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, 2016-December 31, 2018

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, 2016–December 31, 2018

August 2021

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

August 2021

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, 2016, through December 31, 2018.

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 five critical technical issues. The Board evaluated DOE activities on deep borehole disposal, 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, management and disposal of high burnup commercial SNF.

The Board hopes that Congress and the Secretary will find the information in this summary 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

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

JEAN M. BAHR, PH.D., CHAIR
University of Wisconsin, Madison, Wisconsin

STEVEN M. BECKER, PH.D.
Old Dominion University, Norfolk, Virginia

ALLEN G. CROFF, NUCLEAR ENGINEER, M.B.A.
Vanderbilt University, Nashville, Tennessee

TISSA ILLANGASEKARE, PH.D., P.E.
Colorado School of Mines, Golden, Colorado

KENNETH LEE PEDDICORD, PH.D., P.E.
Texas A&M University, College Station, Texas

PAUL J. TURINSKY, PH.D., DEPUTY CHAIR
North Carolina State University, Raleigh, North Carolina

Note: Dr. Susan Brantley of Pennsylvania State University served as a Board member from September 25, 2012 to July 21, 2021. Dr. Mary Lou Zoback of the U.S. Geological Survey (retired) served as a Board member from September 25, 2012 to May 17, 2021. They played instrumental roles in developing this report.

U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD STAFF

Executive Staff

Nigel Mote	*Executive Director*
Neysa Slater-Chandler	*Director of Administration*

Senior Professional Staff

Hundal (Andy) Jung	*Materials Engineering, Corrosion*
Bret W. Leslie	*Geoscience, External Affairs*
Chandrika Manepally	*Hydrogeology*
Daniel G. Ogg	*Nuclear Engineering, Operations*
Roberto T. Pabalan	*Geochemistry, Physical Chemistry*

Professional Staff

Yoonjo (Jo Jo) Lee	*Nuclear Engineering, Corrosion*

Administrative & Support Staff

Davonya S. Barnes	*Information Systems Specialist*
Jayson S. Bright	*Systems Administrator*
Sonya Townsend	*Secretary*
Casey Waithe	*Financial Manager*

Contents

Executive Summary xiii

The Context of the Board's Review xiv

Geologic Disposal xiv

Deep borehole disposal xv

Disposal of SNF in dual-purpose canisters xv

Salt as a host rock for disposal xv

HLW glass corrosion xvi

Performance monitoring in, and retrievability of waste from, a repository xvi

Packaging, Storage, and Transportation of SNF and HLW xvi

Management of DOE SNF xvii

Packaging and transportation of SNF and HLW xvii

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

Integrated SNF and HLW Management and Disposal System xviii

International Activities xix

Preface xxi

Board Activities 1

The Board and Its Mission 1

Developments in Nuclear Waste Management 3

Board Review: Deep Borehole Disposal 6

Technical evaluation of research and development program 7

Board Review: Disposal in a Mined Geologic Repository 11

Disposal of SNF in dual-purpose canisters 12

Salt as a host rock for SNF and HLW disposal 13

Board Review: DOE's Management of Its HLW and SNF 14

Disposition of vitrified HLW 15

Management and disposal of DOE SNF 18

Board Review: Packaging, Storage, and Transportation of SNF and HLW 23

Packaging and transportation of SNF and HLW 24

Long-term dry storage and transportation of high burnup commercial SNF 30

Board Interactions with Congress 38

International Activities 38

Survey of national programs 39

Performance monitoring in, and retrievability of waste from, a repository 39

Board visit to Belgium and Switzerland 41

Board participation in the activities of the Advisory Bodies to Government 44

Board participation in the activities of the International Atomic Energy Agency 44

Board participation in the activities of the Nuclear Energy Agency 45

REFERENCES 47

ACRONYMS 51

GLOSSARY 53

APPENDICES 57

Appendix A Board Members During the Reporting Period 59

Appendix B Board Strategic Plan 2018–2022 75

Appendix C Board Publications 87

Appendix D Board Meetings: January 1, 2016–December 31, 2018 105

Appendix E Correspondence with the U.S. Department of Energy January 1, 2016–December 31, 2018 109

FIGURES

Figure ES-1. Timeline of Board activities, meetings, and correspondence from January 1, 2016 to December 31, 2018. xiii

Figure 1. Timeline of Board activities, meetings, and correspondence from January 1, 2016 to December 31, 2018. 2

Figure 2. Comparison of the concepts of radioactive waste disposal in (A) a mined, geologic repository and (B) a deep borehole [Not to scale]. 6

Figure 3. A heater test conducted in a borehole within a tunnel wall. 14

Figure 4. L Basin storage facility. 18

Figure 5. Transfer of ENSA test cask from a cargo ship to a rail car. 29

Figure 6. High burnup dry storage research project demonstration cask. 31

Figure 7. Cable array used at the Grimsel Test Site. 42

Figure 8. Board delegation learned about DOE's participation in the Mont Terri Project full-scale emplacement (FE) heater test. 43

Executive Summary

The U.S. Nuclear Waste Technical Review Board (Board) was established by Congress in the 1987 Nuclear Waste Policy Amendments Act (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 reports the results of its evaluations, along with its findings, conclusions, and recommendations, to Congress and to the Secretary of Energy.

Between January 1, 2016 and December 31, 2018, the period covered by this report, the Board focused its evaluation on five critical technical issues dealing with geologic disposal and on three crucial technical issues dealing with the packaging, storage, and transportation of SNF and HLW destined for disposal. The Board also explored in depth the crosscutting issue of the development of an integrated system for the management and disposal of SNF and HLW. Figure ES-1 depicts a timeline of activities the Board completed in pursuit of its mission between 2016 and 2018, including correspondence with DOE, Board reports to Congress and the Secretary of Energy, and fact-finding and public Board meetings with DOE.

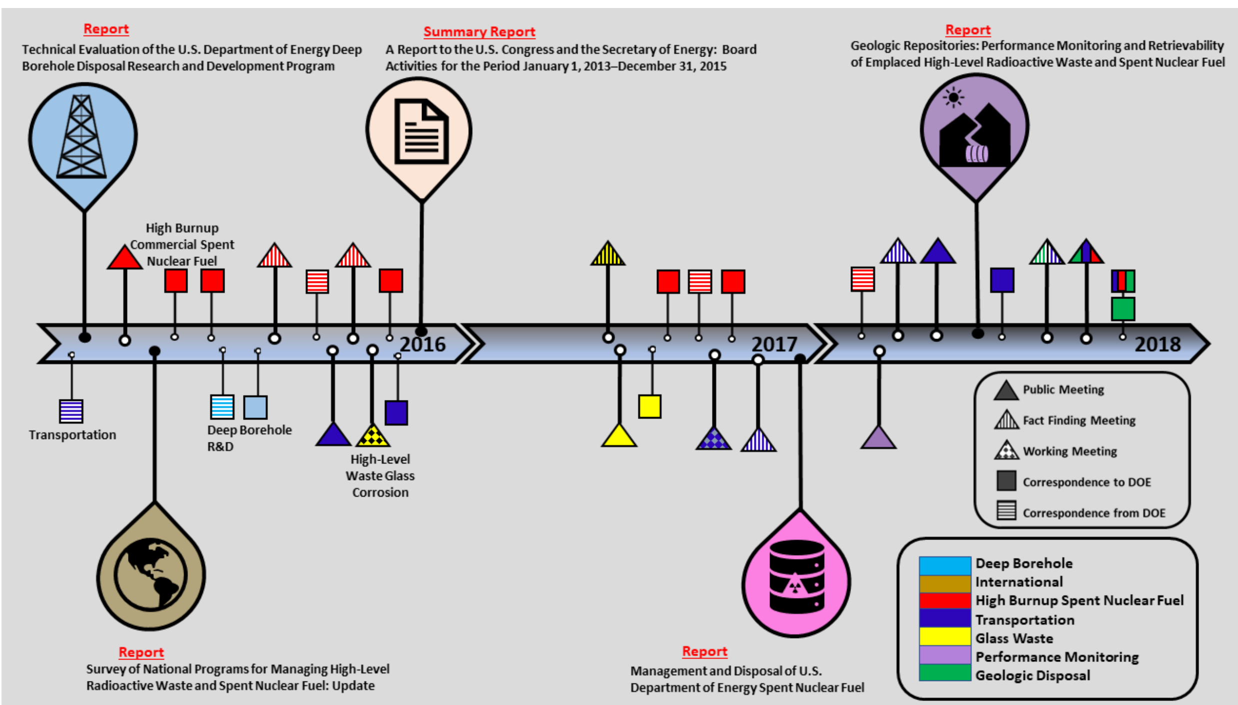

Figure ES-1. Timeline of Board activities, meetings, and correspondence from January 1, 2016 to December 31, 2018.
See legends to the bottom right: subject matters are color-coded and shapes indicate a type of activity. Board reports are offset with large balloons; triangles symbolize meetings; and squares symbolize correspondence to or from DOE, as indicated.

The Board used insights gained from international activities as a basis for reviewing DOE's research and development (R&D) activities and to highlight issues that affect the success of national programs for the management and disposal of SNF and HLW. The Board's views on the technical issues associated with geologic disposal, packaging, storage, and transportation, and an integrated system for the management and disposal of SNF and HLW, as well as the Board's international activities, are summarized below and are explained in greater detail in the body of this report.

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, delineated the scope of DOE's activities during this reporting period. The strategy included a phased, adaptive, and consent-based approach to siting and implementing a comprehensive 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 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. These 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. In its strategy, DOE also identified several initiatives it was undertaking, including R&D on the deep borehole disposal concept, consent-based siting, and transportation evaluations that could prioritize DOE's acceptance of SNF from shut-down reactors. Most of these initiatives continued through the period covered by this report, with the exception of deep borehole disposal and consent-based siting.

In 2017, the Administration of President Donald Trump 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, DOE continued its efforts through 2018 to develop an integrated waste management system that was consistent with its 2013 strategy and existing legislative authority. Practically, this meant that DOE continued, through the end of 2018, to conduct R&D on storage, packaging, transportation, and non-site-specific geologic disposal options for both commercial and DOE SNF and HLW.

Geologic Disposal

The Board focused its evaluation on five critical technical issues. The Board evaluated DOE's activities related to:

- deep borehole disposal,
- disposal in a mined geologic repository of dual-purpose (storage and transportation) SNF canisters that are used at utility sites,
- salt as a geologic repository host rock for disposal,
- and HLW glass corrosion and its long-term performance in a geologic repository.

The Board evaluated international efforts on performance monitoring in, and retrievability of emplaced SNF and HLW from, a geologic repository. These activities will be integral to any repository program that DOE develops.

Deep borehole disposal

The Board closely followed DOE's activities regarding the deep borehole disposal concept since DOE created a technology roadmap in 2012 for fielding a demonstration program. The culmination of the Board's critical evaluation of DOE's plans for a Deep Borehole Field Test and its R&D activities was a Board report (Figure ES-1). The Board found that deep borehole disposal will not eliminate the need for a geologic repository. Moreover, deep borehole disposal was not any less complicated than geologic disposal from a technical viewpoint and would require substantial effort from DOE. The Board recommended that the Deep Borehole Field Test planners carefully consider key parameters and information to evaluate the feasibility of the disposal option. However, during the reporting period (as of May 2017), the Department redirected its budgetary priorities and terminated its deep borehole disposal activities.

Disposal of SNF in dual-purpose canisters

The R&D work DOE has completed since 2013 indicates that there are engineering solutions to some of the technical challenges posed by disposal of commercial SNF in dual-purpose canisters. On this basis, DOE has eliminated a number of technical issues, such as packaging and handling, from consideration in future evaluations. One exception is post-closure criticality. The Board concurred with DOE that it was important to evaluate the consequences of post-closure criticality to provide a basis for determining its impact on post-closure repository performance, but noted that DOE's proposed multiphysics modeling would face technical challenges, particularly with model validation and in the treatment of uncertainties.

The DOE R&D on disposal of SNF in dual-purpose canisters could inform decisions on whether it will be necessary or desirable to repackage SNF prior to disposal. The Board observed that a decision to accommodate large packages in a repository would place some significant constraints on repository design and may limit the range of geologic environments that could be considered for repository development.

Salt as a host rock for disposal

DOE was conducting R&D activities underground at the Waste Isolation Pilot Plant (WIPP), an underground facility constructed in salt near Carlsbad, New Mexico, which was being used by DOE as a geologic repository for transuranic waste. These activities informed DOE about the technical issues that could arise if SNF and HLW were to be emplaced in a salt-rock repository and helped identify the R&D work that would be required to support development of such a repository. The Board's tour of WIPP in October 2018 focused on a series of underground heater tests. Since underground activities stopped at Yucca Mountain and domestic disposal-related underground experiments had been severely curtailed, there had been a concomitant loss of expertise in field tests. DOE had learned anew about experimental test designs from early tests and was applying lessons learned in designing a new proposed heater test conducted in a borehole within one of the tunnels in the facility. From its visit to WIPP, the Board gained insights on nuclear waste transportation issues and repository operations that are similar to those issues that DOE would face when it transports SNF and HLW to a geologic repository.

HLW glass corrosion

DOE R&D activities conducted in the past few years in collaboration with international scientists had significantly advanced understanding of HLW glass corrosion and development of models for generic repository performance assessments. DOE had effectively used state-of-the-art analytical equipment, conducted long-term experiments, and begun compiling and analyzing a database of glass corrosion experimental data to advance its understanding of HLW glass corrosion. However, there were still significant technical uncertainties regarding when and what triggers accelerated glass corrosion in late stages of the experiments. The Board observed that additional long-term experiments, judicious use of natural analogs, enhancement of the glass corrosion experiments database and its analysis, and a more robust evaluation of model uncertainties could enhance DOE's HLW glass corrosion activities.

Performance monitoring in, and retrievability of waste from, a repository

The Board reviewed international efforts on performance monitoring in, and retrievability of emplaced SNF and HLW from, a geologic repository, to gain insights into these crucial activities that are integral to any repository that DOE could develop. The culmination of the Board's critical evaluation of this topic was a Board report (Figure ES-1). Development of a repository was strengthened when retrievability was considered in the initial repository design phase and consideration of monitoring to assess operations and to support decisions related to repository operations or waste retrieval was integrated from the beginning. The Board considered underground research laboratories useful resources to provide information needed to make decisions on monitoring and retrievability, because they would allow for testing and practical demonstration of waste emplacement and retrieval techniques and monitoring in prototypical environments that could also help improve public understanding and garner public acceptance of a waste management program.

Packaging, Storage, and Transportation of SNF and HLW

The Board focused its evaluation on three critical technical issues. The Board evaluated DOE's activities related to the management of DOE SNF; DOE's R&D program on packaging and transportation of SNF and HLW; and its activities related to long-term dry storage and transportation of high burnup commercial SNF.

Management of DOE SNF

The Board completed a multi-year comprehensive evaluation of DOE's management of its SNF and released a report on the results of its review in 2017 (Figure ES-1). The Board found that DOE's program to manage its SNF, including degradation of the SNF, the materials that contain it, and the facilities in which it was stored, had not been fully implemented. Regarding packaging and dry storage of DOE SNF, the Board found that an improved technical basis was needed for proposed drying procedures for DOE SNF before packaging it in multi-purpose (storage, transportation and disposal) canisters. In addition, the Board concluded that measuring and monitoring conditions of the SNF during dry storage was important. The Board also recognized that technical and regulatory uncertainties complicate planning for packaging facilities. The Board recommended that DOE take actions to understand, manage, and monitor degradation of DOE SNF, and the facilities in which it was stored, and complete R&D and licensing of the DOE standardized canister, which is a multi-purpose canister. Since release of the report, Congress specifically appropriated money to DOE to address the Board's recommended actions and DOE began acting on the recommendations.

The Board found that some DOE SNF was not managed by DOE Office of Nuclear Energy (DOE-NE) according to the procedures DOE had developed to maintain the SNF in a condition that would allow it, or products from processing the SNF, to be accepted for geologic disposal. The Board recommended that DOE should implement existing waste acceptance system requirements for all its SNF.

The Board found that the diversity of DOE SNF combined with differences in physical and chemical characteristics of potential repository environments could complicate the potential disposal of DOE SNF. For DOE's non-site-specific disposal R&D program, the Board recommended that DOE should identify and prioritize its R&D concerning DOE SNF degradation in each host-rock environment that it was investigating.

Packaging and transportation of SNF and HLW

The Board reviewed DOE's preliminary evaluations of removing commercial SNF from sites where reactors have been shut down, which involved working with site personnel, utilities, and local stakeholders. The Board observed that these evaluations had generated information that would be valuable for planning and implementing removal of the SNF. The Board observed that DOE had advanced the development of system analysis and planning tools that would be a major asset in designing the transportation program, particularly as development of the tools was continued and as DOE gained access to the detailed technical information necessary to conduct realistic system analyses. DOE completed a test program for evaluating transportation of an SNF cask with fuel assemblies using various transportation modes, such as truck, cargo ship, and train. The Board observed that this test program was a model of international and domestic collaboration and effectively leveraged resources and talents.

In its review of these efforts, the Board observed that there was a need for early and continuous engagement and collaboration between DOE and stakeholders at the state and local level, as well as with other organizations such as nuclear utilities and rail carriers. All of these players would be essential to ensuring an effective nationwide transportation program. Furthermore, the Board observed that DOE needed to develop designs for new casks and canisters for transporting DOE-managed SNF and HLW. However, given the magnitude of the effort to coordinate a transportation program, the Board noted that the lack of adequate and predictable funding would adversely affect the development of the program.

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

DOE had made significant progress, including from its participation in the Extended Storage Collaboration Program, toward developing the technical bases needed to support the extended storage and subsequent transportation of commercial SNF. An increasing quantity of SNF discharged from commercial nuclear reactors in the future will be fuel that was utilized for longer times and achieved higher burnups. To investigate further the behavior of high burnup commercial SNF during extended storage, transportation, and subsequent operations, DOE had engaged in the following research activities: the High Burnup Dry Storage Cask Research and Development Project to gather necessary data on the behavior and potential degradation of high burnup commercial SNF; tests using vibrational loads to simulate conditions that high burnup commercial SNF is expected to experience during rail and road transportation; and investigations to understand hydride reorientation and processes that could affect cladding integrity.

The Board observed generally good integration of DOE R&D activities on high burnup commercial SNF, and high-quality data were being acquired from the High Burnup Dry Storage Cask Research and Development Project. However, more work was needed in research areas involving cask drying to better quantify the amount and form of water that remains in a dry storage cask following drying operations, and more work was needed to develop a physical-chemical model that can predict behavior of irradiated cladding using data obtained from experiments using unirradiated cladding. The Board noted it was important for DOE to accord a high priority to gaining access to new fuel design information and post-irradiation examination results, which would be needed to support the efforts of national laboratories to understand SNF characteristics during extended storage and subsequent transportation, such as the potential for hydride reorientation and criticality analysis of SNF in loaded dual-purpose canisters.

Integrated SNF and HLW Management and Disposal System

DOE had shown marked progress in integrating R&D activities within several areas such as the HLW waste glass corrosion program and subsets of the storage and transportation program. However, integration across all relevant program areas (i.e., storage and transportation, disposal, and integrated waste management) within the DOE-NE and with other relevant DOE offices with responsibility for waste management and disposal remained a challenge. The Board noted that DOE-NE's effort to plan and develop a nationwide transportation program did not appear to be well-integrated with the activities of the DOE Office of Environmental Management (DOE-EM), and did not consider the full range of SNF and HLW materials and packages that were managed by DOE-EM.

The Board noted that implementation of an integrated nuclear waste management and disposal program was also dependent on national policies related to radioactive waste management, and on actions that would need to be taken by parties other than DOE. While this dependence on policies and other parties could limit some of DOE's ability to fully establish an integrated program, the Board recommended that DOE take immediate actions to lay the foundation for such a system and implement efforts to advance an integrated system. The Board recommended that DOE should establish a comprehensive database to record information on all commercial and DOE SNF and HLW, develop an integrated (end-to-end) system analysis tool for waste management, optimize the system using an end-to-end approach, and assess and optimize new canister designs for end-to-end compatibility.

International Activities

The Board issued two reports focused on aspects of other countries' radioactive waste programs and interacted with other nations and international radioactive waste management organizations. The Board updated its previous international survey of 30 attributes of nuclear waste management programs in the United States, Belgium, Canada, China, Finland, France, Germany, Japan, South Korea, Spain, Sweden, Switzerland, and United Kingdom. As described above, the Board reported on international efforts on performance monitoring in, and retrievability of emplaced SNF and HLW from, a geologic repository. A study visit to Belgium and Switzerland allowed the Board to obtain information directly on developments in each country's radioactive waste management program and view underground research facility experiments in which DOE was collaborating. The Board met with the International Atomic Energy Agency on R&D activities in underground research facilities, the Nuclear Energy Agency's Integration Group for the Safety Case, and with other advisory bodies to national governments that are comparable to the Board. The Board also hosted representatives of some countries' programs when they visited the United States and included them in Board meetings, when appropriate.

