field Demonstration to run a field-based controlled study to measure the deposition of corrosive species (chloride salts) from marine coastal ambient air onto prototypic spent nuclear fuel (SNF) canisters.
  - The large scale, long term, dry storage cask research and development project for spent nuclear fuel. That is the High Burnup (HBU) demo cask, currently on the pad at Dominion's North Anna storage facility, and the associated post-irradiation testing/characterization of the HBU fuel rods (sibling pins).
  - Studies of Dual-Purpose Canister (DPC) direct disposal evaluating various processes including potential future basket/neutron absorber modifications. Associated corrosion testing of advanced neutron absorbers to gain knowledge in "other" repository environments to inform absorber selection. External review of the DPC studies includes industry staff.
  - Rail Car Optimization
  - The Studsvik Cladding Integrity Project (SCIP-IV) on SNF characterization/testing, the 1/3-scale drop test at the German Federal Institute for Materials Research and Testing (Bundesanstalt für Materialforschung und-prüfung, or BAM) facility in Germany, and the multimodal transportation test with the Korea Atomic Energy Research Institute (KAERI) of the Republic of Korea and ENSA (Equipos Nucleares S.A) of Spain.
- SFWD partners with EPRI for development of the Used Nuclear Fuel (UNF) standards and technology transfers.
- The GC-859 web-based application development effort is being conducted to allow utilities to easily provide information on spent fuel, and plans to incorporate their feedback based on pilot testing the application.
- SFWD collaborates with utilities to perform on-site and near-site transportation infrastructure evaluations.
- SFWD collaborates with the cask vendors on cask/canister-related data collection.
- SFWD collaborates with the railroad industry on the Association of American Railroads (AAR) Standard 2043 for railcar design and testing.

ii) Potential Future Actions:

- Work with vendors to develop "universal" transportation casks.
- As planned, support the 2022 NEI Used Fuel Conference.
- Possibility of future collaboration between DOE and cask vendors (and NRC) on a full-scale rail-sized cask package performance study.
- Collaborate with NEI and cask vendors on their performance margin-related efforts.
- Collaborate with utilities and cask vendors on developing dry cask loading that will support direct disposal.
- Collaborate with cask vendors in the areas of additive manufacturing of basket/canister/cask.

d) ***NWTRB Recommended Action Item 1d:*** *Find additional innovative ways of information sharing through DOE-led conferences or workshops that might encourage the different entities in the implementation matrix in Table 3-1 to improve communications and engagement.*

i) Relevant Existing Activities*:*

- Leading the development of the 2022 International High Level Waste Conference. Note that Sylvia Saltzstein (SNL) is the General Chair and both Rob Howard (PNNL) and Brady Hanson (PNNL) are technical program chairs.
- Funded the National Academy of Sciences (NAS) Study on Waste Aspects of Advanced Reactors.
- Annual SFWD meeting with industry/vendor/university/other agency collaborators.
- Leading the international DECOVALEX (DEvelopment of COupled Models and their VALidation Against EXperiments in Nuclear Waste Isolation) model validation initiative, which holds regular workshops twice a year.

ii) Potential Future Actions:

- Reconstitute and support the Ad Hoc Working Group on Transportation Communications.
- Develop plenary presentations for the 2022 National Transportation Stakeholders Conference.

2) NWTRB Recommendation #2: Anticipate Required Infrastructure and Personnel Needs

a) ***NWTRB Recommended Action Item 2a**: Develop and communicate an integrated plan regarding physical infrastructure, information technology, and personnel needs over the next decade.*

i) Relevant Existing Activities:

- SFWD Knowledge Management (KM) activities are directly related to preserving and making available to DOE-NE and associated Labs existing critical knowledge and information, including the tacit knowledge of individual staff members, for training, development, and succession planning of more junior staff.
- The SFWD cloud-based information technology (IT) platform is capable of supporting a full-scale generic nuclear waste management program with applications to support organizational and quality assurance (QA) requirements. This cloud-based solution could facilitate fully integrated program-wide collaboration with the ability to communicate and share easily between multiple remote locations and multiple participating parties. A sample of capabilities includes email, teleconferencing, document/records management, project management, data storage, legacy applications, and a project portal.
- A pilot program for development of geoscience expertise was initiated in fiscal year 2022 to educate, attract, develop and train early-career scientists to build a diverse next-generation workforce for disposal research in the U.S.

ii) Potential Future Actions

- Create a deliverable in FY2022 related to creation of a draft integrated plan.[7]

b) ***NWTRB Recommended Action Item 2b:** Formulate and implement research programs and other supporting infrastructure consistently to anticipate the effects of aging of facilities*

i) Relevant Existing Activities:

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[7] DOE will likely need to develop a separate document for federal staffing needs.