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, 2016 and December 31, 2018. 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. Rodney C. Ewing (past Chair); Dr. Efi Foufoula-Georgiou; Dr. Gerald S. Frankel; Dr. Tissa Illangasekare; Dr. Linda K. Nozick; Dr. Kenneth L. Peddicord; Dr. Paul J. Turinsky (Deputy Chair); and Dr. Mary Lou Zoback.[1] 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, 2016 and ending on December 31, 2018.[2] 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.[3] 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, 2016 to December 31, 2018.

---

[1] Dr. Susan Brantley served from September 25, 2012, until her resignation on July 21, 2021. Dr. Rod Ewing served from July 28, 2011 and was appointed by the President to serve as Chairman of the Board on September 25, 2012. He served in that role until he resigned on January 5, 2017, at which time the President appointed Dr. Jean Bahr to serve as Chair of the Board. Dr. Efi Foufoula-Georgiou served from September 25, 2012, until her resignation on May 17, 2021. Dr. Gerald Frankel served from September 25, 2012, until his resignation on August 15, 2016. 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.

[2] This report does not discuss the Board's 2016 summary report to Congress and the Secretary of Energy (NWTRB 2016a) that summarized Board activities that occurred from January 1, 2013 until December 31, 2015.

[3] The website also contains fact sheets 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.

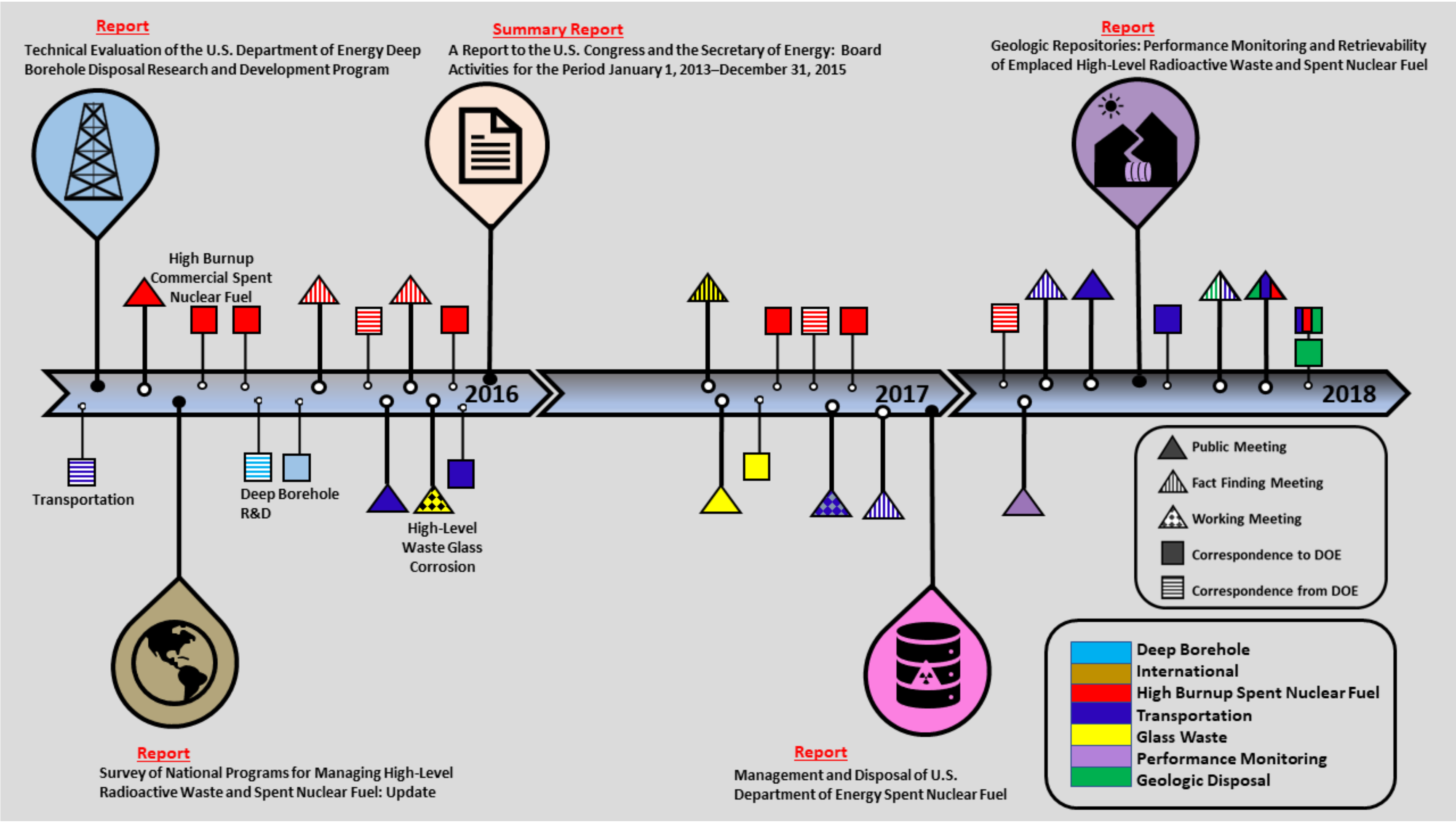

Figure 1. Timeline of Board activities, meetings, and correspondence from January 1, 2016 to December 31, 2018. See legends to the bottom right: subject matters are color-coded and shapes indicate a type of activity. Board reports are offset with large balloons; triangles symbolize meetings; and squares symbolize correspondence to or from DOE, as indicated.

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 NRC had to continue the licensing process using remaining appropriated funds of approximately $11.1 million.[4] 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). In May 2016, the NRC staff completed the supplement to DOE's environmental impact statement. During 2016 and 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 Yucca Mountain license application review. As of December 31, 2018, approximately $0.41 million in unobligated funds remained.

In parallel with seeking to withdraw the license application in 2010, President Obama instructed Secretary of Energy Steven Chu to establish a Blue Ribbon Commission on America's Nuclear Future (BRC). The group 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 (BRC 2012):

---

[4] *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 implementing a 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 SNF and HLW 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 into whether some DOE-managed HLW and SNF should be disposed of in a repository 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.[5] Noting the significant changes that had taken place over the

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

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 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 disposal of its own waste in a repository, in accordance with the authority DOE already held under the Atomic Energy Act. 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 prototype railcars 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.

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 research and development (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.

DOE continued the deep borehole disposal, consent-based siting, and transportation evaluation initiatives during this reporting period of 2016 to 2018. 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 2018 its efforts to develop an integrated waste management system that was consistent with the *Strategy* (DOE 2013). Practically, 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.

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

Board Review: Deep Borehole Disposal

The *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* (DOE 2013) described DOE's mined geologic repository disposal R&D efforts and announced that DOE was "developing a research and development plan for deep borehole disposal." These disposal concepts are compared in Figure 2.

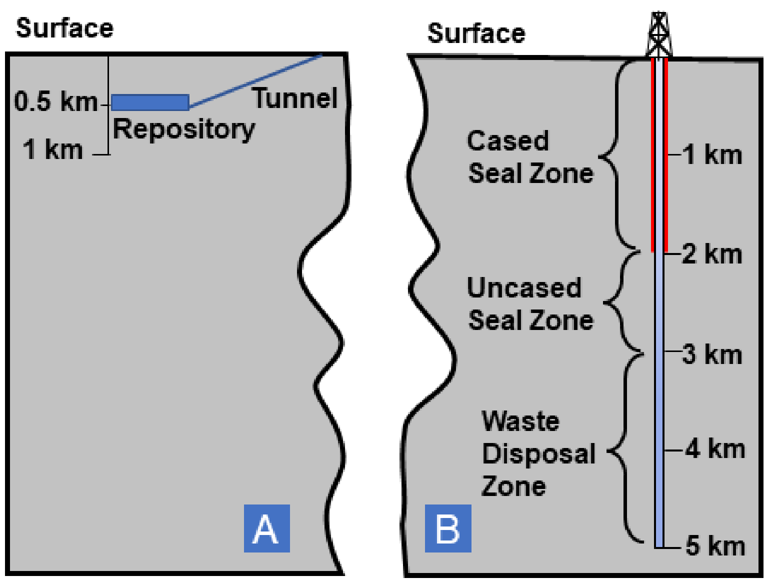

Figure 2. Comparison of the concepts of radioactive waste disposal in (A) a mined, geologic repository and (B) a deep borehole [Not to scale].
A. A geologic repository for SNF and HLW is typically excavated around 500 meters [1,640 feet] beneath the surface. Access to the repository horizon is usually through a large-diameter tunnel that will allow the waste to be conveyed underground via a rail system or a large vehicle. The meters-wide tunnel and repository excavations allow extensive underground characterization of the disposal site. B. A deep borehole for disposal of waste would be drilled (drilling rig depicted on surface is not to scale) to a multi-kilometer depth. The bottom few kilometers of the borehole would be for waste disposal and the overlying portions of the borehole would be for sealing the borehole. The 10s-of-centimeters-wide borehole limits underground characterization of the disposal site and severely limits the amount of waste that can be disposed of per unit length of excavation.

From 2012 to 2015, DOE created and began implementing a deep borehole technology roadmap (Arnold et al. 2012) that included the technical basis for fielding a demonstration program, defined the scientific research tasks associated with site characterization and post-closure safety, and defined the engineering demonstration tasks associated with deep borehole drilling and surrogate waste package emplacement. As part of that effort, DOE proposed a DBFT. In October 2015, the Board held an international technical workshop to review the technical and scientific validity of DOE activities assessing the feasibility of using deep boreholes to dispose of some radioactive waste (NWTRB 2016a). In January 2016, the Board released a report, *Technical Evaluation of the U.S. Department of Energy Deep Borehole Disposal Research and Development Program* (NWTRB 2016b) and replied to DOE's response to the Board's report. In May 2017, DOE terminated its deep borehole R&D activities because of changes in budget priorities.

Technical evaluation of research and development program

Based on the information presented at the Board's international technical workshop, in January 2016, the Board released its evaluation report (NWTRB 2016b). The report focused on two main topics: (1) technical and scientific issues that may affect the feasibility of deep borehole disposal option for select radioactive waste forms and (2) whether the results that would be obtained from the DOE DBFT would provide the necessary technical data and scientific understanding for determining the feasibility of disposing of select waste forms in deep boreholes.

The following summarizes the Board's findings, conclusions, and recommendations documented in that report. The principal findings were:

- **Disposal of radioactive waste in deep boreholes did not eliminate the need for a mined, geologic repository.** The Board observed that available performance assessments did not indicate any discernible improvement in the long-term safety of geologic disposal of radioactive waste using a deep borehole, as compared with a mined, geologic repository. Although deep boreholes might provide a disposal option for certain types of DOE-managed waste, all of the waste forms that DOE considered for deep borehole disposal could be disposed of in a mined, geologic repository. Many large waste forms, such as the packages of vitrified high-level waste of the type being produced at the Savannah River Site (SRS), were not suitable for disposal in deep boreholes, given the technical limits on borehole diameter.

- **A deep borehole disposal system could be as complex as a mined, geologic repository, and assessing the performance of each of these disposal options may require an equivalent level of data collection and testing.** Deep boreholes, however, lacked the easy working access for characterizing the disposal zone that shafts, ramps, and tunnels would provide in the case of a much shallower mined, geologic repository. Thus, the ability to characterize the disposal zone in a borehole was extremely limited as compared with a mined, geologic repository. Also, DOE had not presented the Board with any compelling evidence that deep borehole disposal could be accomplished more quickly than disposal in a mined, geologic repository. Both approaches will pass through a lengthy, sequential process of developing regulations, site selection, data acquisition and analysis, licensing, and construction.

- **DOE ran the risk that information later found to be necessary to support its evaluation of the feasibility of the deep borehole disposal concept at other sites would not have been obtained during the test.** The DOE approach to assessing the feasibility of the deep borehole disposal concept was focused on confirming the assumptions underpinning the DOE safety case for the deep borehole disposal concept: long radionuclide travel time to sources of drinking water due to the great distance and the low permeability of the rocks at depth; increasing salinity with depth that would promote stable stratification based on fluid density and prevent the buoyant movement of water upward; and chemically reducing conditions at depth that would decrease the solubility and mobility of some radionuclides. The DOE approach did not fully take account of the potential heterogeneity of the subsurface environment and the complex set of interactions and feedbacks among the engineering activities related to drilling the borehole and the conditions of the natural geologic system at depth, nor did it fully consider how data from the potentially complex system at one site could be applied to another site.

- **The operational safety strategy required for drilling and emplacement operations involving radioactive material was very different from that for operations involving non-radioactive material**. Hence, it was important to consider the operational implications and limitations of handling and emplacing actual, highly radioactive waste, and how these could be simulated during the DBFT. The operational implications and limitations presented by handling and emplacing radioactive waste could impact the assessment of the feasibility of deep borehole disposal of radioactive waste.

The presentations made at the international technical workshop made clear that substantial time and effort would be required to fully evaluate the concept of deep borehole disposal. In the Board's view, the DBFT needed to carefully consider the key parameters and information that would be necessary to fully evaluate the feasibility of deep borehole disposal of radioactive waste. This would have provided a basis for additional planning, including defining specific technological and scientific goals, and obtaining a broader range of data, such as those from surface-based characterization methods and those needed to support regulatory interactions, and would have greatly improved the technical basis and rationale for the DOE deep borehole disposal R&D program.

Based on its findings, the Board made the following recommendations:

- **DOE should ensure the drilling program design and implementation are reviewed by experts with extensive experience in drilling and down-hole operations (e.g., logging, testing, well completion) and in designing and operating equipment for handling highly radioactive**

material. These experts should be independent of the DBFT contractor and of the lead national laboratory on the project, and should be able to monitor the progress of the project and report on it to the Secretary of Energy.

- **DOE should complete a more comprehensive risk analysis for all aspects of the drilling and emplacement program as part of assessing the feasibility of deep borehole disposal of radioactive waste**. In particular, an analysis should be conducted of what options will be available in the event of an accident during waste emplacement and the implications of such an accident for the safety of recovery operations and the isolation of waste. A transparent and comprehensive assessment of the five possible emplacement modes for deep borehole disposal, including their absolute and relative risks for having and recovering from an accident, also should be completed.

- **DOE should strengthen its assessment of the feasibility of the deep borehole disposal option by addressing the technical and scientific issues related to the potential heterogeneity of the subsurface geology and the complex in situ conditions at depth**. DOE should take into consideration the potential implications [of subsurface heterogeneity], with a focus on conducting a defensible safety analysis and demonstrating the transferability of the data and results of analysis to other sites. DOE should address these issues in the guidance it provides to the contractor for developing the drilling and test plan. Specifically, the project team should carefully consider the key parameters for the safety case that need to be measured during sampling and testing in the 2- to 5-km (1.2- to 3.1-mile) depth range encompassing the seal and disposal zones. For example, DOE should identify down-hole logs, tests, and monitoring techniques that could lead to a better understanding for the potential development of a free gas phase (e.g., hydrogen from the rapid corrosion of steel components) and its implications for disposal system behavior. The goal for characterization should be obtaining relatively continuous down-hole profiles based on multiple measurements, rather than relying on, and interpolating between, a limited set of measurements. DOE also should consider using the characterization and field test boreholes to conduct cross-hole monitoring to provide information on the characteristics of the rock volume surrounding the boreholes. Moreover, ongoing subsurface monitoring after the emplacement testing, to continue to test and evaluate starting assumptions, should be included in the drilling and test plan.

- **The DBFT should include surface-based geophysical surveys to delineate subsurface structure and physical conditions prior to drilling (e.g., detailed gravity, magnetic, seismic, or electrical data)**. These measurements could help in the design of the DBFT drilling and test plan and provide knowledge for using surface-based measurements to evaluate the subsurface characteristics of potential deep borehole sites prior to drilling.

- **DOE should explicitly analyze the potential safety benefits of using more robust waste forms and waste packages as part of assessing the feasibility of the deep borehole disposal concept and in developing the associated safety case**. The DBFT should be used to demonstrate emplacement of potential seals and to test the efficacy of seal materials in dealing with breakouts and evolving damage zones around the borehole when exposed to in situ thermal, hydrogeologic, geomechanical, microbiological, and chemical conditions. Geophysical techniques (e.g., acoustic sonic and ultrasonic tools) should be used to verify the seals between the casing and rock where the casing remains in the borehole.

- **DOE should develop an operational safety strategy for the DBFT that integrates conventional borehole operations and remote handling of highly radioactive materials**. This might include emphasizing the use of engineering controls (e.g., automated equipment to protect workers) over administrative controls (i.e., processes that rely on personnel actions and procedures). The DBFT should simulate implementation of deep borehole disposal as if radioactive wastes were being emplaced, in order to test the features of an operational safety strategy that can be applied to a future borehole disposal site and to provide the basis for ensuring safe operations, limiting exposure of workers to hazards or release of radioactive material to the environment, and mitigating waste emplacement risks.

- **As part of its assessment of the feasibility of deep borehole disposal of radioactive waste, DOE should place a high priority on engaging regulators to define retrievability requirements in the context of deep borehole disposal of radioactive waste**. DOE should begin defining and clarifying the types of technical information that may be needed to address regulatory issues and then collect that information to the extent practicable as part of the DBFT.

- **DOE should use the DBFT to gain experience related to its siting approach.** DOE should begin to incorporate new standards of transparency and data access, and should explore avenues to engage stakeholders.

- **The DOE DBFT program should have a chief scientist responsible for integrating the engineering activities (i.e., drilling the characterization and field test boreholes, emplacing and retrieving the simulated waste) and the site characterization activities**. The chief scientist should have the scientific understanding required to ensure the technical integrity of information gathered in the DBFT and its use for developing the safety case for deep borehole disposal of radioactive waste.

On June 9, 2016, DOE formally responded to the Board's report on deep borehole disposal (DOE 2016a). That response is reproduced in Appendix E. DOE reported that many of the Board's suggestions had already been incorporated into its plans for the DBFT, a program designed to evaluate the technical and programmatic feasibility of the deep borehole disposal concept. DOE disagreed with the Board's recommendation that a chief scientist be appointed and stated that other recommendations went beyond the scope of their program or were not warranted by their cost relative to informational value (e.g., a comprehensive risk analysis of the five emplacement modes and surface-based geophysical surveys). DOE concluded that it was incorporating into its plans the Board recommendations that were consistent with both the research focus of the program and its budget and schedule considerations that constrained the program.

On July 7, 2016, the Board responded (Ewing 2016a) to DOE's letter (DOE 2016a). The Board acknowledged that budget and schedule limitations would necessarily constrain the scope of the DBFT program, but the Board remained concerned that any field test should be designed to take advantage of the opportunity to develop a solid technical and operational basis for deep borehole disposal. Subsequently, DOE discontinued work on the DBFT and its deep borehole disposal R&D program.

Board Review: Disposal in a Mined Geologic Repository

In this reporting period, DOE continued to evaluate different disposal concepts for the full inventory of commercial and defense HLW and SNF. The concepts included disposal in a mined, geologic repository (Figure 2) constructed in salt, clay/shale, and crystalline host rock. To advance its non-site-specific geologic disposal R&D program, DOE used data collected by other countries, and the designs these countries developed. During the period covered by this report, the Board continued to review DOE's R&D efforts for these different disposal media. In the period covered by the previous Summary Report (NWTRB 2016a), the Board reported on DOE's R&D activities that focused on salt as a geologic medium for disposal of SNF and HLW (NWTRB 2016a). DOE was conducting salt-related R&D activities underground at the Waste Isolation Pilot Plant (WIPP), which is DOE's geologic repository for transuranic waste, to support development of its SNF and HLW disposal concept in salt. In October 2018, the Board toured WIPP to advance its review of DOE's salt-related R&D activities.

The Board also continued its focused review on disposal of dual-purpose (storage and transportation) canisters. This was a particularly important topic because a decision on the disposability of dual-purpose canisters, which were not designed for disposal, will impact DOE's options for managing and disposing commercial SNF. For example, storage times before disposal may need to be greatly extended if SNF remains stored in dual-purpose canisters and other countries' repository design limits for heat-load are used. Repackaging the SNF from dual-purpose canisters into smaller waste packages that are consistent with other countries' repository designs would be a major undertaking. If DOE chose to not repackage SNF into smaller waste packages and decided 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 were implementing.