- SFWD has several ongoing activities to address this sub-recommendation, for example:
    - Active R&D on aging of commercial SNF (CSNF) canisters at storage sites, including potential changes to the stored CSNF.
    - The high burnup (HBU) demo canister is a long-term test (fielded at North Anna facility) to study aging of stored HBU SNF.
    - The Canister Deposition Field Demonstration in the Spent Fuel and Waste Science and Technology (SFWST) R&D program has acquired and is instrumenting storage canisters for the Canister Deposition Field Demonstration.
- SFWD has supported several DOE Nuclear Energy University Program (NEUP)-funded Science & Technology projects. Examples include the Hanford Lead Canister project, Cold Spray Coating (CSC) and Friction Stir Welding (FSW).
- SFWD is developing railcars (Cask railcars, a buffer railcar, and a rail escort vehicle) all of which are designed for 50-year service lives from the time of manufacture.
- SFWD has studied the transportation infrastructure at and near to utility sites that will be the origin points for the transportation system with an understanding that local infrastructure may change over time, so there is a focus on major thoroughfares which not likely to change (mainline railroads, interstates, and navigable waterways) in our transportation planning activities.

c) ***NWTRB Recommended Action Item 2c:*** *Develop and maintain the capability to utilize DOE's leading-edge, high-performance computing (HPC) resources for the analysis and simulation of processes and systems related to the back-end of the fuel cycle.*

i) Relevant Existing Activities:

- The SFWST campaign utilizes HPC for the Geological Disposal Safety Assessment (GDSA) Framework[8]. The GDSA is used for system analyses as well as for subsystem work. Both the systems models and subsurface analyses (including uncertainty quantification and sensitivity analyses) rely on access to HPC resources, though they can be executed on less powerful platforms.

ii) Potential Future Actions:

- High performance computing can be applied to the Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS)[9]/COBRA-SFS[10].
- Collaborate with the National Laboratories to apply their HPC capabilities to data analytics, data visualization, machine learning, and artificial intelligence.

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[8] GDSA Framework (https://pa.sandia.gov) is an open-source software framework developed to leverage the US DOE's high-performance computing (HPC) resources. The availability of this unique computing capability enables appropriately detailed modeling of the coupled physical and chemical processes affecting repository evolution and radionuclide transport, implementation of model domains with geologic fidelity, forward simulation over the 10^4- to 10^6-year timescale typically required by regulation, and propagation of uncertainty over many realizations of the problem.

[9] ST&DARDS is thermal hydraulics code developed for steady-state and transient analysis of multi-assembly spent-fuel storage and transportation systems

[10] COBRA-SFS is a module within ST&DARDS that is devoted to spent fuel package thermal analysis. It is a thermal-hydraulics code developed for steady-state and transient analysis of multi-assembly spent-fuel storage and transportation system.

d) ***NWTRB Recommended Action Item 2d:*** *Develop infrastructure for and implement data management systems that can meet the needs for long-term and efficient retrieval of information from current and, to the extent possible, previous relevant R&D programs.*

i) Relevant Existing Activities:

- The SFWD Cloud Project has migrated all the key project applications and their functionality and document collections from previous active nuclear waste disposal programs to an integrated cloud platform. The migrated information includes all materials pertaining to the technical and regulatory aspects associated with licensing a facility. This action preserves and facilitates efficient utilization of information related to that program. In addition, the cloud project provides a platform that enables the same capabilities to operate under a future nuclear QA program.
- SFWD Knowledge Management (KM) activities are directly related to preserving and making available existing critical knowledge and information, including the tacit knowledge [11] of individual personnel, to train and develop more junior staff, as well as to conduct succession planning.[12] A taxonomy developed on the knowledge base of nuclear waste management has been implemented to tag this content with metadata facilitating enhanced search for the database user.

e) ***NWTRB Recommended Action Item 2e****: Address the challenges of an aging workforce by expanding mentorship of a new generation of staff through: technical training programs; more effectively targeting undergraduate scholarships, graduate fellowships, and post-doctoral fellowships in areas of need; establishing internships at underground research laboratories (URLs); and promoting careers in nuclear waste management as an opportunity to address this grand environmental challenge.*

i) Relevant Existing Activities:

- National Laboratories supporting SWFD have developed internal programs for succession planning.
- SFWD has a pilot program for more active recruitment of junior geoscience personnel into the disposal research (DR) field. This pilot program for workforce development leverages the International Activities and the Geologic Disposal System Analyses (GDSA) activities to encourage student and post-doc involvement to grow a more diverse workforce.[13]
- Senior- and mid-career staff commonly serve as Control Account Managers (CAMs) while early-career staff serve as work package managers (WPMs).
- When appropriate, senior- and mid-level staff are actively paired with junior-level staff on projects to facilitate knowledge transfer and promote staff development.
- Funding of dozens of NEUP projects annually includes technical points of contact assigned from SFWST junior- through senior-level technical staff.

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[11] *Tacit knowledge* can be defined as skills, ideas and experiences that are possessed by people but are not codified and may not necessarily be easily expressed. With tacit knowledge, people are not often aware of the knowledge they possess or how it can be valuable to others.

[12] The KM Repository is designed to contain the multimedia datasets of many types and to make them easy to retrieve and use in multiple manners that are preferred by different users.

[13] The Workforce Initiative would focus on underrepresented groups and collaborate with minority-serving institutions.

- SFWD has recently hired and begun mentoring new technical staff to cover anticipated near-term and longer-term needs, including management of research work in the area of integrated waste management systems involving advanced reactor types, and consent-based siting.

ii) Potential Future Actions:

- SFWD will consider more active involvement with universities to prepare the next generation of researchers and engineers.
- SFWD plans to continue hiring new federal staff in FY22 to support new program areas and cover program areas where retirements are anticipated.

3) NWTRB Recommendation #3: Expand the Research Paradigm to Embrace Hypothesis Testing

a) ***NWTRB Recommended Action Item 3a:*** *Anticipate surprises or unexpected results that may arise during the R&D program and assure all research programs include ample provisions to accommodate possible changes in direction and focus.*

i) Relevant Existing Activities

- The SFWD research approach is aligned with this associated action item. Modeling and testing work includes hypothesis testing and provides for the possibility of unexpected results and changes in direction. For example:
  - o The HBU demo cask testing work (and sibling pins characterization testing) was analyzed with thermal models prior to the setting up the demo cask at the North Anna facility. The thermal models were benchmarked against the thermal testing facility-controlled experiments. The data collection in the test resulted in key refinements to specific modeling constraints such as thermal boundary conditions and heat transfer characteristics that improved the accuracy of the models. [14]
  - o The results from the above example as well as other storage and transportation (S&T) testing (e.g., the international multi-modal transportation test) have been used to revise the gap analyses and reprioritize the R&D programs.
  - o Within Disposal Research (DR), models of bentonite buffer are corroborated and/or adjusted as needed based on results from field-scale tests and laboratory experiments.

b) ***NWTRB Recommended Action Item 3b:*** *Test alternative hypotheses using careful experimental design over multiple scales from laboratory to full-scale in-situ tests in a URL.*

i) Relevant Existing Activities

- The SFWD research approach is aligned with this associated action item as is our fundamental approach to the coupling of modeling and testing. Tests are performed from laboratory- to field-scale throughout the R&D activities. Specific examples include:
  - o Field-scale S&T work on the North Anna HBU demo (refer to 3a for additional information) with coupled testing of sibling pins and thermal modeling. All of

[14] Ultimately this approach led to the understanding that prior models overestimated peak cladding temperatures of fuel rods within the canisters and provided an improved basis for assessing evolution of stored CSNF.

this work demonstrated conservatism of previous estimates and resulted in modification of thermal modeling approaches.