Disposal of SNF in dual-purpose canisters

Following discharge from nuclear reactors, SNF continues to generate heat, which decreases over time due to radioactive decay. Typically, and as a first step, nuclear power utilities store SNF in water-filled pools at the nuclear power plant sites. Because the United States has no centralized storage facility or geologic repository for SNF, when these pools approached their licensed capacity, most utilities transferred some SNF assemblies to large dry-storage canister systems. By doing this, they created space in the pools to meet regulatory requirements and accommodate subsequent SNF discharges from continued reactor operation. To minimize the near-term economic and operational impacts of transferring SNF from pools to dry storage, nuclear utilities worked with storage system vendors to maximize the capacity of dry storage systems. However, these storage systems were not designed for disposal and many dry-storage canisters in use at utility sites today exceed the size, weight, and/or heat-load limits for repository concepts developed to date. Dual-purpose (storage and transportation) canisters are the predominant type of large dry-storage systems in use. Currently, dual-purpose canisters in the United States number more than 3,000 and this number will increase significantly with time as more SNF discharged from reactors is transferred from spent fuel pools into dry storage systems. During its January 2012 public meeting (NWTRB 2012), the Board suggested that DOE look into the disposability of SNF in dual-purpose canisters and this suggestion led to DOE investigating this topic. The Board reviewed DOE's R&D efforts in a 2013 workshop (NWTRB 2016a).

As part of its review of DOE's activities, the Board requested that DOE Office of Nuclear Energy (DOE-NE) discuss their post-2013 efforts. At a public meeting on October 24, 2018, in Albuquerque, New Mexico, the Board heard an overview of DOE R&D activities on the potential disposal of commercial SNF in dual-purpose canisters. DOE summarized the recommendations that came out of those activities, as well as the planned activities for fiscal year 2019. Presentations described ongoing DOE studies to address one of the main technical challenges related to disposal of SNF in dual-purpose canisters—the risks from nuclear criticality occurring during the repository post-closure period. In its November 27, 2018 letter to DOE, the Board provided comments on the presentations and made a set of observations (Bahr 2018a), which are summarized below.

- **The DOE R&D on disposal of SNF in dual-purpose canisters would be useful in considering the potential for disposing of the dual-purpose canisters, rather than repackaging the SNF**. Disposal without repackaging could decrease the cost of SNF disposal, reduce the complexity of the SNF management system, reduce risks resulting from the additional handling operations required for repackaging, lower the cumulative worker dose, and decrease the amount of secondary waste. However, the Board noted that a decision to accommodate large packages in a repository would place some significant constraints on repository design and may limit the range of geologic environments that can be considered for repository development.

- **The R&D work DOE had completed indicated that there are engineering solutions to some of the technical challenges posed by**

disposal of SNF in dual-purpose canisters. On this basis, DOE had eliminated several technical issues, including handling and packaging, and surface-to-underground transport, from consideration in future evaluations. One exception was post-closure criticality. DOE had begun an effort to evaluate the consequences of a post-closure criticality event if it were to occur. The Board concurred with DOE that it was important to evaluate the consequences of post-closure criticality to provide a basis for determining its impact on post-closure repository performance. The Board considered this work a step in the right direction but noted that the proposed multiphysics modeling would face technical challenges, particularly with model validation and in the treatment of uncertainties.

Salt as a host rock for SNF and HLW disposal

The Board had planned to tour WIPP in conjunction with an April 2014 public meeting in Albuquerque, New Mexico (NWTRB 2016a) to hear about DOE's R&D activities on salt as a potential host rock for disposing of SNF. However, two accidents in WIPP (a salt truck fire and a radiological release) during February 2014 made the Board's tour not possible. In October 2018, the Board returned to Albuquerque, New Mexico for a meeting on recent DOE R&D activities related to managing and disposing of commercial SNF, and toured WIPP. The Board thanked both DOE Office of Environmental Management (DOE-EM) and DOE-NE for their close coordination that led to a successful tour (Bahr 2018b).

The Board noted in its letter (Bahr 2018b) that in addition to serving as the nation's only operating deep geologic repository for disposal of defense-related transuranic waste, the WIPP site hosted underground R&D experiments relevant to disposal of SNF and HLW in salt host rock. In that capacity, the site was part of an international network of underground research laboratories devoted to studies that could improve understanding of processes affecting isolation of radioactive wastes in geologic repositories.

The main purpose of the Board's WIPP tour was to learn about a program of heater tests at WIPP (Figure 3), which were funded by DOE-NE. The frank discussions about the heater tests, including the canister heater buried in run-of-mine salt, the borehole heater shake-down test, and the proposed borehole heater test, were enlightening.

The Board observed that DOE-NE had learned about experimental design from the early tests and the lessons learned were being used in designing the proposed borehole heater test. The Board noted (Bahr 2018b) that it anticipated hearing more about the WIPP borehole heater test at the Board Spring 2019 workshop on underground research laboratories.

At its June 2018 public meeting on DOE R&D activities in support of SNF and HLW transportation issues that was held in Idaho Falls, Idaho, the Board heard about the transportation lessons learned from the WIPP transportation program. The Board gained further insights on waste transportation issues and WIPP repository operations during its WIPP tour.

Figure 3. A heater test conducted in a borehole within a tunnel wall.
Board members and staff learned about the borehole heater test at WIPP. There is a small quantity of water in the salt that could be mobilized once heat-emitting waste is disposed of that could adversely affect the emplaced waste package. To mimic the expected effects of waste disposal, the proposed Brine Availability Test in Salt (BATS) would assess the source and mobility of the water by emplacing a heater in a borehole and monitoring conditions within and around the borehole. In this preliminary shake-down test, scientists evaluated different heaters and monitoring techniques that could be used in the BATS heater test.

Board Review: DOE's Management of Its HLW and SNF

As a part of its ongoing technical oversight activities involving disposal of DOE-managed HLW and SNF, the Board closely followed efforts at the five locations across the United States where that waste is currently being stored and managed.[6] As part of this effort, the Board wrote and posted to its website (www.nwtrb.gov) ten fact sheets on DOE and commercial SNF and HLW. The Board developed these fact sheets solely to provide information on, and increase understanding of, technical issues related to the management and disposal of SNF and HLW. During the period of January 1, 2016 to December 31, 2018, the Board released a report that addressed management and disposal of DOE SNF and presented the results to three site-specific advisory boards associated with cleanup at the Hanford Site, the Idaho National Laboratory (INL), and the SRS, as well as to the Nevada Legislative Committee on High-Level Radioactive Waste. The Board also held two preparatory meetings and visited a laboratory supporting DOE's

[6] Washington State, Idaho, South Carolina, Colorado, and New York.

HLW program prior to holding a public meeting in Richland, Washington, on HLW glass corrosion and touring related waste glass facilities.

Disposition of vitrified HLW

In the United States and internationally, HLW destined for disposal in a geologic repository is immobilized in borosilicate glass via vitrification.[7] However, the corrosion mechanisms and long-term repository performance of waste glasses for purposes of post-closure safety assessment were not fully understood.

The Board monitored DOE R&D activities related to the long-term repository performance assessments of HLW glass waste forms. DOE conducted R&D activities to further elucidate the corrosion mechanisms of borosilicate HLW glasses and to develop a basis for reducing conservatisms in glass corrosion models that can be used to assess long-term disposal system performance. DOE-NE and DOE-EM had additional ongoing R&D activities on HLW forms. These activities included R&D to improve the formulation and processing rate of borosilicate glass, developing new waste forms, and efforts to better understand waste form degradation. As part of its review of DOE activities (Figure 1), and to prepare for a public meeting with DOE, the Board engaged international experts at a working meeting and held a fact-finding meeting with DOE. In June 2017, the Board held a public meeting on HLW glass corrosion and the long-term performance of HLW in a repository.

In November 2016, the Board held a working meeting and heard presentations from internationally renowned experts[8] on glass corrosion and corrosion of SNF, among other topics. The objectives for the meeting were to learn more about glass corrosion and DOE R&D activities related to HLW glass and to prepare for interactions with DOE on the topic. The Board heard about current understandings in glass dissolution and factors influencing radionuclide release, modeling of glass corrosion, and further research that could improve long-term predictions of glass behavior in a repository environment. The international experts indicated that corrosion of borosilicate glass is a complex process, but it is fairly well-settled that it involves three main stages: an initial (high) corrosion rate (Stage I) followed by a residual (low) corrosion rate (Stage II), and, under certain conditions, a resumption of a higher corrosion rate (Stage III) that is still less than the initial rate.

In May 2017, a small number of Board and staff held a fact-finding meeting in Washington, DC. The purpose of the meeting was to hear presentations from DOE and its national laboratory experts on technical issues related to HLW glass corrosion and its long-term repository performance and the history of DOE efforts on the topic.[9] The speakers provided information on topics like masses and composition of glasses, current understandings in HLW glass models, model testing, and implementations and lessons learned. Because of the Board's interest in the

---

[7] More information on HLW glass is found in a fact sheet on the Board's website (www.nwtrb.gov).

[8] The experts were David Shoesmith, from the University of Western Ontario, Canada; Lawrence Johnson, Nagra [retired], Switzerland; and Bernd Grambow, SUBATECH, France.

[9] The presentations made at the May 2017 fact-finding meeting are available on the Board's website (www.nwtrb.gov), with the June 2017 meeting materials.

long-term response of the glass waste form in a repository environment, the Board team heard more about the “bounding” glass corrosion model used by DOE in repository performance assessments. While in Washington, DC, members of the Board review team toured the Vitreous State Laboratory at the Catholic University of America that conducts DOE-funded HLW-glass related R&D.

On June 20, 2017, the Board toured HLW-related laboratories at Pacific Northwest National Laboratory (PNNL) and the next day held a public meeting in Richland, Washington, titled “High-level Radioactive Waste Glass Corrosion.” The Board heard presentations from representatives of three DOE national laboratories and the Vitreous State Laboratory of the Catholic University of America on their DOE-funded R&D activities. In addition, international experts presented their perspectives on the current state of the art on measuring and modeling HLW glass performance. After the public meeting, a poster session was held during which scientists and engineers from the United States and other countries presented their research related to nuclear waste glass corrosion.

What follows below is limited to the Board’s evaluation of DOE’s R&D activities related to the HLW glass corrosion and the new model DOE was developing for use in repository performance assessments (Bahr 2017a).[10] The Board noted that as DOE continues this model development, and if the resulting model is used for future performance assessments, DOE should consider the Board observations, which have been summarized below.

- **Substantial progress, but significant technical uncertainties remain.** The Board observed that DOE R&D activities conducted in the past few years in collaboration with international scientists had significantly advanced understanding of HLW glass corrosion and development of models for generic repository performance assessments. However, there were still significant technical uncertainties regarding when and what triggers advanced stages of glass corrosion (Stage III).

- **Effective utilization of state-of-the-art analytical equipment.** Utilization of new and novel analytical and experimental methods had facilitated DOE’s understanding of HLW glass corrosion mechanisms and models. DOE’s continued support for development and use of cutting-edge analytical devices and techniques would enhance analysis of specimens from long-term corrosion experiments and also the predictive capability of glass corrosion models.

- **Robust international collaboration.** The Board commended DOE’s support of its R&D program participants in international forums on HLW glass corrosion. The Board noted that DOE participation in the European Commission’s Joint Programme on Radioactive Waste Management and Disposal would foster increased interaction among international

[10] The correspondence can be found in Appendix E.

researchers and help DOE make more progress towards developing a new model.

- **Database enhancement and data analysis.** There was an immense amount of experimental data on glass corrosion from around the world. A sustained effort to compile all available data on glass corrosion and to develop data analysis tools and techniques would help identify empirical correlations between parameters and corrosion rates, reduce duplicative experiments, and identify additional experimental studies that were needed to reduce uncertainties in model parameters.

- **Long-term experiments are important.** Long-term experiments appeared to have been crucial to providing needed data on Stage III initiation. Additional long-term studies on a wider range of glass compositions could help identify glass formulations that have the potential to exhibit Stage III corrosion.

- **Considering model uncertainties.** "Consensus" models that DOE was developing may not include phenomena (e.g., micro-organisms and organic molecules in chemical processes) that were deemed unimportant in developing the model but may actually lead to glass corrosion rates higher than the "best estimate" or "consensus" models. The Board noted it was important to identify and understand processes that could occur in a repository environment that could lead to corrosion rates higher than "best estimates."

- **Natural analogs.** Characterization of alteration layers in natural analogs and attempts to simulate the observed levels of alteration using geochemical models developed for nuclear waste glasses could provide important tests of the conceptual and rate models that are used to simulate glass corrosion in geologic repositories. However, using natural analogs to validate models for HLW glass corrosion was challenging because there was limited knowledge on the exposure environment of the natural analogs materials and their compositional range did not match those of waste glasses.

- **Bounding estimates of glass durability.** A question deserving continued attention, as more becomes known about glass corrosion, was whether the industry standard test procedures assured that usage of the reference glass for comparison would still provide bounding estimates of glass durability.

- **Effective integration of DOE program.** There was notable integration within the DOE program and between the various groups working on the glass R&D program. Collaboration among the different DOE groups had increased since the Board's meeting in 2013 on vitrifying HLW stored at the Hanford site.

Management and disposal of DOE SNF

Based on a critical evaluation of information obtained from Board public meetings, site visits to the Hanford Site, INL, and SRS during the period of 2013 to 2015 (NWTRB 2016a), and preparation of related correspondence to DOE through early 2017, the Board released a report in December 2017, titled *Management and Disposal of U.S. Department of Energy Spent Nuclear Fuel* (NWTRB 2017). The three main issues addressed in the report were aging management, packaging, and disposal of DOE SNF. The report recorded the quantities and characteristics of DOE SNF by storage site and examined DOE's packaging and storage activities and plans related to DOE SNF.

As of 2017, DOE managed about 2,500 metric tons of heavy metal of SNF, most of which was stored at four locations: the Hanford Site in Washington State; INL in Idaho; the SRS in South Carolina; and the Fort St. Vrain independent spent fuel storage installation in Colorado. At these sites, DOE stored about 50 metric tons of heavy metal in three storage pools (see Figure 4), and the remainder was stored dry in eleven facilities. The DOE SNF inventory included over 250 types of fuel that originated from defense activities (e.g., plutonium production reactors), commercial SNF whose title had been transferred to DOE (e.g., Fort St. Vrain), and from DOE R&D activities, including domestic and foreign research and test reactors.

Figure 4. L Basin storage facility.
Board members and staff learned about the L Basin pool storage facility at the SRS. There was degraded vinyl sealer along the inside wall of the pool. Vertical tube storage racks containing bundles of SNF were visible in the unlined concrete basin. The ceiling-mounted rail system (along the length of the pool and the red-tipped rails in the upper left) was used to move SNF through the L Basin.

As materials age, they can degrade. An aging management program helps manage degradation effects for in-service materials to ensure continued safe operations for extended periods of time. Different fuel compounds—and the cladding that surrounds the fuel—have different rates of degradation in storage, and the stability of an individual fuel compound or cladding material depends on the storage environment. For example, DOE's storage practices, particularly those of storing some aluminum-based SNF in water pools, could adversely affect DOE's ability—decades in the future—to retrieve and package stored SNF into a canister for disposal.

Outstanding packaging issues were primarily related to the DOE standardized canister.[11] DOE had not finished R&D activities for the DOE standardized canister that would be needed to design and operate any packaging facility it developed. DOE still needed to develop both the remote welding techniques required to seal the canisters and the advanced neutron absorbers—metal sheets used to create baskets for the SNF—required to reduce the potential for criticality for canisters containing SNF with high fissile isotope concentrations. Finally, DOE also planned to add water-bearing pelletized supplemental neutron absorbers to hundreds of DOE standardized canisters, but DOE had not decided the final composition of the material that will surround the absorbers. Defining and proving suitable drying criteria for the SNF and any water-bearing materials that would be added during packaging of the DOE standardized canister was crucial. Water remaining in the standardized canister after drying would affect degradation within the canister and could create conditions (e.g., generation of hydrogen, a combustible gas) that impacted the suitability for future canister transport.

The types of DOE SNF varied widely, were mostly different from commercial SNF, and would behave differently depending on the disposal environment. Since 2010, DOE's disposal R&D activities had focused on a range of geologic disposal options, including repositories in crystalline, clay/shale, salt host rocks, and deep boreholes. Earlier in DOE's program, the focus had been on volcanic tuff. The variability in physical and chemical characteristics of the SNF affected processes that could occur in geologic repositories. If damaged, uranium metal DOE SNF could react with water and create hydrogen gas. Damaged thorium-uranium carbide DOE SNF could react with water and create methane and acetylene gas. Understanding gas generation and migration was a key issue in the assessment of repository performance, especially for crystalline and clay/shale repositories.

The following summarizes the Board's findings, conclusions, and recommendations documented in that report (NWTRB 2017).

- **Finding: DOE's aging management programs were not fully implemented**. Some DOE SNF storage facilities lacked aging management programs to facilitate retrieval of stored SNF and subsequent packaging into multi-purpose canisters needed to transport it to either a consolidated interim storage facility or a permanent repository. Aging management programs provided assurance that the SNF could continue to be safely stored and transported when required and retrieved if necessary. For most of its SNF storage facilities, DOE had not completed an aging management assessment to identify the actions it needed to take to facilitate retrieval of stored SNF many decades in the future. DOE had an aging management assessment for the SRS pool facility, but it had not implemented all the activities identified in the assessment. Furthermore,

[11] The Board adopted DOE's nomenclature for this canister even though it was not "standard" by any conventional definition. The DOE standardized canister was a canister system that consisted of four cylindrical stainless steel canisters with two different diameters (18 inches and 24 inches) and two different lengths (10 feet and 15 feet). The different sizes and eight internal basket designs of the multi-purpose canisters accommodated the wide dimensional variability of DOE SNF.

DOE had not completed aging management assessments that could facilitate continued use of the multi-purpose canisters at its existing storage facilities beyond 40 years and during subsequent transportation and geologic repository operations.

- **Recommendation:** DOE should develop and fully implement programs to manage degradation of SNF, the materials that contain SNF, and SNF facilities for additional multiple decades of storage operations at all storage facilities. Managing degradation included assessing its potential of occurring, and—when it was predicted to occur at unacceptable rates—monitoring storage conditions of the SNF and the materials in which it was stored to prevent degradation or to mitigate degradation effects.

- **Finding: Measuring and monitoring conditions of the SNF during dry storage was important.** The ability to measure and monitor conditions of the SNF in the storage facility during future dry storage (e.g., monitoring gas composition in a multi-purpose canister like that being done for the multi-canister overpacks) was important to the design, development, and deployment of new DOE storage systems. Although DOE had considered including monitoring capability for new storage systems, it had not done so in its baseline design for the DOE standardized canister.

- **Recommendation:** DOE should include the capability for measuring and monitoring the conditions of the SNF in new DOE storage systems, such as the DOE standardized canister, and in new packaging and storage facilities to aid in establishing the condition of the SNF during subsequent operations and its acceptability for those operations.

- **Finding: An improved technical basis was needed for proposed drying procedures for DOE SNF before packaging it in multi-purpose canisters.** A better understanding of how much water remained in sealed multi-purpose canisters and the cumulative conditions inside the canisters added confidence that proposed drying procedures for DOE SNF would be satisfactory. DOE assessed physical and chemical processes that could occur inside sealed DOE standardized canisters over a 50-year storage period. DOE proposed drying procedures for aluminum-based SNF, but it had not considered all the sources of water that could be in the canisters. It had not considered how long the sealed multipurpose canisters would have to serve as a radionuclide containment barrier. Using the expected amount of residual water, including chemisorbed water associated with supplemental neutron absorbers and hydrated SNF corrosion products, would improve DOE's understanding and technical basis for drying SNF procedures. An understanding of gas composition and pressure in multi-purpose canisters could inform the technical and regulatory considerations for following storage, transport, and disposal operations. Predicting—and monitoring—gas composition and pressure of sealed multi-purpose canisters could confirm DOE's understanding of and the basis for its conclusion that proposed SNF drying procedures were adequate.

- **Recommendation:** DOE should conduct R&D activities to confirm that reactions between DOE SNF and any water remaining in any multi-purpose canister would not cause cumulative conditions inside the canister (e.g., combustibility, pressurization, or corrosion) to exceed either the design specifications or applicable regulatory operational requirements. The period of interest would extend over the duration of canister use, including the time spent in storage, in transportation, and at a repository, until DOE closed the repository.

- **Finding: Technical and regulatory uncertainties complicated planning for packaging facilities.** A key step in DOE's SNF management plans was developing packaging facilities at INL, Hanford, and SRS for DOE SNF that still needed to be placed into about 3,500 DOE standardized canisters. DOE had not completed all the R&D activities for the standardized canister that would define the full capabilities required for a packaging facility. DOE did not know whether the INL packaging facility would be licensed by NRC, or which NRC licensing regulation(s) would apply if NRC regulated the facility. NRC would also need to approve the canister for transport that would occur years later. Hence, any conditions associated with NRC's approval could affect the design for the canister and packaging facility. These technical and regulatory uncertainties complicated planning for these packaging facilities, the first of which was planned for INL.

- **Recommendation:** To minimize complications in developing and operating a packaging facility for DOE SNF at INL, DOE should complete research, development, and licensing-related activities for the DOE standardized canister—and any other canisters that may be used—prior to completing the facility's preliminary design.

- **Finding: Waste acceptance system requirements affected the disposition of DOE SNF, and DOE-NE was not subject to the requirements.** Both the DOE-EM and the naval nuclear propulsion program were waste custodians and had signed agreements[12] with the DOE Office of Civilian Radioactive Waste Management (OCRWM) to accept their SNF for disposal. These agreements required waste custodians to use waste acceptance system requirements, which applied to all SNF and HLW that would be disposed of in a repository, in order for the DOE organization responsible for waste disposal (at that time the agreements

[12] Memorandum of Agreement for Acceptance of Naval Spent Nuclear Fuel (Bowman and Itkin 2000). Memorandum of Agreement for Acceptance of Department of Energy Spent Nuclear Fuel and High-Level Radioactive Waste (DOE 2007).

were signed it was OCRWM) to accept the waste for disposal. Both DOE-EM and the naval nuclear propulsion program continued to manage their waste according to the existing waste acceptance system requirements established for Yucca Mountain.[13] DOE-NE managed some SNF and was treating sodium-bonded SNF to yield two HLW forms, both of which would need to be shown to be acceptable for geologic disposal. Previously, DOE-NE transferred some of its SNF from the Advanced Test Reactor to DOE-EM. DOE-NE was not a "waste custodian" and did not have a waste acceptance agreement with OCRWM.

- **Recommendation:** DOE-NE should implement the existing OCRWM waste acceptance system requirements to increase the likelihood that SNF managed by DOE-NE and that waste forms resulting from electrochemical processing of sodium-bonded SNF would be acceptable for geologic disposal in a repository.

- **Finding: The diversity of DOE SNF combined with differences in physical and chemical characteristics of potential repository environments complicated the potential disposal of DOE SNF.** Since 2010, DOE had focused on alternative geologic disposal options, including generic environments other than tuff and deep borehole disposal of some types of wastes. The diversity of DOE SNF in terms of chemical composition and radionuclide content, combined with the diverse physical and chemical environments that could occur in repositories located in environments such as crystalline, clay/shale, and salt, complicated potential disposal of DOE SNF. Understanding processes that may adversely affect the isolation properties of the repository, such as gas generation, was a key issue in the assessment of repository performance. Evaluations of repository post-closure performance depended on the mass and radionuclides content of SNF in a specific package and the number of packages. The diversity of chemical and physical characteristics of DOE SNF would lead to widely variable masses of SNF and radionuclides in each package, depending on the specific fuel type and the design of engineered barrier systems. DOE identified and prioritized its research on these different disposal environments based on disposing of commercial SNF without thoroughly considering the need to dispose of DOE SNF that had a wide variety of compositions and conditions.

- **Recommendation:** If DOE continues to conduct non-site-specific investigations of a range of potential repository environments, DOE should identify and prioritize its research efforts concerning DOE SNF

[13] Civilian Radioactive Waste Management System Waste Acceptance System Requirements Document (DOE 2008).

degradation related to disposing of DOE SNF in each of the potential host-rock environments.

Since release of the report, Congress specifically appropriated money to DOE to address the Board's recommendations that it understand, manage, and monitor degradation of DOE SNF, and the facilities in which it was stored, and complete R&D and licensing of the DOE standardized canister, and DOE began acting on the recommendations.

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

Packaging, storage, and transportation of SNF and HLW, including an integrated SNF and HLW management and disposal system, were topics for continued Board review during the 2016 to 2018 reporting period (Figure 1). Starting in 2010, as the nation's waste management priorities and strategies began to transition, 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 Extended Dry Storage and Transportation of Used Nuclear Fuel* (NWTRB 2010). The report reviewed, from publicly available literature, storage and handling of SNF related to extended-term dry storage and transportation of commercial SNF after long storage periods, and in doing so, the report identified key research needs. Since then, the Board conducted numerous review activities on DOE's packaging, storage, and transportation R&D efforts related to both SNF and HLW (NWTRB 2014, 2016a).

One important development over the past few decades that affected SNF management was the decision by power plants to irradiate nuclear fuel for longer times in order to increase fuel utilization and to improve plant economics. Fuel was increasingly being discharged from commercial reactors at higher burnup levels.[14] Nuclear fuel utilized beyond 45 gigawatt days per metric ton of uranium (GWd/MTU) was defined by the NRC as high burnup fuel (HBF). While dry storage of lower burnup SNF (less than 45 GWd/MTU) had occurred, and been studied in the past, the dry storage of HBF had not been well-studied in comparison, and data were lacking for this type of SNF under typical dry storage conditions (NWTRB 2010). R&D on extended dry-cask storage and transportation of HBF became important in the past decade (NWTRB 2010, 2016a). In 2012, DOE solicited proposals to develop an R&D project on extended dry storage of HBF, and the result of that solicitation process was an award to the Electric Power Research Institute (EPRI) to develop the program (EPRI 2014). That program was known as the High Burnup Dry Storage Cask Research and Development Project (CDP, subsequently designated as the HDRP). The Board noted that, based on DOE activities between 2013 to 2015, very little data were available at that time to project how HBF would behave if it were stored for decades (NWTRB 2016a). Moreover, the Board noted that the CDP needed a much more extensive program, infrastructure, and facilities to inspect and examine the HBF at the conclusion of a 10-

[14] 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).

year storage project (NWTRB 2016a). The Board continued its focused review on extended dry-cask storage and transportation of HBF during the 2016-2018 reporting period (Figure 1).

Regarding DOE and Board interactions during the 2016 to 2018 reporting period, as cited below there were ten letters of correspondence with DOE that stemmed from three Board meetings on transportation, two Board meetings that addressed HBF, and five fact-finding meetings with DOE. In addition to the fact-finding and public meetings with DOE, the Board participated in multi-organization meetings like those organized by the Extended Storage Collaboration Program (ESCP),[15] visited facilities where DOE-funded work was being conducted and observed DOE-related storage and transportation activities. The summary of the Board's activities below is organized into two topics: packaging and transportation of SNF and HLW, which addresses an integrated waste management system; and long-term dry storage and transportation of HBF commercial SNF.

Packaging and transportation of SNF and HLW

In the United States, SNF produced from commercial nuclear power stations, DOE R&D and defense activities, and the U.S. Navy had been packaged and stored at more than 80 locations across 35 states (as of April 2019). Nearly all of the 80 sites were commercial nuclear power plant sites. In addition, at DOE sites, DOE managed defense HLW, a small amount of solid HLW of commercial origin, and HLW from DOE's defense nuclear material production and R&D activities. However, it was envisioned that future, large-scale shipments will move SNF and HLW from their current locations to either a centralized facility for interim storage and subsequent transport to a geologic repository for disposal or directly to a repository from their current locations. DOE was responsible for transporting SNF and HLW to a federal interim storage facility or repository.[16] In order to complete such a national SNF and HLW transportation campaign, DOE would need to address numerous technical and integration issues. Moreover, all shipments of these wastes must comply with safety requirements promulgated by the U.S. Department of Transportation and the NRC.

In January 2016, DOE responded (DOE 2016b) to an August 2015 letter from the Board (Ewing 2015) on the Board's Summer 2015 public meeting. The Board's letter had addressed several technical areas including transportability of SNF from operating nuclear power plant sites, waste integration, and planning tools[17] that could be used in engaging communities; chloride-induced stress corrosion cracking under dry-storage conditions; and the development of standardized transportation, aging, and disposal canisters. In the August 2015 letter, the Board noted that technical challenges remained regarding transportability of SNF stored in canister and casks at operating nuclear power plants and the potential difficulty of meeting NRC regulatory

---

[15] ESCP, which is coordinated by EPRI, is a group of organizations in the United States and other countries representing the nuclear industry, national governments, research laboratories, and suppliers of dry-storage systems for SNF. DOE participates in ESCP. ESCP is investigating aging effects and mitigation options for the extended storage and transportation of SNF and HLW.

[16] DOE's responsibility for transporting commercial SNF, once it has title to the waste, was defined in the NWPA.

[17] These tools include Stakeholder Tool for Assessing Radioactive Transportation, Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System, and Next Generation System Analysis Model.

requirements for transportation of commercial SNF and certain commercial SNF canisters. DOE responded that their ongoing efforts would "take into account" Board recommendations that the Department do the following:

- Collaborate with the utilities and NRC to identify and resolve issues that could affect the ability to transport SNF in current canisters and casks.
- Assume a greater role in integrating R&D being performed on dry-storage canisters, as well as the identification and communication of technical information on storage, transportation, and repackaging.
- Continue its work exploring the costs and potential benefits of implementing a standardized transportation, aging, and disposal canister (DOE 2016b).

Pursuant to another Board recommendation (Ewing 2015) that DOE finalize and publish documentation supporting waste integration and planning tools, DOE had held a demonstration of their system analysis and crosscut tools, which were under development. Two Board members attended the demonstration (DOE 2016b). The Board (Ewing 2015) had recommended that DOE produce a version of Stakeholder Tool for Assessing Radioactive Transportation that was accessible to the public. DOE indicated that they were working to increase public access to elements of the Department's data, reports, and integration and planning tools (DOE 2016b).

In August 2016, the Board held a public meeting in Washington, DC. The primary purpose of the meeting was to hear from DOE, national laboratory researchers, and other experts on developing an integrated program for management and disposal of canisters for SNF and HLW systems, and the challenges DOE faces in implementation. The integrated waste management system may include one or more consolidated interim storage facilities and one or more SNF repackaging facilities (Ewing 2016b). The meeting covered DOE activities related to integrating the management and disposal of the many different designs of canisters for SNF and HLW that were in service and under development. Since nuclear materials were stored in various casks and canisters of varying age, size, and robustness, there were several technical challenges that DOE would need to address to develop an effective and efficient transportation system, equipment, facilities, and logistics for shipping and eventual disposal of SNF and HLW. The Board heard presentations from representatives of the DOE-NE, DOE-EM, two DOE national laboratories [SNL and Oak Ridge National Laboratory (ORNL)], the Naval Nuclear Propulsion Program, and the Nuclear Energy Institute. The information presented was considered by the Board in the context of the need to develop an integrated program for management and disposal of SNF and HLW.

Following the August public meeting, in December 2016, the Board provided its conclusions and recommendations on the need to develop an integrated system for the management and disposal of SNF and HLW to DOE-EM and DOE-NE (Ewing 2016b). The Board's summarized recommendations are listed next.

- **Establish a comprehensive database of SNF and HLW.** Develop a single database containing all of the information on SNF and HLW necessary to support developing an integrated management and disposal system, or the software necessary to successfully integrate the separate databases that contain the necessary information.

- **Develop an integrated (end-to-end) system analysis tool for waste management.** Develop new, or modify existing, system analysis tools to allow successful analysis of the full scope of the integrated waste management system.

- **Optimize the system using an end-to-end approach.** Complete the necessary system analyses to identify actions that can be taken to (i) optimize the complete system against key program objectives (schedule, cost, operator doses, etc.) and (ii) avoid introducing additional complexities by decisions made independently at the facility, site, office, or other level.

- **Assess and optimize new canister designs for end-to-end compatibility.** Avoid the introduction of new canister designs for packaging SNF and HLW unless absolutely necessary. If new designs need to be used, ensure that, as far as possible, they are compatible with the handling, storage, and transportation facilities, systems, and equipment already in service or necessary to support the management and disposal of canisters already in use or licensed for use.

In October 2017, the Board held a working meeting to advance Board review activities on dual purpose canisters, HBF, and transportation of SNF and HLW. DOE activities to assess and evaluate transportation readiness were introduced as a potential topic for a Board report or future public meeting.[18]

In December 2017, a small number of Board and staff held a fact-finding meeting at Argonne National Laboratory (ANL) in Lemont, Illinois, with DOE and ANL personnel on the Next Generation System Analysis Model (NGSAM) tool. DOE funded development of the NGSAM tool to assist it in analyzing the system architecture of possible arrangements of an integrated system for all aspects of the back-end of the fuel cycle: packaging, storage, transportation, and disposal. Developed with the collaboration of several national labs and ANL as the lead laboratory, NGSAM has broad capabilities and flexibilities, and the small number of Board and staff observed that there had been significant progress in refining NGSAM. However, the tool was limited to modeling management of commercial SNF, and modeling of DOE-managed SNF and HLW was not included. Although some informal benchmarking and verification checks had been completed for NGSAM, no formal validation had been done.

---

[18] As described in this section, the Board reviewed DOE's activities and corresponded with DOE on interim results of its review. The Board released the results of its full review in the report *Preparing for Nuclear Waste Transportation–Technical Issues that Need to be Addressed in Preparing for a Nationwide Effort to Transport Spent Nuclear Fuel and High-Level Radioactive Waste* in September 2019.

In May 2018, a small number of Board and staff held a fact-finding meeting at Oak Ridge, Tennessee, on Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS). DOE and ORNL personnel discussed the underlying computer code, features, and capabilities of the DOE-sponsored UNF-ST&DARDS. UNF-ST&DARDS was part of a suite of tools developed by DOE to assist in planning for nationwide integrated waste management. The tool utilized a large database of commercial SNF information (e.g., thermal, shielding, criticality, containment analyses of SNF casks and canisters, etc.). Information about DOE-managed SNF and HLW was not yet included in the database. A small number of Board and staff observed that ORNL researchers realized they lacked high-quality data but that they had been working on filling several data gaps.

In June 2018, the Board held a public meeting in Idaho Falls, Idaho (Bahr 2018c). The purpose of the meeting was to identify and discuss technical and integration issues that would need to be addressed before DOE could implement a nationwide program to transport commercial and DOE-managed SNF and HLW. The Board heard presentations from representatives of DOE involved in developing the waste management system and the system analysis tools that will aid with decisions-making processes. Representatives from commercial nuclear industry in the United States and a utility in Switzerland presented information to the Board on the commercial industry perspective on preparing to transport SNF and HLW. Other presentations provided additional observations from those with experience with the former OCRWM and also discussed the perspectives of the NRC and stakeholder groups. Based on the presentations at the June meeting and previous interactions with DOE, the Board provided DOE with some preliminary observations (Bahr 2018c). The Board's preliminary observations are summarized as follows:

- **DOE's preliminary evaluations of removing commercial SNF from shutdown sites, which involved working with site personnel, utilities, and local stakeholders, had generated valuable information and were important to continue.** Considerable planning and coordination will be required to refurbish or re-establish the capabilities to handle and load SNF containers, re-constitute needed site infrastructure (e.g., electrical power, radiological controls), and rebuild the roadways and /or rail lines necessary to support SNF transportation.

- **The current effort by DOE-NE to plan and coordinate a nationwide transportation program did not appear to be well-integrated with activities of the DOE-EM.** Furthermore, the current transportation program plan did not fully consider the SNF and HLW materials and packages that were managed by DOE-EM.

- **The WIPP transportation approach represented a useful model and provided relevant lessons for the development of a nationwide transportation program for SNF and HLW.** However, transuranic waste was transported to WIPP by road, while transportation of commercial SNF was expected to be mostly by rail, so the differences between highway and rail transport would need to be considered in applying WIPP experience in developing the SNF and HLW transportation program.

- **There was a need for early and continuous engagement and collaboration between DOE and stakeholders at the state and local level as well as other organizations such as nuclear utilities and rail carriers that were essential to ensuring an effective nationwide transportation program.**

- **The lack of adequate and predictable funding adversely affected the development of a transportation program, including, for example, advanced procurement of casks and other essential equipment, full stakeholder engagement, and emergency preparedness planning**.

- **DOE needed to develop designs for new casks and canisters for transporting DOE-managed SNF and HLW.** Given the need for new cask and canister designs, several presenters noted that the lead times for licensing and procurement of any new types of casks and canisters could be greater than ten years, and therefore, considerable advanced coordination with NRC would be required.

- **The advances made by DOE-NE in developing the system analysis and planning tools were commendable.** These tools would be a major asset in designing the transportation program, particularly as development of the tools was continued and as DOE gained access to the detailed technical information necessary to conduct realistic system analyses.

In October 2018, the Board held a public meeting in Albuquerque, New Mexico, on DOE R&D activities related to managing and disposing of commercial SNF (Bahr 2018a). As part of the meeting, DOE described its R&D activities on disposal of commercial SNF in dual-purpose canisters. The Board's review of that topic is described in the "Disposal of dual-purpose canisters" discussion in the "Disposal in Mined Geologic Repository" section above.

At the October 2018 meeting, DOE presented information on its R&D activities related to the performance and potential degradation of high-burnup SNF during extended storage and subsequent transportation. The presentations described DOE's progress on obtaining the required data, including those related to cask drying, thermal measurements and modeling, hydride reorientation, and SNF rod non-destructive and destructive evaluations. The Board's review of those DOE activities is described in the "Long-term dry storage and transportation of high burnup SNF" section below.

Also at the October 2018 meeting, DOE described a recently completed test program to determine the actual stresses SNF may experience during normal conditions of transport. The test involved transportation of an Equipos Nucleares Sociedad Anónima (ENSA) SNF cask containing simulated SNF assemblies from Spain to the United States, via truck, barge, cargo ship, and train, supplemented by additional testing at the Transportation Technology Center in Pueblo, Colorado (Figure 5).

Figure 5. Transfer of ENSA test cask from a cargo ship to a rail car.
The ENSA cask was offloaded from a cargo ship in Baltimore, Maryland, onto a rail car for transport to Transportation Technology Center in Colorado. Instrument cables that transmitted data from sensors inside the horizontal cylindrical cask exited from the right side of the cask through the cask lid and entered the white cubic container that contained the battery-powered data acquisition system (SNL 2018).

Representatives of the testing team[19] from SNL and PNNL provided an overview of the ENSA cask multimodal transport test and discussed the results of the test. The researchers concluded that the data showed the shock and vibration loads on the simulated SNF rods during normal conditions of transport were below the level at which damage to the SNF would be expected to occur in transport of actual SNF. The presentations also discussed the use of the test data to validate structural response models, which would be used to evaluate the impact of similar shock and vibration loads on other fuel types and during transportation operations using other conveyance systems.

Based on the presentations and discussions at the meeting, the Board sent its observations to DOE (Bahr 2018a) on obtaining data to advance understanding of SNF behavior during storage, transportation, and disposal. The summarized observations on this theme are listed as follows:

- **The Board was impressed with DOE's level of international engagement in its R&D program and with DOE's collaborations and partnerships with other organizations, particularly with ESCP.** DOE's participation in the ENSA cask transport test and the planned SNF cask drop tests by the German Federal Institute for Materials Research and

[19] In 2018, the International Multi-Modal Surrogate Spent Nuclear Fuel Transportation Test Team that was responsible for the test program received the Secretary of Energy's Achievement Award, which is DOE's highest group award.

Testing in Germany were also noteworthy. DOE's collaborations helped it leverage resources by enabling DOE to have access to potentially useful data from other organizations or programs and by avoiding duplication of research undertaken elsewhere. The Board encouraged DOE to maintain awareness of other opportunities for international collaborative research.

During this reporting period, as part of its review of DOE activities, the Board also attended multi-organization meetings that involved DOE, conducted site visits to facilities where DOE-funded work is being conducted, and observed DOE-related transportation activities. Those activities include the following:

- "Transportation Core Group" meeting in Colorado Springs, Colorado.
- University of South Carolina, DOE-NE-funded, Integrated Research Project on Vacuum Drying SNF in Columbia, South Carolina.
- Navy SNF Transportation Emergency Response Exercise in Mechanicville, New York.
- Southern Corridor "Roadshow" for Waste Isolation Pilot Plant shipments in Jackson, South Carolina, and Riverdale, Georgia.