  - The Brine Availability Test in Salt (BATS) (refer to 3d, 3e and 5ai for additional information) is the field-scale component of the Salt R&D program, which includes laboratory testing, coupled process modeling (e.g., TH, THM[15]), and refinement of constitutive models using all of the above to provide GDSA the bases and models for system-scale analyses.
  - Testing on natural and engineered barriers, including different host rocks, bentonite buffers and cementitious materials, occurs from small-scale in the laboratories to field-scale measurements and long-term tests in international URLs. Processes are evaluated with models from the molecular-scale to the drift scale to evaluate model concepts and scaling issues.

c) ***NWTRB Recommended Action Item 3c:*** *Continue to make new measurements to build a database that tests the abilities of existing models to capture important processes and evaluate the possible need for new conceptual models to improve estimates of system properties and thus prediction accuracy.*

   i) <u>Relevant Existing Activities:</u>

      - The SFWD research approach is aligned with this associated action item as is our fundamental approach of the coupling of modeling and testing throughout the R&D activities.
      - Each technical R&D area has various principal-investigator-created/managed databases utilized to test models and improve representations, for example:
        - Sandia and Lawrence Livermore National Laboratories manage thermochemical data obtained during geochemical studies and modeling.[16]
        - Argonne National Laboratory has constructed data sets for SNF characteristics to use for testing models and improving understanding.[17]

d) ***NWTRB Recommended Action Item 3d****: Use results of repeated testing of existing and evolving hypotheses to enhance the usefulness of models in performance assessment.*

   i) <u>Relevant Existing Actions:</u>

      - The SFWD research approach is aligned with this associated action item as is our fundamental approach of the coupling of modeling and testing throughout R&D activities. Examples discussed above include:
        - The HBU demo project on thermal conditions in storage and the evolution of CSNF fuel rods during storage and transportation.
        - The BATS research program conducted in bedded salt in the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico.
        - Research activities in underground research laboratories in our international collaborations as discussed under Recommendation #6 below.

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[15] THM = Thermal-Hydro-Mechanical

[16] The geochemical studies and modeling referenced are conducted under the disposal research (DR) program.

[17] The SNF data compilation referenced is conducted under the Science and Technology R&D program.

- The international DECOVALEX Project involves model comparison studies between research teams from multiple organizations for the purpose of hypothesis testing. DOE is a partner in the DECOVALEX Project and the project is chaired by a National Lab scientist.

e) ***NWTRB Recommended Action Item 3e***: *Establish one or more dedicated domestic underground research laboratories that will provide the necessary opportunities for researchers and students to conduct in-situ investigations into sub-surface processes at scale, test models, and further international collaboration.*

i) Relevant Existing Activities:

- SFWD is conducting generic salt R&D testing in the underground at WIPP. This work, known as the Brine Availability Test in Salt (BATS), is evaluating heated salt beds to understand mobilization of brine during thermal perturbations. SFWST staff are leaders in the Nuclear Energy Agency (NEA) Salt Club and the BATS is being used as a data set for international model validation activities. Additional testing expansion is underway in this area.
- Work is ongoing in SFWD to refurbish and utilize a tunnel in unsaturated tuff as a URL for studies on generic unsaturated disposal systems.[18]

ii) Potential Future Actions

DOE considers the current utilization of underground research facilities (including the Waste Isolation Pilot Project in bedded salt, and participation with international partnerships such as research in argillite (Mt. Terri in Switzerland) and crystalline media (Grimsel Test Site in Switzerland)) adequate for current research needs. Establishing a dedicated domestic URL is not appropriate at this time, however, as the research program and repository program advances, DOE will consider additional research opportunities as appropriate in the future, such as:

- Supporting the collaborative establishment of a state-of-the-art borehole to advance subsurface science and technology. The borehole laboratory design is a flexible, multi-purpose configuration that enables one or more borehole utilizations for singular or multiple simultaneous experiments to study phenomena at all scales.
- Consider use of the Sanford Underground Research Facility (SURF)[19], URL located in Lead, South Dakota. There is potential to use this full-scale, crystalline rock URL to:
  - Develop and advance technologies for repository characterization that can improve the uncertainty quantification and sensitivity analyses for modeling efforts.
  - Develop and advance technologies for long-term and/or real-time monitoring of waste packages.
  - Design engineered processes and systems for applied energy and national security.