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

Historically, dry storage of commercial SNF began in the 1980s when utilities needed to remove relatively low burn up fuel[20] from spent fuel storage pools to allow space for additional SNF to be stored from reactor operations. Based on earlier studies of fuels (e.g., EPRI 2000), researchers concluded that no change in the condition of low burnup fuel was expected during dry storage over a period of 20 years (EPRI 2002) and subsequent transportation. However, two notable circumstances have emerged since this earlier situation. The first 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. The second issue was the introduction of fuel assembly designs by manufacturers that would allow the fuel to reach higher burnups. An increasing quantity of the SNF loaded to dry storage casks since the 1990s has been HBF. The characteristics of HBF were different from those of lower burnup fuels to varying degrees. Thus, these different HBF characteristics could affect storage and transportation under normal, off-normal, and accident conditions.

To better understand HBF performance during extended storage and subsequent operations, DOE initiated new research tasks. Three of the more significant efforts by DOE were the High Burnup Dry Storage Cask Research and Development Project (the HDRP; Figure 6); the study of

[20] 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 spent nuclear fuel currently stored in the United States is low burnup fuel.

Figure 6. High burnup dry storage research project demonstration cask.
Loading of the TN®-32 cask with high burnup commercial SNF started November 14, 2017, and the cask was placed on the storage pad at the Dominion North Anna, Virginia, site in early December 2017. The demonstration was planned to run for a minimum of ten years, after which the cask would be transported to a facility where some of the SNF rods would be extracted and re-characterized (EPRI 2019).

vibrational loads on SNF expected during rail or road transportation; and research to better understand the effects of hydride reorientation on cladding embrittlement. DOE began each of these efforts prior to 2016 (NWTRB 2016a) and continued them in this reporting period.

The Board continued its review of DOE's HBF R&D efforts, and these three efforts were discussed at the Board's public meeting in Knoxville, Tennessee, in February 2016 (Ewing 2016c). The Board's meeting addressed DOE's R&D on HBF performance during storage and transportation. The Board heard presentations from representatives of DOE, NRC, and national laboratories.

The Board's meeting in Tennessee addressed DOE's R&D on HBF performance during storage and transportation. The Board heard presentations from representatives of DOE, NRC, and national laboratories. In conjunction with the public meeting, the Board members and staff members also toured some of the ORNL facilities to observe HBF testing equipment and research. Because of the breadth of topics included in HBF research activities and time constraints, the Board did not discuss all topics and, thus, planned follow-up discussions with DOE and laboratory researchers to obtain additional information. For the public meeting, the Board focused on DOE's research related to determining the performance and potential degradation of commercial HBF during storage and transportation. Storage scenarios considered were storage at a nuclear utility site and subsequent transportation to a geologic repository, as well as the potential effects of a second period of extended storage, possibly at an interim storage site, followed by transportation to a geologic repository.

Based on the public meeting presentations, the Board provided DOE with its observations and recommendations (Ewing 2016c) in May 2016. The Board's observations and recommendations addressed the need to frame the technical issues within a risk context, relating the behavior of unirradiated cladding to irradiated cladding and the HDRP. The Board's recommendations are summarized as follows:

- **DOE's research program should be structured such that the focus is on the likelihood and consequences of cladding failure during interim storage, transportation, possible repackaging, and eventual disposal of HBF in a repository.**

- **DOE should develop a physical-chemical model that relates the behavior of unirradiated cladding to the behavior of irradiated cladding. This work should also include experimental work to test the model's predictions and evaluate the associated uncertainties.**

- **DOE should make transparent how it integrates the results from Nuclear Energy University Programs, and other relevant United States and foreign research activities into its overall research program on HBF degradation.**

In closing the letter (Ewing 2016c), the Board noted some issues that the Board intended to follow up with DOE, which included the following: the effect of vibrational loads measured in road and rail transportation tests on the probability of degradation of cladding during normal transportation conditions; the consequences of cladding degradation; the applicability of cladding embrittlement data obtained from testing unirradiated cladding to the embrittlement of irradiated cladding; details of the characterization of the "sister rods"[21] planned at ANL, ORNL, and PNNL, and how the resulting data would be used; and details of planned gas sampling in the HDRP cask.

In early July, DOE responded to the Board's letter on the Board's February 2016 public meeting (DOE 2016c). DOE stated that it hoped that its letter, coupled with a planned follow-on technical meeting in July, would provide the Board with sufficient information to assess the status of the DOE R&D program associated with the degradation characteristics of commercial SNF in extended storage and transportation (DOE 2016c). DOE also responded to the Board's

---

[21] A "sister rod" is a rod that been determined to have very similar characteristics to one that will be stored in the HDRP Cask. There are two potential donor fuel assembly sources for sister rods: assemblies having similar operating histories to those assemblies that have been chosen for storage in the HDRP Cask and actual fuel assemblies selected for storage. Properties that must be similar in order to be considered a "sister" are the cladding type (e.g., Zircaloy-4, low-tin Zircaloy-4, ZIRLO®, or M5®), the initial enrichment, the relative reactor core location, and the reactor operating history when the fuel was being irradiated.

recommendations (Ewing 2016c). DOE's responses to the Board recommendations are summarized as:

- DOE had taken a systems engineering approach to identify and prioritize these gaps rather than using a risk-based approach. The systems engineering approach included risk-based evaluation that included likelihood and consequence factors. DOE believed that the systems engineering approach provided a more comprehensive evaluation of prioritization by including other factors into the evaluation than just risk.

- DOE pointed to published information that raised doubts about the feasibility of the Board's recommendation to develop a physical-chemical model that related the behavior of unirradiated cladding to the behavior of irradiated cladding. DOE also indicated that it had other high priority issues (e.g., stress corrosion cracking of stainless steel canisters) and the current experimental work on irradiated cladding focused on closing this technical gap. DOE explained that the planned experimental work for the sister rods made developing the physical-chemical model an activity that did not rise to a priority level that would warrant the type of funding that would have been required.

- DOE agreed with the Board's recommendation on the need to provide increased clarity regarding how Nuclear Energy University Programs work was integrated to achieve the desired results in HBF research and described actions it was taking to address the Board's recommendation.

During this reporting period, the Board reviewed and commented on various drafts of DOE's plans for the "sister rods" in the HDRP, including its plan for post-irradiation examinations (PIE) of "sister rods." In June 2016, the Board commented on an early draft of the *Post Irradiation Examination Plan for High Burnup Demonstration Project Sister Rods* in a letter to DOE (Ewing 2016d). The plan described the characterization and experimental test activities proposed to be undertaken on 25 high burnup SNF "sister rods" having characteristics like SNF "test rods" being used in the HDRP. The Board found the characterization and experimental test activities described in the plan useful for providing important data on potential degradation of HBF during extended storage. However, the Board also commented that the plan should be revised to address several additional issues. These summarized issues are provided next.

- **Justification for Proposed Sister Rod Examinations and Testing.** The PIE plan proposed an extensive suite of non-destructive and destructive tests on the sister rods. However, it was not evident how the results from each test would be used to fill the information gaps identified in previous reports. The PIE plan should a) link each proposed test to one or more information gaps identified in the most recent gap analysis and b) explain how the results of each proposed test will be used to fill the gap or support modeling of HBF performance during dry storage.

- **Establishing a Baseline.** The PIE plan should emphasize, as the first priority, the characterization necessary to establish a baseline for the HDRP and should show how the results would be used to assess degradation of the test rods from the HDRP cask. It was expected that, at a minimum, profilometry, visual inspection, gamma scans, measurement of fission gas release, microscopy, and characterization of mechanical properties would be necessary.

- **Whole Rod Heating Tests.** The PIE plan included heating some of the sister rods to simulate the temperature changes experienced by the fuel in the storage cask, followed by monitoring those rods until the end of the HDRP. The PIE plan should provide details on a) the purpose of the tests, b) how measurements on the conditions inside the test cask (e.g., temperature, radiation, gas composition) would be obtained, and c) how the conditions to which the sister rods would be exposed would be simulated to match those in the test cask. If the heat-treated rods would not be stored under conditions similar to those for the test rods, then the relevance of the test needed to be explained.

- **Test Method Verification.** All test methods to determine mechanical properties of the cladding that were not approved by the American Society for Testing and Materials[22] should be fully developed and verified to assure that they produced valid data that would be defensible and acceptable to regulators.

- **Preservation of Sister Rods.** Obtaining and characterizing the sister rods would be an expensive undertaking. These rods constituted a valuable resource for R&D to meet presently unforeseen needs related to SNF management and disposal in the future. DOE should consider preserving selected sister rods, or rod segments and components, for future use.

- **Low Temperatures in the HDRP Cask.** The Board was concerned that the maximum cladding temperature in the HDRP predicted by modeling was substantially below what was originally anticipated. This called into question the usefulness of the HDRP to determine the effects of hydride reorientation during storage of other HBF at reactor sites, which might experience temperatures as high as 400°C. Before any fuel was loaded into the HDRP cask or sister rod characterization is initiated, the Board recommended that DOE look into methods to raise the cladding temperatures, for example, by means external to the cask or including some fuel assemblies with shorter cooling times. If the maximum cladding temperature could not be raised, DOE should re-evaluate the utility of the

[22] ASTM International, formerly known as American Society for Testing and Materials, is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services.

HDRP as planned and consider delaying the project until the issues associated with maximum temperature could be resolved.

- **Modeling.** DOE should undertake a detailed analysis of how the data obtained from the HDRP and the sister rod testing program would be used to develop models for the behavior of spent fuel rods under other conditions reflective of the expected population of HBF in dry storage. This would include rods that have other cladding types, have been irradiated to higher burnups, or have experienced higher cladding temperatures.

Later in July 2016, after DOE had responded (DOE 2016c) to the Board's letter on the February 2016 Board meeting (Ewing 2016c), a small number of Board and staff held a fact-finding meeting in Las Vegas, Nevada, on DOE's R&D on HBF performance during storage and transportation. During the fact-finding meeting, the Board and DOE discussed research that DOE was performing to obtain the data needed to characterize high burnup SNF, including the degradation that may occur during extended storage and transportation. A small number of Board and staff held a second fact-finding meeting with DOE in October 2016 on the same topic in Idaho Falls, Idaho. The Board team and DOE discussed how data from HBF performance research could be used with computer models being developed by DOE and the national laboratories. Subsequently, the Board thanked DOE for supporting the fact-finding meetings (Ewing 2016e). Ewing (2016e) stated that the meetings were very productive and provided additional clarity to the discussions on high burnup SNF that took place at the Board's open public meeting in Knoxville, Tennessee, in February 2016. The Board also indicated that it was currently preparing a report on high burnup SNF, drawing information from the public meeting, correspondence with DOE, and two fact-finding meetings (Ewing 2016e).

In November 2016, the Board held a working meeting in Stanford, California, to discuss corrosion of SNF and characteristics of HBF and its impact on geologic disposal. The meeting is described in the "Disposition of vitrified HLW" section above. The Board also used the working meeting to advance its review efforts of DOE's HBF R&D activities.

In February 2017, one Board member and one staff member participated in a meeting as observers involving DOE staff and SNL researchers in which a member of SNL staff was charged with generating an overall integrated approach to the sister rod testing plan to support the HDRP. A draft of the revised test plan, referred to as the *EPRI/DOE High Burnup Fuel Sister Pin Test Plan Simplification and Visualization* (Saltzstein et al 2017a), was provided to the Board in early August 2017. In August 2017, the Board documented its review of the draft revised test plan and presented DOE its comments (Bahr 2017b). In the letter to DOE, the Board provided specific technical comments to further strengthen and clarify the test plan for destructive characterization of HBF rods. The five technical comments on details of the plan are summarized by the Board's statement that the Board looked forward to reviewing the evolving technical details of how testing would be accomplished in a practical, relevant manner and how the results would be linked to modeling efforts. Almost immediately DOE responded to the Board's comments (Bahr 2017b). DOE's response (DOE 2017) thanked the Board for its review and stated that the Board's comments on DOE's test plan provided useful insights.

In November 2017, in a letter to DOE, the Board provided comments (Bahr 2017c) based on its technical review of the latest draft of the test plan (Saltzstein et al 2017b). The Board cited specific points that could be clarified to improve the draft plan. The Board also noted that the latest draft plan (Saltzstein et al 2017b) did not address some issues the Board raised (Bahr 2017b) on the earlier version of the plan (Saltzstein et al 2017a) and encouraged DOE to address the issues before releasing their final plan. The issues DOE did not address in the revised plan are summarized here:

- **One of the purposes of the heat treatment tests was to provide data to support modeling efforts that would allow the test results to be extended to other types of HBF.** However, the revised plan did not address how test results would be used in the modeling efforts.

- **The HDRP "sister rods" constituted a valuable resource for R&D to meet presently unforeseen needs related to SNF management and disposal.** How the rods would be stored so that their characteristics did not appreciably change during storage and how documentation on these rods would be preserved for future use needed to be considered in the near term.

In February 2018, DOE responded (DOE 2018) to the Board's letter (Bahr 2017c) on the updated draft plan (Saltzstein et al 2017b). DOE responded individually to the Board's specific comments (DOE 2018). DOE acknowledged that in the Phase 1 work described in Saltzstein et al. (2017b), rods heat treated to 400°C would not be pressurized to the highest pressure in the current reactor fleet but that it was aware there were different types of rods in the fleet that had higher pressures and those conditions may be addressed in Phase 2 of the HDRP (DOE 2018). DOE stated it may try to obtain some Integral Fuel Burnable Absorber rods that often have higher pressures, or that it may take a more analytical approach to address these rods. DOE (2018) also addressed the Board's specific issues on identifying the models and the test data that the models would use and provided details on how DOE planned to store sister rods after the experiment. DOE replied that the Board's request to identify specific models was out of the scope of the test plan (Saltzstein et al. 2017b), but that DOE intended for all the data in the Phase 1 testing to be used in models and that DOE would share the data with interested modelers.

In August 2018, a small number of Board and staff held a fact-finding meeting in Las Vegas, Nevada, to discuss recent progress in DOE R&D on HBF and direct disposal of dual-purpose canisters for commercial SNF. DOE indicated that the HDRP was recognized for providing useful data to build the technical basis for extended storage and transport of SNF, including HBF.[23] DOE updated the Board team on its R&D activities related to the HBF, transportation testing, and the potential direct disposal of large dual-purpose SNF canisters. That update prepared DOE for a public Board meeting in October 2018 on the same topics.

[23] In 2018, the High-Burnup Cask Demonstration Project Team was awarded the Secretary of Energy's Achievement Award.

In October 2018, the Board held a public meeting in Albuquerque, New Mexico, that focused on DOE R&D activities related to managing and disposing of commercial SNF, where HBF technical issues were discussed (Bahr 2018a). Speakers from DOE-NE and several national laboratories presented R&D projects related to extended storage and transportation of HBF, including DOE's collaborations and partnerships with other organizations, particularly in ESCP. DOE described its recent progress in the HDRP. The day after the meeting, the Board toured experimental facilities at SNL.

In November 2018, the Board thanked DOE personnel and the technical experts at the national laboratories for preparing and participating in the August fact-finding meeting in Las Vegas, Nevada, and the October public meeting in Albuquerque, New Mexico (Bahr 2018a). The Board also thanked SNL for the tour of their experimental facilities in Albuquerque. Both meetings helped the Board better understand DOE's R&D on SNF behavior during extended storage and transportation. The Board's letter to DOE (Bahr 2018a) provided the Board's observations on obtaining data to advance understanding of SNF behavior during storage, transportation, and disposal. The summarized observations on several themes are the following:

- **Obtaining Data to Advance Understanding of SNF Behavior during Storage, Transportation, and Disposal.** The Board believed it was important for DOE to make it a priority to gain access to new fuel design information and post-irradiation examination results needed to support the efforts of national laboratories to understand SNF characteristics, such as the potential for hydride reorientation and criticality analysis of loaded DPCs.

- **Performance and Potential Degradation of High-Burnup SNF during Storage and Transportation.** For the fuel and cladding types included in the HDRP testing, DOE was making significant progress toward developing the technical bases to support the extended storage and subsequent transportation of commercial SNF. There was generally good integration of DOE R&D activities on high-burnup SNF and high-quality data were being acquired. The ongoing HDRP cask monitoring and sister rod testing would provide additional useful information. More work also was needed to quantify the amount and form of moisture that remained in a dry storage cask following drying performed according to typical industry practices.

- **Integration of DOE Storage and Transportation R&D Results into DOE Disposal R&D Activities.** There appeared to be generally good integration of DOE R&D activities on storage and transportation of high-burnup SNF. However, DOE had not integrated the results from these R&D activities into the DOE R&D program on SNF disposal. For example, the HDRP thermal measurements indicated the temperatures inside dry-storage canisters are lower than previously had been assumed in at least some cases. Because thermal management was a key consideration in the design and operation of any geologic repository, the lower-than-expected canister temperatures could have implications for repository design and operation that need to be evaluated by DOE.

As part of its review of DOE extended SNF storage activities, the Board also participated in multi-organization meetings that involved DOE, such as EPRI ESCP, and conducted site visits to facilities where DOE-funded work was being conducted. Those activities in which the Board participated include the following:

- Five EPRI ESCP meetings during the 2016 to 2018 reporting period.
- Robotic demonstrations for inspection of dry storage canisters at the McGuire Nuclear Station, North Carolina.
- A tour of DOE-NE funded canister inspection research at Pennsylvania State University in State College, Pennsylvania.

Board Interactions with Congress

Between 2016 and 2018, the Board provided no testimony to Congress. The Board had no correspondence with Congress aside from distribution of Board reports to members of Congress and Congressional staff. The Board continued to brief members of Congress, their staff, and committee staff on Board reports. During this reporting period, the Board began briefing Congressional Research Service staff on each new Board report submitted to Congress and the Secretary of Energy.

International Activities

Between 2016 and 2018, the Board issued two reports focused on aspects of other countries' radioactive waste programs and interacted with radioactive waste management programs abroad. The Board interactions included a Board visit to Belgium and Switzerland. During the visit, the Board obtained information directly on developments in each country's radioactive waste management program and viewed underground research facility experiments in which DOE is collaborating. Separately, the Board met with the Advisory Bodies to Government group, the International Atomic Energy Agency (IAEA) on R&D activities in underground research facilities, and the Nuclear Energy Agency's Integration Group for the Safety Case. The Board interacted 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 national approaches to defining and carrying out a multi-decadal disposal RD&D program. 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. 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.

Survey of national programs

Previously, the Board catalogued 15 institutional arrangements and 15 technical approaches in 13 countries for long-term management of SNF and HLW (NWTRB 2009). However, since 2009, there had been substantial changes in national waste management programs in many of the 13 countries.[24]

In February 2016, the Board issued the report, *Survey of National Programs for Managing High-Level Radioactive Waste and Spent Nuclear Fuel: An Update* (NWTRB 2016c).[25] In the report, the Board updated its previous international survey of 30 attributes of nuclear waste management programs in the United States, Belgium, Canada, China, Finland, France, Germany, Japan, South Korea, Spain, Sweden, Switzerland, and United Kingdom.[26] The report did not make judgments about any of the programs but rather compiled the experiences in the United States and other countries to provide useful technical and scientific information for decision-makers in Congress and the Administration on different approaches for management and disposal of SNF and HLW. The report noted that there was a strong international consensus that a deep-mined, geologic repository used to dispose of high-activity, long-lived radioactive waste provided an unprecedented level and duration of protection of public health and safety and the environment. Such a system would take advantage of the capabilities of both the local geology and the engineered materials to fulfill specific safety functions in a complementary fashion and would provide multiple and diverse barrier roles.

Performance monitoring in, and retrievability of waste from, a repository

In June 2018, the Board issued the report, *Geologic Repositories: Performance Monitoring and Retrievability of Emplaced High-Level Radioactive Waste and Spent Nuclear Fuel* (NWTRB 2018). The report was based on presentations and discussions at the Board's March 27, 2018, meeting in Washington, DC, on that topic. The report recorded the views of experts from several countries who made presentations at the meeting on challenges intrinsic to both monitoring and waste retrieval.[27] It also included Board observations based on the meeting discussions.

---

[24] For example, in the United States, one of the most impactful changes since 2009, was the decision by the Obama Administration to suspend the effort to develop a deep-mined, geologic repository at Yucca Mountain, Nevada. Much of the information compiled was relevant irrespective of whether the repository would be developed specifically at the Yucca Mountain site. When the information was related specifically to the Nevada site only; however, this context was carefully noted in the survey report.

[25] The report is available on the Board's website (www.nwtrb.gov).

[26] At the time of the report, the 13 selected countries accounted for over 80 percent of the world's nuclear power capacity, which formed some basis to report on their waste management activities. Other countries were not included in the survey because their programs, relative to the 13 selected countries, were either in their infancy or because the status of their programs could not be independently documented.

[27] Both meeting materials, such as presentations and transcript, and the report are available on the Board's website (www.nwtrb.gov). Although DOE did not present information at the meeting because their current non-site-specific disposal R&D program did not specifically address these topics, they did attend the meeting. DOE addressed the meeting topics as part of their application for construction authorization for the Yucca Mountain, Nevada, repository.

Worldwide, the value of a stepwise process or phased approach for implementing a geologic repository program for the disposal of HLW and SNF was well-recognized. Many international repository programs considered such a process important because it helped preserve the ability of future generations to modify decisions that would be taken during the implementation of the repository program. Two actions were identified as integral to the success of a stepwise implementation of a repository program: (i) successful monitoring of the repository (either during repository operations or both during operations and after closure of the repository), including its engineered components and natural barriers, and (ii) retaining the option to retrieve the emplaced waste in the event retrieval was determined to be necessary.

Based on the information provided in the meeting, the Board documented observations and provided discussion related to the implementation and monitoring of geologic repositories and the retrievability of emplaced HLW and SNF (NWTRB 2018), which are summarized as follows:

- **Retrievability was an important consideration in the initial repository design, adding only a small increment to the cost of repository development but offering substantial cost reduction if retrieval was determined to be necessary**. The value of establishing a contingency option for waste retrieval was broadly recognized in other countries. It was also generally agreed upon that the initial repository design should facilitate waste retrieval if that was deemed necessary; waste retrieval would become more difficult and more costly as implementation of the repository program matured.

- **Monitoring to assess operations and to support decisions related to repository operations or waste retrieval was also an integral part of repository development**. The Board observed that monitoring activities to generate the data required for a decision to modify operations or retrieve waste should not be simple add-ons to a repository program, but instead considered integral to repository development and should be considered in the early design stages with a level of flexibility throughout repository development. The Board recognized that monitoring informed decision-making, experiments, and models but also gave the public confidence that authorities have a long-term commitment to the safety of the host community.

- **It was essential that the monitoring objectives and limitations are understood, the indicators that would signal the need for a modified path or retrieval were transparent, and the collected data were broadly accessible to enhance public trust and for use in performance confirmation modeling by the implementer and other stakeholders**. It was important to acknowledge limitations to what can be monitored. The Board observed that the implementer needs to be open and honest about the objectives, strengths, and limitations of monitoring so the public was well-informed of the limitations.

- **Underground research laboratories and repository pilot facilities improved the technical basis and confidence in the future success of monitoring technologies and potential retrieval and could serve as demonstration sites to build public acceptance**. The Board considered underground research laboratories and pilot facilities useful tools that could provide information needed to make decisions on monitoring and retrievability, because these allowed for testing and demonstration of waste emplacement, retrieval, and monitoring in prototypical environments that could also help public acceptance of the repository.

- **Long-term research, development, and demonstration of monitoring and sensor technologies were needed to address current technology limitations.** Most of the key parameters of interest in repository performance confirmation could be measured using existing monitoring and sensor technologies. However, the Board meeting indicated that much work (probably many years of sustained research, development, and demonstration) was still needed to improve these technologies for long-term stability, reliability, and practical use in a geologic repository for SNF and HLW.

- **A stepwise approach to repository program implementation and decision-making was important because it provided opportunities to reassess decisions and modify future plans**. All countries with a geologic repository program, including the United States, had a stepwise or phased approach to repository program implementation. In a discrete, stepwise approach, the regularity of decision-making (e.g., periodically updating the safety documentation or the research, development, and demonstration program) facilitated systematic reassessment of the program over time and allows potential changes on a regular basis. Smaller steps meant more frequent engagement between the implementer, the regulator, and the stakeholders.

- **Measures were needed to facilitate knowledge transfer to future generations so that expertise was available to access and interpret monitoring data**. From initiation of repository operations to pre-closure monitoring, given the long period expected between the phases of a repository program, the Board observed that particular effort was needed to develop institutional and other mechanisms to ensure the transfer of relevant knowledge, the capability to apply that knowledge, and the sustainability of stewardship into the future.

Board visit to Belgium and Switzerland

As noted earlier, in June of 2016, a Board delegation visited Switzerland and Belgium to exchange information with key scientific and technical organizations dealing with long-term management of HLW and SNF. Both countries were planning to phase out nuclear power from their energy portfolios. These countries had a strong R&D program in geologic disposal and a long history of experimental work in underground research laboratories.

In Switzerland, the Board delegation met with officials from the Swiss regulator, and the Board's sister agency, the Swiss Federal Nuclear Safety Commission, and other organizations associated with siting the Swiss repository. The delegation received detailed presentations from the implementer, the National Cooperative for the Disposal of Radioactive Waste (Nagra), which is not a government agency, but rather a government-industry cooperative established by Swiss waste producers. The Board delegation visited the Grimsel Test Site underground research laboratory that Nagra developed in 1984 for its R&D activities and the Board learned about experiments (Figure 7), including those that included DOE's participation.

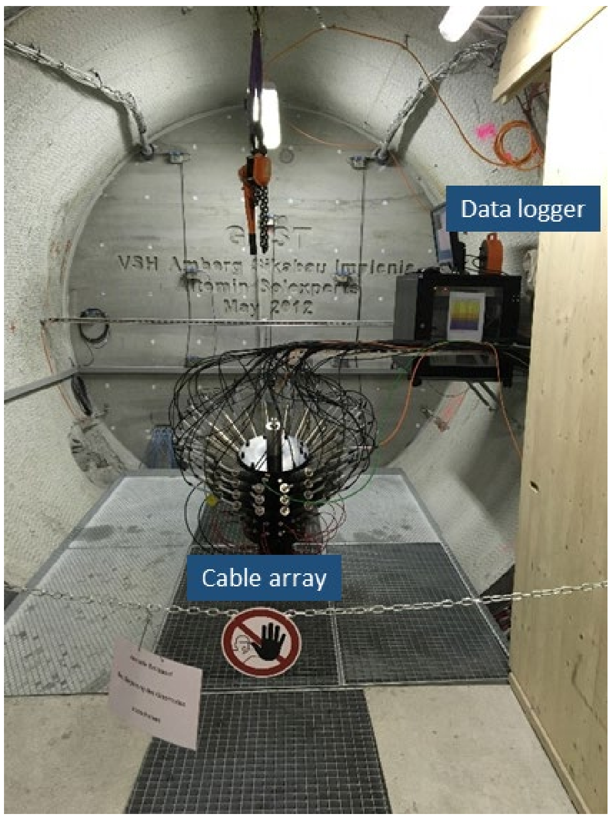

Figure 7. Cable array used at the Grimsel Test Site.
The Gas-Permeable Seal Test collected gas and water permeabilities data from sensors in sand and bentonite mixtures that could be used as engineered emplacement drift seals. The data were transmitted from the sensors, located beyond the end of the sealed drift, through cables to the data logger.

The Board delegation also visited Switzerland's second underground research laboratory, the Mont Terri Project, which DOE joined as a formal partner in 2012. The Mont Terri Project was an international research project for the hydrogeological, geochemical, and geotechnical characterization of a clay/shale formation suitable for geologic disposal of radioactive waste. DOE-funded researchers have engaged in several projects ranging from large-scale heater tests (Figure 8) to damage zone, diffusion, and fault slip experiments.

Figure 8. Board delegation learned about DOE's participation in the Mont Terri Project full-scale emplacement (FE) heater test.
The FE experiment was one of the largest and could be the longest duration heater test ever conducted. This was the only experiment that DOE was collaborating on with international partners that examined the integrated system behavior expected in a repository.

The Board delegation studied Switzerland's approach to interim storage by visiting ZWILAG, its storage facility for both SNF from Swiss power reactors and HLW resulting from reprocessed Swiss SNF in La Hague, France, and Sellafield, United Kingdom.

In Belgium, the Board delegation met with officials from the Belgian regulator and the Belgian Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS). That agency was responsible for cradle-to-grave management of radioactive waste, which included short- and medium-term waste management (i.e., transport, processing, and interim storage) and long-term waste management (i.e., disposal at a near-surface facility or in a deep geologic repository). The Board also met with representatives of other organizations associated with siting the Belgian surface disposal facility for low activity radioactive waste. The Board visited HADES, which was the only underground research laboratory in Belgium for experimental research on geologic disposal of high-level and/or long-lived radioactive waste in clay. The Board delegation met with a European Union official to learn about the European Commission's Directive 2011/70/Euratom on Responsible and Safe Management of Spent Fuel and Radioactive Waste.

The Board observed that Switzerland had made significant progress in siting a repository for SNF and HLW, and they had an integrated radioactive waste management program with longevity, funding continuity, and programmatic consistency. The Board was impressed by the approaches used by Nagra for stakeholder and public engagement. The Board observed that the lack of a long-term national policy continued to hamper Belgium's efforts to find a repository site for SNF and HLW.

Compared to the United States, both Belgium and Switzerland had smaller waste management programs. Both Belgium and Switzerland used underground research laboratories for research, development, and demonstration activities, and for public engagement. The Board felt that DOE's participation in the Swiss underground activities was welcomed by the international waste management community, and DOE was gaining a lot of knowledge from its participation. Notably, the breadth and depth of public engagement in the siting processes for both countries were impressive to the Board. From these information exchanges, the Board gained valuable insights for its interactions with DOE and policy makers as the United States seeks a path forward in disposing of its HLW and SNF.

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 countries involved in these activities included: France, Germany, Japan, Sweden, Switzerland, United Kingdom, and the United States. The purpose of the group was to bring together the chairs of entities, such as the Board, that 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 an Advisory Bodies to Government meeting in Stockholm in June 2018 and visited the Final Repository for Short-lived Radioactive Waste and the proposed SNF repository site, both at Forsmark. At this meeting, the Nuclear Energy Agency indicated its support for formalizing the group and for annual meetings of the group.

Board participation in the activities of the International Atomic Energy Agency

Between 2016 and 2018, a member of the Board's staff served as an expert and attended consultancy meetings in Vienna, Austria, for IAEA's coordinated research project on demonstrating performance of SNF and related storage system components during very long-term storage. The IAEA research project was addressing issues like those DOE was investigating in its HDRP.

A Board and staff member attended a technical meeting on underground research laboratories [IAEA refers to them as underground research facilities (URF)][28] in Vienna, Austria, to gain

[28] The international nuclear waste community preferred to refer to them as "underground research facilities" because other countries focused on demonstrating repository excavation and proposed operation technologies in their

insights for potential topics, speakers, and agenda for the Board's planned Spring 2019 workshop on recent advances in repository science and operations from international underground research laboratory collaborations.[29] Another goal of the gathering in Vienna was to help revise a draft IAEA report on results from RD&D activities in URFs. DOE was conducting its underground activities and collaborative underground research laboratory experiments to support its non-site-specific disposal R&D program. URFs played a critical role in developing safety cases for geologic disposal. Also, some nations had not selected a specific host rock type for its repository and did not have an operating URF. Thus, they benefited from taking part in other countries' URFs and collaborating with those countries to develop the capabilities to move their own repository programs forward.

Board participation in the activities of the Nuclear Energy Agency

In October 2018, a member of the Board's staff attended the Nuclear Energy Agency's Integration Group for the Safety Case Symposium in Rotterdam, Netherlands. The attendee presented an invited paper on the Board's 2018 performance monitoring and retrievability report (NWTRB 2018), described above. Attendance at the symposium allowed 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 symposium helped identify challenges that may arise as a repository program matures, and the safety case develops to represent an actual facility and inventory. International regulators praised the Board's report and its observations within it, because the report emphasized the integral nature of performance monitoring for repository development.

---

facilities without using radioactive materials in addition to carrying out experiments, like those conducted in a laboratory, albeit at a larger scale. In contrast, DOE used the term "underground research laboratory" in its non-site-specific disposal R&D program where it focused on experiments rather than demonstrations.

[29] The Spring 2019 workshop agenda, list of speakers and panelists, presentations, and transcript of proceedings are available on the Board's website (www.nwtrb.gov).

REFERENCES

Arnold, B. et al. 2012. *Research, Development, and Demonstration Roadmap for Deep Borehole Disposal.* SAND 2012-8527P, August.

ASLB (Atomic Safety and Licensing Board). 2011. "Memorandum and Order (Suspending Adjudicatory Proceeding)," 74 NRC 368, September 30.

Bahr, J. 2017a. August 16 letter from Jean M. Bahr, Chair, U.S. Nuclear Waste Technical Review Board, to Mr. James M. Owendoff, Acting Assistant Secretary for Environmental Management, and Mr. Edward McGinnis, Acting Assistant Secretary Nuclear Energy, "Comments on the June 21, 2017, Meeting."

Bahr, J. 2017b. August 25 letter from Jean M. Bahr, Chair, U.S. Nuclear Waste Technical Review Board, to Mr. Edward McGinnis, Acting Assistant Secretary for Nuclear Energy, "Comments on Draft Sister Rod Characterization and Testing Plan."

Bahr, J. 2017c. November 7 letter from Jean M. Bahr, Chair, U.S. Nuclear Waste Technical Review Board, to Mr. Edward McGinnis, Acting Assistant Secretary for Nuclear Energy, "Comments on Sister Rod Characterization and Testing Plan."

Bahr, J. 2018a. November 27 letter from Jean M. Bahr, Chair, U.S. Nuclear Waste Technical Review Board, to Mr. Edward McGinnis, Principal Deputy Assistant Secretary for Nuclear Energy, "Comments on the October 24, 2018, Meeting."

Bahr, J. 2018b. November 27 letter from Jean M. Bahr, Chair, U.S. Nuclear Waste Technical Review Board, to Dr. William Boyle, Deputy Assistant Secretary for Spent Fuel and Waste Disposition, DOE-NE, and Mr. Ken Picha, Acting Associate Principal Deputy Assistant Secretary for Field Operations, "Thank You for October 22, 2018, Waste Isolation Pilot Plant Tour."

Bahr, J. 2018c. June 27 letter from Jean M. Bahr, Chair, U.S. Nuclear Waste Technical Review Board, to Ms. Anne White, Assistant Secretary Environmental Management, and Mr. Edward McGinnis, Principal Deputy Assistant Secretary for Nuclear Energy, "Comments on the June 13, 2018, Meeting."

Bowman, F. and I. Itkin. 2000. "*Memorandum of Agreement for Acceptance of Naval Spent Nuclear Fuel* between the Director, Naval Nuclear Propulsion Program, Department of the Navy, Arlington, VA, and the Director, Office of Civilian Radioactive Waste Management (OCRWM), U.S. Department of Energy (DOE), Washington, DC." Rev. 1, April 11.

BRC (Blue Ribbon Commission on America's Nuclear Future). 2012. *Report to the Secretary of Energy*. January 26.

DOE. 2007. "*Memorandum of Agreement for Acceptance of Department of Energy Spent Nuclear Fuel and High-Level Radioactive Waste* between the Assistant Secretary for

Environmental Management (EM), DOE, Washington, DC, and the Director of OCRWM, DOE, Washington, DC." Rev. 2, February.

DOE. 2008. *Civilian Radioactive Waste Management System Waste Acceptance System Requirements Document*. DOE/RW-0351, Rev. 5, ICN 01. March.

DOE. 2013. *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste*. January.

DOE. 2015a. *Report on Separate Disposal of Defense High Level Radioactive Waste*. March.

DOE. 2015b. *Deep Borehole Field Test: Site and Characterization Borehole Investigations Request for Proposal*. September 17.

DOE. 2015c. "Invitation for Public Comment to Inform the Design of a Consent-Based Siting Process for Nuclear Waste Storage and Disposal Facilities." *Federal Register*, 80, 79,872-79,874, December 23.

DOE. 2016a. June 9 letter from John Kotek, Acting Assistant Secretary for Nuclear Energy, to Rodney C. Ewing, Chairman, U.S. Nuclear Waste Technical Review Board, "Response to the Board's report *Technical Evaluation of the U.S. Department of Energy Deep Borehole Disposal Research and Development Program*."

DOE. 2016b. January 27 letter from John Kotek, Acting Assistant Secretary for Nuclear Energy, to Rodney C. Ewing, Chairman, U.S. Nuclear Waste Technical Review Board, "Response to the Board's Comments on the Transportation of Spent Nuclear Fuel."

DOE. 2016c. July 13 letter from John Kotek, Acting Assistant Secretary for Nuclear Energy, to Rodney C. Ewing, Chairman, U.S. Nuclear Waste Technical Review Board, "Response to the Board's Comments on Extended Storage and Transportation of High Burnup Spent Nuclear Fuel."

DOE. 2017. September 12 letter from Edward McGinnis, Acting Assistant Secretary for Nuclear Energy, to Jean M. Bahr, Chair, U.S. Nuclear Waste Technical Review Board, "Response to the Board's Comments on *EPRI/DOE High Burnup Fuel Sister Pin Test Plan Simplification and Visualization*."

DOE. 2018. February 2 letter from Ray Furstenau, Associate Principal Deputy Assistant Secretary for Nuclear Energy, to Jean M. Bahr, Chair, U.S. Nuclear Waste Technical Review Board, "Response to the Board's Comments on Latest Draft of *EPRI/DOE High-Burn up Fuel Sister Rod Test Plan Simplification and Visualization*."

EPRI (Electric Power Research Institute). 2000. *Dry Cask Storage Characterization Project—Interim Progress Report*. Report Number 1000157, Palo Alto, California, June.

EPRI. 2002. *Technical Bases for Extended Dry Storage of Spent Nuclear Fuel*. Report Number 1003416, Palo Alto, California, December.

EPRI. 2014. *High Burnup Dry Storage Cask Research and Development Project Final Test Plan*. Contract No. DE-NE-0000593, Palo Alto, California, January 20.

EPRI. 2019. *High Burnup Dry Storage Research Project Cask Loading and Initial Results*. Report Number 3002015076, Palo Alto, California, October.

Ewing, R. 2015. August 31 letter from Rodney C. Ewing, Chairman, U.S. Nuclear Waste Technical Review Board, to John Kotek, Acting Assistant Secretary for Nuclear Energy, "Comments on the June 24, 2015, Meeting on the Transportation of Spent Nuclear Fuel."

Ewing, R. 2016a. July 7 letter from Rodney C. Ewing, Chairman, U.S. Nuclear Waste Technical Review Board, to John Kotek, Acting Assistant Secretary for Nuclear Energy, "Response to John Kotek Letter Dated June 9, 2016, on DOE's Comments to Board's Deep Borehole Disposal Report."

Ewing, R. 2016b. December 8 letter from Rodney C. Ewing, Chairman, U.S. Nuclear Waste Technical Review Board, to Dr. Monica Regalbuto, Assistant Secretary Environmental Management and John Kotek, Acting Assistant Secretary for Nuclear Energy, "Comments on the August 24, 2016, Meeting."

Ewing, R. 2016c. May 23 letter from Rodney C. Ewing, Chairman, U.S. Nuclear Waste Technical Review Board, to John Kotek, Acting Assistant Secretary for Nuclear Energy, "Comments on the February 17, 2016, Meeting."

Ewing, R. 2016d. June 3 letter from Rodney C. Ewing, Chairman, U.S. Nuclear Waste Technical Review Board, to John Kotek, Acting Assistant Secretary for Nuclear Energy, "Comments on the Post Irradiation Examination Plan for High Burnup Demonstration Project Sister Rods."

Ewing, R. 2016e. December 7 letter from Rodney C. Ewing, Chairman, U.S. Nuclear Waste Technical Review Board, to John Kotek, Acting Assistant Secretary for Nuclear Energy, "Thank You for Participating in High Burnup Spent Nuclear Fuel Fact-Finding Meetings."

NRC (U.S. Nuclear Regulatory Commission). 2011. "Memorandum and Order," CLI-11-07, September 9.

NRC. 2015. *Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada*. NUREG-1949, Volume 5.

NWTRB (U.S. Nuclear Waste Technical Review Board). 2009. *Survey of National Programs for Managing High-Level Radioactive Waste and Spent Nuclear Fuel*. October.

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

NWTRB. 2012. Transcript of Nuclear Waste Technical Review Board January 9, 2012, Meeting. https://www.nwtrb.gov/docs/default-source/meetings/2012/january/12jan09.pdf?sfvrsn=7, pp. 142–144.

NWTRB. 2014. *Report to the U.S. Congress and the Secretary of Energy: Board Activities for the Period January 1, 2008–December 31, 2012*. December.

NWTRB. 2016a. *Report to the U.S. Congress and the Secretary of Energy: Board Activities for the Period January 1, 2013–December 31, 2015*. December.

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

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

NWTRB. 2017. *Management and Disposal of U.S. Department of Energy Spent Nuclear Fuel.* December.

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

Obama, B. 2015. *Presidential Memorandum—Disposal of Defense High-Level Radioactive Waste in a Separate Repository*. The White House, March 24.