[18] The site infrastructure developments have been delayed by COVID. Planning for tests include underground passive monitoring of site gas movement and Muon detection in the subsurface.
[19] For more information on the SURF URL visit https://www.sanfordlab.org/

- Consider support of R&D activities associated with the Deep Vadose Zone (DVZ) Test Site.[20]

4) **NWTRB Recommendation 4: Apply an Iterative, Adaptive Approach in Developing and Managing the Nuclear Waste Management Program.**
   a) ***NWTRB Recommended Action Item 4a:*** *Iterate between testing individual components of the nuclear waste management program and testing integrated models of the entire waste management system, always being ready to adapt each approach based on what is learned from such testing.*
      i) Relevant Existing Activities:
         - This is a core, fundamental process of the coupling of modeling and testing throughout SFWD R&D activities. Please see above examples provided in Recommendation 3 for examples.
         - The development of the Geological Disposal Safety Assessment (GDSA) capabilities is inherently an iterative process of continued evaluation, addition, testing, refinement, and reassessment, both for understanding of process representations and for prioritization of next stages of R&D for disposal system analyses.
         - Systems analyses using the Next-Generation System Analysis Model (NGSAM), embraces this approach. System model representations of waste acceptance, transportation, storage, and disposal operations are developed iteratively.

      ii) Potential Future Actions:
         - The GDSA is currently focused on addressing generic repository systems in the SFWD program, but the capabilities are developed in a manner (both technical and documentation) that facilitates utilization in potential future application in other programs that may evolve to more site-specific focus.

   b) ***NWTRB Recommended Action Item 4b:*** *Be open and structured to adapt to surprises during all aspects of the nuclear waste management program and always be willing to reevaluate and rethink previous decisions.*
      i) Relevant Existing Activities:
         - SWFD is committed to proceeding in a manner that is inclusive, transparent, participatory, and responsive to new information and the suggestions and recommendations of communities, stakeholders, and the public.
         - This is a core, fundamental aspect of the coupling of modeling and testing throughout SFWD R&D activities, for example:
            - The HBU Demo cask studies used thermal measurements of a HBU SNF cask to update the understanding of model representations for boundary conditions and other conservative heat transfer process. Updated models led to improved,

[20] The DVZ Test Site is leveraged for development and demonstration of advanced monitoring technologies within consolidated and unconsolidated sediments and crystalline rock. The unique characteristics of this area allow for in-depth analysis and learning that can be applied to multiple sites and needs across the country.

more realistic representations and better understanding of the peak cladding temperatures in HBU casks.

In implementing its Strategic Framework for DOE-Managed Spent Nuclear Fuel (June 2021) DOE is reevaluating and validating or modifying, as appropriate, previously made decisions with respect to storage and disposition of DOE-managed SNF.

c) ***NWTRB Recommended Action Item 4c:*** *Establish mechanisms as part of on-going evaluations to facilitate and incentivize solicitation of input and feedback from all affected stakeholders, including: independent scientists and engineers outside of the nuclear waste management program; local, state, and tribal governments; nuclear utilities; and the interested public.*
   i) Existing Relevant Activities:
      - Integration of inputs/constraints from all relevant sources is a fundamental activity in the coupling of modeling and testing throughout the R&D activities within SFWD.
   ii) Potential Future Actions:
      - Develop and implement a Strategic and Comprehensive Stakeholder Engagement and Communications Plan that includes mechanisms to facilitate and solicit input from affected stakeholder groups and tribal representatives.

5) **NWTRB Recommendation #5: Expand Engagement with the International Community to Benefit from Lessons Learned.**
There are four sub-recommendations under Recommendation #5, however because there is an actively integrated collaborative international program, a single response to all four sub-recommendations is provided. The four sub-recommendations for NWTRB Recommendation #5 are as follows:

a) ***NWTRB Recommended Action Item 5a:*** *Build on current initiatives and continue to expand engagement with the international community, recognizing the need for global cooperation in science and technology in this world-wide grand environmental challenge.*

   NWTRB Recommended Action Item 5b: *Sustain active engagement in international programs given the tangible benefits derived from close involvement.*

   NWTRB Recommended Action Item 5c: Continue and *expand participation in collaborative international underground research laboratory activities. If, as recommended, DOE develops one or more underground research laboratories, it should encourage international participation, which could benefit the DOE program by incorporating broader perspectives and expertise.*