Saltzstein, S. et al. 2017a. *EPRI/DOE High Burnup Fuel Sister Pin Test Plan Simplification and Visualization.* SAND2017-7597, July.

Saltzstein, S. et al. 2017b. *EPRI/DOE High Burnup Fuel Sister Pin Test Plan Simplification and Visualization.* SAND2017-10310 R, September.

SNL (Sandia National Laboratories) 2015. *Deep Borehole Field Test Specifications*. FCRD-UFD-2015-000132, Rev. 1.

SNL 2018. *CaskTest_9_12largeFINAL.mp4*. SAND-20185-5898V.

ACRONYMS

ANL	Argonne National Laboratory
ASLB	Atomic Safety and Licensing Board
BATS	Brine Availability Test in Salt
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
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
ENSA	Equipos Nucleares Sociedad Anónima, a Spanish industrial company
EPRI	Electric Power Research Institute
ESCP	Extended Storage Collaboration Program
FE	Full-scale Emplacement test, Grimsel Test Site, Switzerland
HBF	high burnup fuel
HDRP	High Burnup Dry Storage Cask Research and Development Project
HLW	high-level radioactive waste
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
Nagra	National Cooperative for the Disposal of Radioactive Waste, Switzerland
NGSAM	Next Generation System Analysis Model
NRC	U.S. Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
NWPAA	Nuclear Waste Policy Amendments Act

OCRWM	Office of Civilian Radioactive Waste Management
ORNL	Oak Ridge National Laboratory
PIE	post-irradiation examination
PNNL	Pacific Northwest National Laboratory
R&D	research and development
RD&D	research, development, and demonstration
SKB	Swedish Nuclear Fuel and Waste Management Company
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
SRS	Savannah River Site
URF	underground research facility
UNF-ST&DARDS	Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System
WIPP	Waste Isolation Pilot Plant

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 other materials 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 a shale deposit. Both clay and shale have relatively low permeability and relatively high capacity for sorption of positively charged chemical species.

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 from 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 as 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 called fuel assemblies, which are loaded individually into the reactor core. Also called "fuel pins."

Fuel pellet A thimble-sized ceramic cylinder, 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 The 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 Shale is 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 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 Any of a group of alloys of zirconium, tin, and other metals, used chiefly as cladding for nuclear reactor fuel.

APPENDICES

A. Board Members During the Reporting Period

B. Board Strategic Plan 2018–2022

C. Board Publications

D. Board Meetings: January 1, 2016–December 31, 2018

E. Correspondence with the U.S. Department of Energy: January 1, 2016–December 31, 2018

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 is the 2012 recipient of the Association for Women Geoscientists' Outstanding Educator Award.

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 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 and Chair of the School 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 crisis and emergency 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 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 18 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 Geological Society of America (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.

RODNEY C. EWING, PH.D.[**]

Dr. Rodney C. Ewing was appointed to the U.S. Nuclear Waste Technical Review Board by President Barack Obama on July 28, 2011 and was designated by the President to serve as Chairman of the Board on September 25, 2012. Dr. Ewing was reappointed as Chairman and member of the Board by the President on July 1, 2014.

Dr. Ewing is the Frank Stanton Professor in Nuclear Security in the Center for International Security and Cooperation, and a Professor of Geological Sciences in the School of Earth, Energy and Environmental Sciences at Stanford University. He is also the Edward H. Kraus Distinguished University Professor Emeritus at the University of Michigan and Regents' Professor Emeritus at the University of New Mexico.

Dr. Ewing is a fellow of the Geological Society of America, the Mineralogical Society of America, the American Geophysical Union, the Geochemical Society, the American Ceramic Society, American Association for the Advancement of Science, and the Materials Research Society. He was a guest scientist at numerous institutions, including the Centre d'Études Nucléaires, Commissariat à l'Énergie Atomique et aux Énergies Alternatives in Fontenay-Aux-Roses, France; Hahn-Meitner Institut in Berlin; and the University of Tokyo.

Among Dr. Ewing's numerous awards and honors are the Royal Society of Canada, Foreign Fellow; an Honorary Doctor of Université Pierre et Marie Curie; the Dana Medal of the Mineralogical Society of America; the Lomonosov Great Gold Medal of the Russian Academy of Sciences; the Roebling Medal of the Mineralogical Society of America; and the Association of Earth Science Editors Award for Outstanding Editorial or Publishing Contributions.

Dr. Ewing has written extensively on issues related to nuclear waste management and is co-editor of *Radioactive Waste Forms for the Future* (1988) and *Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste* (2006). He has published over 700 scientific papers in journals and proceedings volumes.

Dr. Ewing received a Ph.D. from Stanford University in 1974 and an M.S. from Stanford in 1972. He received a B.S. in geology from Texas Christian University.

Dr. Ewing lives in Menlo Park, California.

[**] Dr. Ewing, former Board Chairman, resigned from the Board effective January 5, 2017.

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 National Science Foundation, 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.

GERALD S. FRANKEL, SC.D.****

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

Dr. Frankel is the DNV Chair, Professor of Materials Science and Engineering, and Director of the Fontana Corrosion Center at The Ohio State University (OSU). Before joining OSU, he was a postdoctoral researcher at the Swiss Federal Technical Institute in Zurich and a research staff member at the IBM Watson Research Center in Yorktown Heights, New York. His primary research interests are in the passivation and localized corrosion of metals and alloys, corrosion inhibition, and protective coatings.

Dr. Frankel is a member of the editorial boards of the journals *Corrosion*, *Corrosion Reviews*, *Materials and Corrosion*, and *The Journal of the Electrochemical Society*. He also is past chairman of the Corrosion Division of The Electrochemical Society and past chairman of the Research Committee of NACE. Dr. Frankel is a fellow of NACE International, The Electrochemical Society, and ASM International. He received the W.R. Whitney Award from NACE International in 2015, the U.R. Evans Award from the Institute of Corrosion in 2011, the OSU Distinguished Scholar Award in 2010, the 2010 ECS Corrosion Division H.H. Uhlig Award, the Alexander von Humboldt Foundation Research Award for Senior US Scientists in 2004, the 2007 T.P. Hoar Prize from the UK Institute of Corrosion, the 2000 H.H. Uhlig Award from NACE, and the Harrison Faculty Award from the OSU College of Engineering in 2000. He was on sabbatical at the Max Planck Institute for Iron Research in Dusseldorf in 2005, a visiting professor at the University of Paris in 2008, and a visiting professor at Monash University in Melbourne, Australia in 2012.

Dr. Frankel earned an Sc.B. degree in materials science and engineering from Brown University in 1978 and an Sc.D. degree in materials science and engineering from The Massachusetts Institute of Technology in 1985.

Dr. Frankel resides in Bexley, Ohio.

**** Dr. Frankel resigned from the Board effective August 15, 2016.

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 Review and co-editor of Vadose Zone Journal. He is currently an editor of American Geophysical Unions (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 seventh 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 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, 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 is 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.

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 (DOE) 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 Rensselaer Polytechnic Institute and held engineering and management positions at Westinghouse Electric Corporation. From 2010 to 2016, he served as the Chief Scientist for DOE's Innovation Hub for Modeling and Simulation of Nuclear Reactors. 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 a member of the Society for Industrial and Applied Mathematics, the American Society for Engineering Education, and the American Association for the Advancement of Science.

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 the organization's 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 2018–2022

U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

STRATEGIC PLAN
FISCAL YEARS 2018-2022

FEBRUARY 2018

U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

MESSAGE FROM THE CHAIR

February 2018

It is my pleasure to present the U.S. Nuclear Waste Technical Review Board's *Strategic Plan for Fiscal Years 2018-2022*. This plan supersedes the Board's *Strategic Plan for Fiscal Years 2014-2018*, which was published in 2014. 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 2018-2022* 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 2018-2022
TABLE OF CONTENTS

OVERVIEW……………………………………………………………………………………….....1

MISSION STATEMENT………………………………..1

VALUES………………………………………………………………………………………….1

MEMBERS……………………………………………………………………………………….2

POWERS…………………………………………………………………………………………2

HISTORY AND CONTINUING ROLE……………………………………………………………...2

STRATEGIC OBJECTIVES……………………………………………………………………...3

ACHIEVING THE STRATEGIC OBJECTIVES……………………………………………………...3

STAKEHOLDER AND PUBLIC ENGAGEMENT…………………………………………………….4

TRANSPARENCY, PARTICIPATION, AND COLLABORATION………………………………………4

CROSSCUTTING FUNCTIONS……………………………………………………………….......5

MANAGEMENT CHALLENGES………………………………………………………………...5

EFFECTIVE USE OF RESOURCES………………….……………………………………………6

CULTURE OF ACCOUNTABILITY...…………………………………………………….………….6

U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD
STRATEGIC PLAN
FISCAL YEARS 2018-2022

OVERVIEW

The U.S. Nuclear Waste Technical Review Board was established in the 1987 Nuclear Waste Policy Amendments Act (NWPAA) (P.L. 100-203) 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 NWPAA, the purpose of the Board is to provide independent expert advice to Congress and the Secretary of Energy on technical and scientific issues and to review the technical and scientific validity of the U.S. Department of Energy's (DOE) implementation of the Nuclear Waste Policy Act (NWPA) (P.L. 97-425, as amended). In accordance with this mandate, the Board also develops relevant technical and scientific information that will be useful to Congress and the Secretary of Energy as they consider nuclear waste management policies. The Board reports its findings, conclusions, and recommendations to Congress and the Secretary of Energy at least twice yearly.

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 provided such access to allow the Board to review and comment on DOE decisions, plans, and actions as they occur, not after the fact.

HISTORY AND CONTINUING ROLE

When Congress amended the NWPA in 1987 to identify Yucca Mountain in Nevada as the sole site to be characterized for its suitability as the location for a deep geologic repository, concerns were raised that, without a comparison of sites, the technical and scientific credibility of the site-characterization effort might be questioned. Congress created the Board to ensure that an ongoing, independent peer review of DOE's work related to activities including packaging and transporting SNF and HLW, and developing a repository for their disposal, would be undertaken.

For more than 20 years following the enactment of the NWPAA, the Board reviewed DOE work focused on characterizing the Yucca Mountain site and developing the designs of a deep geologic repository and the associated waste management facilities. Since 2013, the Board has focused its review activities on DOE efforts to integrate the waste management system and research related to the performance of SNF and HLW in a repository. Throughout this period, the Board has continued to report to Congress and the Secretary of Energy its findings, conclusions, and recommendations from its review of the technical and scientific validity of DOE activities.

The Board's objective and independent peer review of DOE activities related to packaging, transportation, and disposal of SNF and HLW will continue to be indispensable to the technical credibility, successful implementation, and public acceptance of DOE's nuclear waste management program in the future.

Strategic Objectives

The Board has established three Strategic Objectives for fiscal years (FY) 2018-2022. 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 2018-2022:

- 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 over more than twenty-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. Meetings are announced in the *Federal Register,* typically four to six weeks before being held. The Board has increased the transparency of its deliberations by "webcasting" its public meetings. Webcasts 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, including, but not limited to, Congress, DOE, the Nuclear Regulatory Commission, the Environmental Protection Agency, the Department of Transportation, the NAS, the Government Accountability Office, the State of Nevada and other state governments, Native American Tribes, 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, and 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 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 indicate why the recommendations could not or should not be implemented. 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.

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

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

> This report presents the Board's observations from a meeting on March 27, 2018. At the meeting, experts from several international repository programs presented information 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's) efforts to manage the 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 DOE related to the packaging, transportation, and disposal of SNF and HLW.

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 judgments; 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 DOE and subject-matter experts from the United States and other countries at a Board workshop on deep borehole disposal held in Washington, DC, 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 HLW and SNF, 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 HLW and SNF, 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 DOE reports and studies supporting a new DOE initiative involving the development of two mined geologic repositories: one to dispose of defense HLW and possibly some DOE-managed 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 SNF and HLW.

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 the 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 U.S. Nuclear Regulatory Commission (NRC) 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 SNF and HLW management on various fuel-cycle options being considered at

that time by the 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 SNF and 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 United States 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 HLW and SNF 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 DOE and Congress about the current state of the technical basis for extended SNF dry storage and subsequent 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 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 judgments; 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 the form of a letter, 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 United States' approach to managing SNF and HLW 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 DOE 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 that 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 DOE'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 report, in the form of a letter 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 DOE 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 DOE's efforts to develop a system for accepting, transporting, and handling HLW and SNF 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 report, in the form of a letter, comprises 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 DOE 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 DOE activities and held meetings on a range of technical and scientific issues, including seismicity, DOE plans for transporting SNF and

HLW, 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 OCRWM 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 DOE 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 DOE's 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 DOE's 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 DOE's repository performance estimates.

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

> This report, in the form of a letter, summarizes the Board's technical and scientific evaluation of DOE's investigations and assessments supporting its recommendation of the Yucca Mountain site as a potential location for a deep geologic repository for SNF and HLW.

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 DOE'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 report, in the form of a letter, presents a brief update of the Board's views on the status of DOE'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 DOE's viability assessment of the Yucca Mountain site. The Board's evaluation of the viability assessment 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 viability assessment. 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 DOE's 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 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 DOE's 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 SNF and HLW. 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 DOE as part of its program for characterizing a site at Yucca Mountain in Nevada as a potential repository for SNF and HLW. 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 DOE's 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; SNF 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 report, in the form of a letter, addresses several key issues, including the DOE'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 DOE's HLW 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 NRC.

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 and the European Nuclear Society. The publication highlights Dr. Cantlon's views on the status of the U.S. repository program, including DOE 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 DOE's HLW 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 SNF and the timing of developing a federal centralized storage facility. The Board suggests in the report that DOE should remain focused on permanent geologic disposal and the site investigations at Yucca Mountain in Nevada. Planning for a federal centralized SNF 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 report, in the form of a letter, discusses the DOE's 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 DOE's Program Approach, DOE's emerging waste isolation strategy, and 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 HLW 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 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 DOE's approach to "resolving difficult issues." Recommendations center on the need for a systems approach in implementing DOE OCRWM 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 OCWRM'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 DOE'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, 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 DOE's 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 SNF and high-level defense waste from generation to disposal; and implement an independent evaluation of the organization and management of DOE's OCWRM. 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 HLW; 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 HLW program in five countries, specifically those issues that might be applicable to the United States 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 SNF and 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 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, NRC, and 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; 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 15 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 DOE, 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 SNF and 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 that the Board identified for further evaluation and highlights five cross-cutting issues.

Appendix D
Board Meetings: January 1, 2016–December 31, 2018

Board Meetings: January 1, 2016–December 31, 2018

February 17, 2016	**Winter Board Meeting** Knoxville, TN High Burnup Spent Nuclear Fuel (SNF)
August 24, 2016	**Summer Board Meeting** Washington, DC Integrating the Management and Disposal of Canisters of SNF and High-Level Radioactive Waste (HLW)
June 21, 2017	**Summer Board Meeting** Richland, WA HLW Glass Corrosion
March 27, 2018	**Spring Board Meeting** Washington, DC Performance Monitoring and Retrievability
August 6, 2018	**Summer Board Meeting** Idaho Falls, ID Technical Issues that Need to be Addressed Prior to Developing a Large, Nationwide Effort to Transport SNF and HLW
October 24, 2018	**Fall Board Meeting** Albuquerque, NM DOE R&D Activities Related to Managing and Disposing of Commercial SNF

Appendix E
Correspondence with the U.S. Department of Energy
January 1, 2016–December 31, 2018

Correspondence with the U.S. Department of Energy January 1, 2016–December 31, 2018

Letter from Mr. John F Kotek, Acting Assistant Secretary for Nuclear Energy (NE), U.S. Department of Energy (DOE), to Dr. Rodney C. Ewing, Board Chairman; January 27, 2016.
Subject: DOE response to August 31, 2015, Board letter.

Letter from Chairman Rodney C. Ewing to Mr. John F Kotek, Acting Assistant Secretary for DOE-NE; May 23, 2016.
Subject: Board comments on information presented at February 2016 Board meeting.

Letter from Chairman Rodney C. Ewing to Mr. John F Kotek, Acting Assistant Secretary for DOE-NE; June 3, 2016.
Subject: Board comments on post-irradiation examination plan for sister rods.

Letter from Mr. John F Kotek, Acting Assistant Secretary for DOE-NE, to Dr. Rodney C. Ewing, Chairman; June 9, 2016.
Subject: DOE response to January 2016 Board report on deep borehole disposal.

Letter from Chairman Rodney C. Ewing to Mr. John F Kotek, Acting Assistant Secretary for DOE-NE; July 7, 2016.
Subject: Board response to June 9, 2016, DOE-NE letter.

Letter from Mr. John F Kotek, Acting Assistant Secretary for DOE-NE, to Dr. Rodney C. Ewing, Chairman; July 13, 2016.
Subject: DOE response to May 23, 2016, Board letter.

Letter from Chairman Rodney C. Ewing to Mr. John F Kotek, Acting Assistant Secretary for DOE-NE; December 7, 2016.
Subject: Thank you for participating in high burnup spent nuclear fuel fact-finding meetings.

Letter from Chairman Rodney C. Ewing to Dr. Monica Regalbuto, Assistant Secretary DOE Office of Environmental Management (DOE-EM), and Mr. John F Kotek, Acting Assistant Secretary for DOE-NE; December 8, 2016.
Subject: Board comments on information presented at August 2016 Board meeting.

Letter from Dr. Jean M. Bahr, Board Chair to Mr. James M. Owendoff, Acting Assistant Secretary DOE-EM, and Mr. Edward McGinnis, Acting Assistant Secretary for DOE-NE; August 16, 2017.
Subject: Board comments on information presented at June 2017 Board meeting.

Letter from Chair Jean M. Bahr to Mr. Edward McGinnis, Acting Assistant Secretary for DOE-NE; August 25, 2017.
Subject: Board comments on draft sister rod characterization and testing plan.

Letter from Mr. Edward McGinnis, Acting Assistant Secretary for DOE-NE to Chair Jean M. Bahr; September 12, 2017.
Subject: DOE response to August 25, 2017, Board letter.

Letter from Chair Jean M. Bahr to Mr. Edward McGinnis, Acting Assistant Secretary for DOE-NE; November 7, 2017.
Subject: Board comments on September 2017 sister rod characterization and testing plan.

Letter from Mr. Ray Furstenau, Associate Principal Deputy Assistant Secretary for DOE-NE, to Chair Jean M. Bahr; February 2, 2018.
Subject: DOE response to Board's November 7, 2017, letter to DOE.

Letter from Chair Jean M. Bahr to Ms. Anne White, Assistant Secretary DOE-EM, and Mr. Edward McGinnis, Principal Deputy Assistant Secretary for DOE-NE; June 27, 2018.
Subject: Board comments on information presented at June 2018 Board meeting.

Letter from Chair Jean M. Bahr to Mr. Edward McGinnis, Principal Deputy Assistant Secretary for DOE-NE; November 27, 2018.
Subject: Board comments on information presented at October 2018 Board meeting.

Letter from Chair Jean M. Bahr to Dr. William Boyle, Deputy Assistant Secretary for Spent Fuel and Waste Disposition DOE-NE, and Mr. Ken Picha, Acting Associate Principal Deputy Assistant Secretary for Field Operations, DOE-EM; November 27, 2018.
Subject: Board comments on tour of Waste Isolation Pilot Plant.

Department of Energy
Washington, DC 20585

January 27, 2016

Dr. Rodney C. Ewing
Chairman
Nuclear Waste Technical Review Board
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201-3367

Dear Dr. Ewing,

Thank you for your letter regarding the Nuclear Waste Technical Review Board 2015 Summer Meeting in Golden, Colorado. The Department of Energy (DOE) appreciates your observations and recommendations related to the transportation of commercial spent nuclear fuel, and appreciated the opportunity for several DOE team members to participate in the meeting.

The Department is committed to developing a robust capability to transport spent nuclear fuel in a safe and effective manner to support a future integrated waste management system. As we continue to evaluate technical issues associated with transporting commercial spent nuclear fuel, we will take into account the Board's recommendations that the Department:

- collaborate with the utilities and the Nuclear Regulatory Commission to identify and resolve issues that could affect the ability to transport spent nuclear fuel in current canisters and casks;
- assume a greater role in integrating R&D being performed on dry-storage canisters, as well as the identification and communication of technical information on storage, transportation, and repackaging; and
- continue its work exploring the costs and potential benefits of implementing a standardized transportation, aging, and disposal canister.