   NWTRB Recommended Action Item 5d: *Emphasize engagement with countries that have advanced to the demonstration and/or construction authorization stages of repository development to enhance knowledge of these stages.*

   Overall, SFWD believes that focus on international collaboration allows close integration with the international waste management R&D community in terms of best practices, new science advances, state of the art simulation tools, new monitoring and performance confirmation approaches, lessons learned, etc. SFWD has therefore established a broad range of international collaboration activities. The joint R&D with international researchers, the worldwide sharing of knowledge and experience, and the direct access to relevant data/experiments from a variety of underground research laboratories and host rocks provides an improved understanding of the current technical basis for disposal in a range of potential host rock environments. Comparison with experimental data allows for testing and validating predictive computational models for evaluation of disposal system performance in a variety of generic disposal system concepts. Comparison of model results with other international modeling groups, using their own simulation tools and conceptual understanding, enhances confidence in the robustness of predictive models used for performance assessment. The possibility of linking model differences to particular choices in conceptual model setup provides guidance into "best" modeling choices and understanding the effect of model uncertainty. These outcomes, including improved predictive models and a deep understanding of conceptual model uncertainties, can be directly incorporated into GDSA activities.

i) Relevant Existing Activities:

- SFWD researchers actively participate in numerous international activities. See previous responses for some examples from the Storage and Transportation (S&T) R&D program as well as from the Disposal Research (DR) R&D programs.
- Disposal Research R&D includes projects in URLs from many countries as well as development of domestic URL programs. The SFWD BATS is a U.S.-based field test with international collaboration. Much of this collaborative international work is available in public reports, journal articles, and conference publications.
- SFWD has a balanced portfolio of international collaboration activities in DR and addresses relevant R&D challenges in near-field perturbation, engineered barrier integrity, radionuclide transport, and integrated system analysis. These activities form a central element of SFWD DR programs, and significant advances have been made across different host rock types and engineered barriers.
- SFWD recognizes that international collaboration enables (1) leveraging a deep knowledge base regarding alternative repository environments developed across the world, (2) utilizing international research facilities, especially operating underground research laboratories not available in the U.S., and (3) sharing the cost of major tasks such as full-scale *in situ* experiments or complex modeling efforts.
- SFWD currently has in place formal collaboration agreements with multiple international partners on several international initiatives, including the following:
    - The DECOVALEX Project[21]
    - The Mont Terri Project[22]
    - SKB Task Forces[23]

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[21] The DECOVALEX project is an international research and model comparison collaboration, initiated in 1992, for advancing the understanding and modeling of coupled thermo-hydro-mechanical-chemical (THMC) processes in geological systems. https://decovalex.org/

[22] The Mont Terri Project is an international research project for the hydrogeological, geochemical, and geotechnical characterization of a clay formation (Opalinus Clay). Mont Terri is located in Switzerland. https://www.mont-terri.ch/

[23] SKB is the Swedish Nuclear Fuel and Waste Management Company that is tasked with finding solutions for the safe management of Sweden's radioactive waste. The SKB Task Force is an international collaboration that focuses on selecting and

- HotBENT[24]

- SFWD researchers are conducting several collaborative R&D activities that align with R&D priorities across most of the technical areas discussed in this section. In these collaborations, SFWD scientists contribute world class analyses, models, and data for both process understanding and system risk modeling and assessment (see e.g., Birkholzer and Faybishenko, 2021[25].
- Early efforts to develop a consent-based siting (CBS) approach to site a SNF repository and/or interim storage facility were built upon examples, experiences and lessons learned from countries such as Canada, Sweden, and Finland.

6) **NWTRB Recommendation #6: Embrace Openness, Transparency, and Engagement**
As noted in the 2017 *Draft Consent Based Process for Consolidated Storage and Disposal Facilities for Spent Nuclear Fuel and High-Level Radioactive Waste*, NE is committed to proceeding in a manner that is inclusive, transparent, participatory, and responsive to new information and the suggestions and recommendations of communities, stakeholders, and the public.
   a) **NWTRB *Recommended Action Item* 6a:** *Inform and engage the public and other affected stakeholders early in the planning and review of all aspects of the nuclear waste management program.*
      i) Relevant Existing Actions:
         - A DOE-NE Request for Information (RFI) was issued in December 2021, that seeks public input on several SFWD programs, including consent-based siting (CBS).
         - Much of the collaborative work generated within SFWD is available in public reports, journal articles, and conference publications.
         - SFWD and its National Lab partners regularly engage in public conferences and meetings with external entities in industry, regulatory agencies, and academia.
         - SFWD funds the Nuclear Energy University Program (NEUP), which has dozens of active projects.
         - Stakeholder feedback from earlier consent-based siting (CBS) efforts was a central component of designing the 2017 *Draft Consent-Based Siting Process for Consolidated Storage and Disposal Facilities for Spent Nuclear Fuel and High-Level Waste*. Over 10,000 pieces of correspondence, received by DOE via a variety of mechanisms, were

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overseeing specific experiments to be performed at the Äspö Hard Rock Laboratory for parallel modeling by more than one participating team. Currently, the SKB Task Force is focused on two tasks: Task 8 is investigating the interface of engineered and natural barriers, and Task 9 seeks to develop more realistic models of solute flow and transport through fractured rock. https://www.skb.com/about-skb/our-task/

[24] HotBENT is a collaborative international effort to evaluate the effects of high temperatures on bentonite-based barriers and their safety functions. Field work for HotBENT takes place in Switzerland at the Grimsel Test Site URL. https://www.grimsel.com/gts-projects/hotbent-high-temperature-effects-on-bentonite-buffers/hotbent-introduction

[25] Birkholzer, J., and Faybishenko, B. 2021. International Collaboration Activities in Geologic Disposal Research: FY20 Progress, Spent Fuel Waste Science and Technology (SFWST), Milestone Report, M2SF-20LB010307012, LBNL-2001433, Lawrence Berkeley National Laboratory, Berkeley, CA USA, 333 pp.

carefully tracked, processed, and summarized using a language processing tool known as the Comment Response Management System (CRMS).[26]

- SFWD is engaged with Native Americans through the Nuclear Energy Tribal Working Group (NETWG) and the Tribal Radioactive Materials Transportation Committee (TRMTC), and with State governments through four State Regional Groups (SRGs) covering the continental US. SFWD funding to TRMTC and the SRGs supports the operation of their respective committees, as well as participation in DOE's National Transportation Stakeholders Forum (NTSF) and its associated topical ad hoc working groups.
- SFWD has operated multiple NTSF ad hoc working groups comprised of federal, State, and Tribal government representatives to address technical and policy topics related to spent nuclear fuel transport. The NTSF Rail/Routing ad hoc working group has worked with States, Tribes, the US Department of Transportation Federal Railroad Administration, and the railroad industry to understand railroad transport operations, regulatory structures, process for identifying transport routes for hazardous materials, and safety inspection practices. The group is currently collaborating on development of a railcar safety inspection protocol for future DOE shipments of spent nuclear fuel that could enable States and Tribes along a transportation route access to safety inspection information on spent nuclear fuel shipments, and enable an inspection reciprocity arrangement, similar to what is available for highway radioactive materials shipments through the Commercial Vehicle Safety Alliance's Level VI inspection.
- SFWD nuclear power plant infrastructure evaluations include participation from State and Tribal government representatives in the region of a plant to both seek local input and expertise on options and challenges for transporting spent nuclear fuel away from reactor sites as well as lend transparency to DOE's considerations for transport modal options, logistical operations, safety, and security.

ii) Potential Future Actions:

- One or more community Funding Opportunity Announcements (FOAs) may be issued in FY2022. The FOAs will allow communities that are potentially interested in hosting a consolidated interim storage facility (CISF) to apply for funding to learn more and develop outreach and engagement activities of their own.
- DOE plans to create opportunities to discuss the Draft Strategic Plan with stakeholders.
- In FY22, SFWD plans to resume operation of the NTSF Section 180(c) ad hoc working group to continue collaborations with State and Tribal governments and work toward a final Departmental policy for how DOE will provide funds to States and Tribes through whose jurisdictions DOE transports spent nuclear fuel and high-level radioactive waste, consistent with the intent of Section 180(c) of the NWPA.

b) ***NWTRB Recommended Action Item 6b:*** *Be transparent in decision-making and provide support for meaningful stakeholder participation.*

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[26] The CRMS is a proven and effective knowledge management tool to provide a rapid and effective way to efficiently synthesize public and stakeholder comments at both large scales and broad scopes. It has been used successfully to process tens of thousands of comments, shortening agency response time, while facilitating consistency and ensuring comments and concerns are captured and incorporated into the decision-making process and record.

i) Relevant Existing Activities:
- Senior-level communications and environmental justice (EJ) personnel are being integrated into the design and implementation of a consent-based siting (CBS) process.
- SFWD is investing in the development of FACET[27] and related tools to develop meaningful engagement and outreach opportunities. FACET is a science-based framework for transparently evaluating tradeoffs among complex environmental, economic, and social issues. It offers support for policy and business decisions, resulting in risk-informed, socially equitable, and defensible evaluations for all stakeholders.

ii) Future Potential Actions:
- Restart bi-annual (every 6 months) Transportation Core Group Meetings.
- Reconvene and support Ad Hoc Working Groups on Transportation Communications.
- Strive to publicly release all fully developed reports and notify State, Tribal, and federal partners, as appropriate, when they are posted publicly.
- Design and implement a Comprehensive and Strategic Stakeholder Engagement and Communications Plan (See NWTRB Recommendation #6 opening paragraph, above).

c) ***NWTRB Recommended Action Item 6c:*** *Take account of lessons learned in other countries about listening to and informing the public, in order to improve communications, better understand community perspectives, and avoid unnecessary delays of the program.*

i) Relevant Existing Activities:
This recommended action item is aligned with SFWDs path forward on developing an integrated nuclear waste management system that includes a consent-based approach to siting waste management facilities. SFWD has consultants with experience from other nuclear waste management programs such as the Canadian Nuclear Waste Management Organization (NWMO) and plans to seek additional advice and lessons learned from international waste management programs, whenever possible.

d) ***NWTRB Recommended Action Item 6d:*** *Though not a license requirement for any new site selected for a repository, DOE should develop and make available a clear characterization of the facility early in the process that describes the waste management concept and its multiple barriers and other attributes that contribute to safety. DOE must also clearly acknowledge and communicate its commitment that the safety concept will be revised to update it as new information and input are received.*

i) Relevant Existing Activities:
- This recommended action item is aligned with SFWDs path forward on developing an integrated nuclear waste management system that includes a consent-based approach to siting waste management facilities. Multiple products need to be developed for a wide range of audiences to explain overall waste management system concepts and approaches, facilities, and safety features.

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[27] FACET = The Framework for Assessment of Complex Environmental Tradeoffs
https://www.pnnl.gov/projects/environmental-justice/facet

e) ***NWTRB Recommended Action Item* 6e:** *Develop site-suitability criteria prior to the start of site selection so as to minimize any ambiguity and latitude in their interpretation, thus helping to ensure the objectivity of the process and public confidence in its outcome. If, at any point during the siting process, the criteria need to be changed, a transparent and meaningfully participatory process to do so needs to be followed.*

i) Relevant Existing Activities

- There is discussion of "Siting Considerations" for both repositories and a CISF in the 2017 *Draft Consent-Based Siting Process for Consolidated Storage and Disposal Facilities for Spent Nuclear Fuel and High-Level Radioactive Waste* document.

f) ***NWTRB Recommended Action Item 6f:*** *If, as recommended, the United States develops one or more underground research laboratories, these laboratories, in addition to their research function, should be utilized for outreach and public engagement, in order to provide access to the subsurface (a vague concept with the public) and to build public confidence and trust and engineering behind the safety concept, as well as in the operational capabilities for remote handling of waste underground.*

i) Relevant Existing Actions:

- URL work in the US is currently used for outreach, however the sites themselves have/may have restrictions regarding direct public access.
- Operational testing for disposal concepts goes well beyond generic disposal system R&D and may not be warranted in the R&D program until further progression into a disposal program timeline. Currently, the international collaboration provides insight into this area for generic disposal system R&D.

ii) Potential Future Actions:

- If DOE develops a specific underground research laboratory in the future to support repository development, DOE will consider the use of the URL for outreach, public engagement, and for testing operations as recommended.

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