Consistent with the Board's recommendation on publishing documentation supporting the Department's integration and planning tools, we recently held a demonstration of our System Analysis and Crosscut Tools that are currently under development. We were very pleased that two members of the Board were able to participate in this demonstration. As discussed at the demonstration, we are working to increase public access to elements of the Department's data, reports, and integration and planning tools. We hope the demonstration provided the Board with an overview of how each of the tools fit together to deliver a robust system to support decision-making. We invite any interested Board members to request access to CURIE on curie.ornl.gov, which serves as our public-facing information exchange.

The Board noted in its observations and recommendations that the time available to discuss chloride induced stress corrosion cracking (CISCC) of dry canisters was insufficient at the meeting. We invite the Board to reach out to the DOE team requesting more information or to schedule further time to discuss the issue at the Board's convenience.

We look forward to further engagement with the Board on these extremely important issues in the future.

Sincerely,

John F. Kotek
Acting Assistant Secretary
for Nuclear Energy

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

May 23, 2016

Mr. John Kotek
Acting Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Mr. Kotek:

The Nuclear Waste Technical Review Board (Board) held its 2016 Winter Meeting in Knoxville, Tennessee, on February 17, 2016, to review U.S. Department of Energy (DOE) research and development activities related to the performance of high-burnup[1] commercial spent nuclear fuel (HBF) during storage and transportation. The public meeting included speakers from DOE, the U.S. Nuclear Regulatory Commission, and national laboratories. Based on presentations given at the meeting, the Board offers several observations and recommendations noted below. Because of the large scope of HBF research activities and the time limitations of a one-day public meeting, not all research topics were discussed. Therefore, the Board plans to conduct follow-up discussions with DOE and laboratory technical experts to obtain additional information. The Board's staff are in contact with your staff to make the needed arrangements.

The Board recognizes the level of effort and coordination required to prepare for a public meeting of this type and thanks your staff and the technical experts from the national laboratories for their work preparing for the meeting and providing informative presentations. The meeting agenda, presentation slides, transcript, and an archived version of the meeting webcast are all available on the Board's website at www.nwtrb.gov/meetings.

In conjunction with the public meeting, several Board members and staff members toured some of the facilities at the Oak Ridge National Laboratory (ORNL) on February 16, 2016. The tour was planned and coordinated by Mr. Rob Howard of ORNL and was extremely informative. The ORNL staff involved in the tour described HBF testing equipment and research, which was very helpful to the Board members in understanding the unique issues involved with testing irradiated material. The laboratory tour was also particularly useful in providing a perspective for the research activities discussed during the Board's public meeting.

Background

History. Dry storage of commercial spent nuclear fuel (SNF) began in the 1980s when utilities needed to remove relatively low-burnup fuel[2] from the spent fuel storage pools at reactor sites to allow space for additional SNF to be stored from reactor operations. Extensive analysis, testing,

---

[1]Burnup is a measure of the amount of thermal energy produced per unit mass of nuclear fuel. In the U.S., "high-burnup" fuel is defined as fuel with a burnup greater than 45 gigawatt-days per metric ton uranium (GWd/MTU).
[2]In the early 1980s, SNF burnup was typically limited to 35 GWd/MTU.

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

and modeling were conducted to determine the potential degradation mechanisms and changes in SNF cladding mechanical properties during both normal and accident conditions of storage and transportation. Based on the early studies of fuel with burnups of less than 35 GWd/MTU, researchers concluded that no change in the condition of the low-burnup fuel was expected during dry storage and transportation. Subsequently, two complicating issues arose in extending the earlier conclusion to HBF.

The first issue is the evolving condition of the SNF in dry storage systems. For example, at a Board meeting held in Las Vegas in 2009, a panel composed of representatives of nuclear utilities, a firm that makes dry storage systems for SNF, and the Electric Power Research Institute concluded that understanding the evolving condition of the SNF in dry storage systems is important because it must be shipped, possibly repackaged, and eventually disposed of after a potentially long period in dry storage. The technical implications of long-term dry storage had not been previously investigated. The Board continued its review of extended storage activities and documented its findings and recommendations in a 2010 report, *Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel.*

A second issue also arose when fuel manufacturers introduced fuel assembly designs that allowed the fuel to reach higher burnups. As fuel burnups increased, changes in the fuel occurred more rapidly than had been observed previously, such as increased mass concentration of metal hydrides in the cladding and higher internal fission gas pressure, As a result, the cladding may be subjected to increased stress. These changes appear in fuel with burnups above 45 GWd/MTU and usually increase with burnup.

The increased mass concentration of metal hydrides in the cladding and their orientation will, to varying degrees, reduce the ductility of the cladding (the ability of the cladding to stretch while retaining its integrity, as opposed to fracturing). Initially, the metal hydrides in the cladding are in the form of platelets aligned as along the direction of the rim of a wheel (circumferential hydrides) when the SNF cools during pool storage. However, when SNF is loaded into dry-storage canisters and vacuum-dried, the fuel temperature temporarily increases significantly, causing greater internal rod pressure and greater stress on the cladding. When the cladding cools following canister loading, drying, and sealing in a storage cask, the hydrogen will precipitate again as hydrides, but may be in the form of platelets aligned as in the direction of the spokes of a wheel (radial hydrides). This phenomenon is called hydride reorientation. The cladding may become more brittle (embrittlement) than with only circumferential hydrides. When the applied stress due to internal pressure and external loads during transportation is perpendicular to the radial hydrides, the cladding is more susceptible to fracturing during handling and transportation to an extent depending on many factors.[3]

Well-established models of hydride reorientation and internal pressure effects can predict the embrittlement behavior of low-burnup fuel. However, these models have not been adapted to and verified for HBF. As a result, DOE undertook more work to determine the applicability of the existing embrittlement models to HBF during extended dry storage and to determine the implications of model results for the probability and consequences of degradation of HBF during subsequent normal transportation operations or transportation accident conditions.

[3] See Dr. Louthan's presentation at the Board's February 17, 2016, meeting.

Current Research Activities In response to growing uncertainties about the performance of HBF during extended storage and subsequent operations, DOE initiated new research efforts. Three of the more significant DOE efforts are the High Burnup Dry Storage Cask Research and Development Project (HDRP),[4] the study of vibrational loads on SNF expected during rail or road transportation, and research to better understand the effects of hydride reorientation on cladding embrittlement. These three efforts were discussed at the Board's public meeting in Knoxville and are summarized in the following subsections.

High Burnup Dry Storage Cask Research and Development Project — Dr. Brady Hanson of the Pacific Northwest National Laboratory (PNNL) presented an update on the HDRP during the Knoxville meeting. In this project, Dominion Virginia Power will load a dry storage cask, modified to include instrumentation, with a variety of HBF assembly types, take initial cask gas samples, seal the cask, and store it for ten years while monitoring fuel temperatures. After ten years in storage, DOE plans to open the cask and withdraw selected fuel rods to undergo characterization in hot cells.

DOE removed 25 "sister rods" from the SNF assemblies that will be placed in the HDRP dry storage cask or from assemblies of the same design and with the same operational power history as the assemblies to be placed in the HDRP dry storage cask. The sister rods will be characterized in hot cells at ORNL and PNNL. The characterization effort will determine the initial characteristics of the sister fuel rods for comparison with the final characteristics of the fuel rods to be withdrawn from the HDRP cask after ten years of dry storage.

In early 2014, the Board provided comments on the HDRP in a letter to DOE Assistant Secretary Peter Lyons during the initial planning stage of the HDRP.[5] Three Board observations from the letter were the need to: 1) use passive instrumentation that can be attached to or installed in the cask to monitor the condition of the HBF, 2) conduct more than one dry storage cask demonstration or examine the condition of the fuel and storage system materials in several casks that contain SNF and have a range of burnups and storage histories, and 3) place a high priority on establishing the capability and infrastructure to receive and open dry storage casks to examine HBF in a dry environment. *Time constraints during the Knoxville meeting prevented full discussion of all these topics. Therefore, the Board plans to include these topics in the follow-up discussions with DOE and laboratory technical experts.*

Vibrational Effects — Results from the second DOE effort, vibrational effects research, were presented by three speakers[6] at the Knoxville meeting. This research is designed to obtain data concerning the effects of the stresses that HBF will experience during transportation. This effort includes tests to determine the number of vibrational cycles that will lead to cladding failure for fuel rods under a variety of vibrational stresses. In addition, measurements of actual road vibrational loads to which the fuel rods will be subjected were made using simulated casks and

---

[4] See the *High Burnup Dry Storage Cask Research and Development Project, Final Test Plan*, Rev. 0, February 27, 2014, Electric Power Research Institute.

[5] Letter to Dr. Peter Lyons, *Comments on the DOE Research and Development Program Related to Long-Term Dry Storage of High Burnup Spent Nuclear Fuel*. June 5, 2014.

[6] Drs. Bevard, McConnell, and Tang.

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

payloads. DOE plans call for measurement of vibrational loads to which SNF will be subjected during transportation to be made in the near future using a full-size rail cask.

Hydride Reorientation — Dr. Mike Billone of the Argonne National Laboratory, and Dr. Mac Louthan, a consultant to the Savannah River National Laboratory, discussed research on hydride reorientation. This effort includes research to better understand changes in cladding properties and degradation mechanisms during storage and transportation due to hydride reorientation, and the resulting implications for cladding embrittlement.

Board Observations and Recommendations

Although the presentations at the meeting in Knoxville provided the Board with insight into a number of the important scientific issues, these issues need to be framed in the context of risk by addressing components of risk:[7]

- **What can go wrong?** For example, what degradation of HBF cladding might occur, leading to an unsafe condition (*e.g.*, HBF cladding rupture and release of radioactive material)?
- **How likely is it?** For example, what is the probability that HBF cladding will degrade due to embrittlement and fracture from the loads imposed on the HBF during normal and accident conditions of storage and transportation?
- **What are the consequences?** For example, what would be the result of HBF cladding failure in terms of release of radioactive material and radiation exposure to workers and the public?

Recommendation 1 - The Board recommends that the research program be structured such that the focus is on the likelihood and consequences of cladding failure during interim storage, transportation, possible repackaging, and eventual disposal of HBF in a repository.

<u>Relating Behavior of Unirradiated Cladding to Irradiated Cladding</u>. The Board recognizes that testing irradiated fuel and cladding is extremely difficult and expensive. It is very costly to maintain the facilities and equipment required to conduct tests on irradiated material and, as a result, the test data are scant. Moreover, the data available from testing irradiated cladding have a built-in uncertainty due to the variability of the type of cladding and its characteristics after irradiation. For example, in irradiated fuel rods, there is variability in cladding hydride mass concentration in the radial, axial, and circumferential directions. The applicability of the resulting data-dependent models may be limited to only the cladding types and burnups from which a significant amount of experimental data were obtained.

Testing unirradiated materials[8] is significantly easier and less expensive than testing irradiated materials, as testing can be conducted in unshielded facilities where equipment is much easier to

---

[7] S. Kaplan and B. J. Garrick, "On the Quantitative Definition of Risk", *Risk Analysis*, Vol. I, No. I, 1981.

[8] In this letter, the term "unirradiated materials" also includes ion-beam-irradiated materials, which are not as radioactive as reactor-irradiated materials and can be characterized more easily than reactor-irradiated materials.

maintain. Consequently, more material types, specimens, and conditions can be tested, and there is the added benefit that testing can also be done in university facilities where costs are lower and the next generation of nuclear materials scientists is being trained.

However, the data obtained from research conducted on unirradiated fuel and cladding need to be defensibly related to the actual behavior of irradiated SNF during storage and transportation. This was one of the major conclusions Dr. Mac Louthan presented in his talk[9] analyzing the outcome of the DOE-sponsored American Society for Testing and Materials meeting[10] on hydride reorientation in Jackson Hole, Wyoming, in June 2014. In its follow up discussions with DOE, the Board plans to include discussion of the applicability of current and future models to other zirconium cladding compositions such as Ziron (Zr-1%Fe) irradiated under different conditions.

Recommendation 2 - The Board recommends that DOE develop a physical-chemical model that relates the behavior of unirradiated cladding to the behavior of irradiated cladding. This work should also include experimental work to test the model's predictions and evaluate the associated uncertainties.

High Burnup Dry Storage Cask Research and Development Project. The presentations by Mr. Ned Larson of DOE and Dr. Brady Hanson of PNNL mentioned that the goal of the HDRP was to "collect data to validate and confirm the technical basis for extended storage of high-burnup spent fuel." The Board interprets this statement to mean that the ongoing DOE work is aimed at confirming the view of DOE and others that the existing understanding of low-burnup fuel forms a reliable basis for predicting the behavior of HBF during extended storage and transportation.

The Board notes that focusing on confirming the current understanding and assumptions can narrow the focus of research and development, which may mean that other potentially important degradation mechanisms and processes are not identified. Additionally, time did not allow full discussion of the HDRP's plans to potentially obtain gas samples from the dry storage cask during the ten-year storage period or to examine the fuel rods to be extracted from the dry storage cask after ten years of storage. These are aspects of the HDRP the Board intends to discuss with DOE and national laboratory technical experts during the follow-up discussions.

A number of studies on HBF characterization and performance are being conducted in other parts of DOE or other national laboratory programs and by other countries. Mr. Larson noted that the DOE Office of Nuclear Energy is funding university research through its Nuclear Energy University Programs. It was not clear how the results of these studies were used, or will be used, in the overall technical evaluation of HBF performance. The Board believes all sources of relevant information should be considered when drawing technical conclusions and will discuss this issue in the follow-up discussions with DOE and the national laboratory technical experts.

---

[9] Dr. Louthan stated that the conclusions were his and did not necessarily reflect the DOE position.

[10] 2nd ASTM International Workshop on Hydrides in Zirconium Alloy Cladding, June 10, 2014, Jackson Hole, WY

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

Recommendation 3 - The Board recommends that DOE make transparent how it integrates the results from Nuclear Energy University Programs, and other relevant U.S. and foreign research activities into its overall research program on HBF degradation.

Focus of the Board Follow-up Discussions with DOE

As noted above, time constraints during the meeting on February 17, 2016, meant that not all of the issues associated with HBF performance during storage and transportation could be discussed fully, and some were not discussed at all. Consequently, the Board is planning additional discussions with representatives of the DOE Office of Nuclear Energy and their technical experts from the laboratories. The follow-up issues include, for example, the effect of vibrational loads measured in road and rail transportation tests on the probability of degradation of cladding during normal transportation conditions, the consequences of cladding degradation, the applicability of cladding embrittlement data obtained from testing unirradiated cladding to embrittlement of irradiated cladding, details of the characterization of the "sister rods" planned at ORNL and PNNL and how the resulting data will be used, and details of plans for gas sampling in the HDRP cask

These additional discussions will provide insights necessary for the Board to review the DOE program that addresses research and development related to HBF extended storage and transportation. In addition, the Board will want to discuss the thermal and structural modeling efforts related to HBF cladding degradation during dry storage and transportation.

On behalf of the Board, thank you again for the participation of the DOE Office of Nuclear Energy staff and technical experts from the national laboratories at the February meeting. We look forward to your response to the Board's recommendations.

Sincerely,

Rodney C. Ewing
Chairman

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

June 3, 2016

Mr. John Kotek
Acting Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Re: U.S. Nuclear Waste Technical Review Board Comments on *Post Irradiation Examination Plan for High Burnup Demonstration Project Sister Rods*

Dear Mr. Kotek:

In accordance with its mandate to review the technical and scientific validity of activities undertaken by the Secretary of Energy related to nuclear waste management, the U.S. Nuclear Waste Technical Review Board (Board) reviewed the report *Post Irradiation Examination* [PIE] *Plan for High Burnup Demonstration Project Sister Rods.*[1] The PIE plan describes the characterization and experimental test activities proposed to be undertaken on 25 high-burnup spent nuclear fuel (SNF) "sister rods" having characteristics similar to SNF "test rods"[2] being used in the High Burnup Dry Storage Cask Research and Development Project (HDRP). According to the report, these activities will be part of a multiyear experimental program to collect data needed to understand important changes that may occur in high-burnup fuel and cladding behavior during long-term dry storage. In this letter, the Board provides initial high-level comments on the PIE plan. In two previous letters to the Department of Energy (DOE),[3,4] the Board commented on the draft test plan[5] for the HDRP and on the broader DOE Office of Nuclear Energy research and development program related to extended storage of SNF.

The Board believes the characterization and experimental test activities described in the PIE plan will provide important data on potential degradation of high-burnup SNF (HBF) during extended storage. However, the Board believes that the plan should be revised to address a number of additional issues.

1. **Justification for Proposed Sister Rod Examinations and Testing –** The PIE plan proposes an extensive suite of non-destructive and destructive tests on the sister rods.

[1] Scaglione, J.M., R.A. Montgomery, and B.B. Bevard. 2016. *Post Irradiation Examination Plan for High Burnup Demonstration Project Sister Rods*, FCRD-UFD-2016-000422, ORNL/SR-2016/111, April 1.
[2] Rods that will be removed from the HDRP cask after 10 years.
[3] Ewing, R.C. 2014. Board letter to Dr. Peter Lyons with comments from November 2013 Board meeting (January 29, 2014). http://www.nwtrb.gov/corr/rce019.pdf.
[4] Ewing, R.C. 2014. Board letter to Dr. Peter Lyons with comments on long-term dry storage of high-burnup spent nuclear fuel (June 5, 2014). http://www.nwtrb.gov/corr/rce024.pdf.
[5] Electric Power Research Institute, 2014. *High Burn-up Dry Cask Research and Development Project – Final Test Plan*, January 20.

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

However, it is not evident how the results from each test will be used to fill the information gaps identified in previous reports (*e.g.*, FCRD-UFD-2014-000050, *Used Nuclear Fuel Extended Storage and Transportation R&D Review and Plan*, August 9, 2014). The PIE plan should a) link each proposed test to one or more information gaps identified in the most recent gap analysis and b) explain how the results of each proposed test will be used to fill the gap or support modeling of HBF performance during dry storage.

2. **Establishing a Baseline**[6] – The PIE plan should emphasize, as the first priority, the characterization necessary to establish a baseline for the HDRP and should show how the results will be used to assess degradation of the test rods from the HDRP cask. It is expected that, at a minimum, profilometry, visual inspection, gamma scans, measurement of fission gas release, microscopy, and characterization of mechanical properties will be necessary. Any additional techniques should be justified as described in Item #1.

3. **Whole Rod Heating Tests** – The PIE plan includes heating some of the sister rods to simulate the temperature changes experienced by the fuel in the storage cask, followed by monitoring those rods until the end of the HDRP. Assuming this is the case, the PIE plan should provide details on a) the purpose of the tests, b) how measurements on the conditions inside the test cask (*e.g.*, temperature, radiation, gas composition) will be obtained, and c) how the conditions to which the sister rods are exposed will be simulated to match those in the test cask. If the heat-treated rods will not be stored under conditions similar to those for the test rods, then the relevance of the test needs to be explained.

4. **Test Method Verification** – All test methods to determine mechanical properties of the cladding that are not currently approved by the ASTM should be fully developed and verified to assure that they produce valid data that will be defensible and acceptable to regulators. The PIE plan could be streamlined by eliminating duplicative mechanical properties testing activities that do not meet this criterion.

5. **Preservation of Sister Rods** – Obtaining and characterizing the sister rods will be an expensive undertaking. These rods constitute a valuable resource for research and development to meet presently unforeseen needs related to SNF management and disposal in the future. DOE should consider preserving selected sister rods, or rod segments and components, for future use.

6. **Low Temperatures in the HDRP Cask** – The Board is concerned that the maximum cladding temperature in the HDRP predicted by modeling is substantially below what was originally anticipated. One study now estimates the maximum cladding temperature will be below 280°C[7]. This calls into question the usefulness of the HDRP to determine the effects of hydride reorientation during storage of HBF, which might experience temperatures as high as 400°C. Before any fuel is loaded into the HDRP cask or sister rod characterization is initiated, the Board recommends that DOE look into methods to

---

[6] The characteristic of the fuel as it is placed in the dry storage cask for the purpose of comparing the characteristics of the test rods after 10 years to determine if any degradation has taken place.

[7] Hanson, B., *Peak Cladding Temperatures: Conservative Licensing Approach vs. Actual* PNNL-SA-117853, presented at the Nuclear Energy Institute Used Fuel Management Conference, May 3, 2016, Orlando, FL

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

raise the cladding temperatures, for example, by means external to the cask or including some fuel assemblies with shorter cooling times. If the maximum cladding temperature cannot be raised, DOE should re-evaluate the utility of the HDRP as planned and consider delaying the project until the issues associated with maximum temperature can be resolved.

7. **Modeling** – DOE should undertake a detailed analysis of how the data obtained from the HDRP and the sister rod testing program will be used to develop models for the behavior of spent fuel rods under other conditions reflective of the expected population of HBF in dry storage. This would include rods that have other cladding types, have been irradiated to higher burnups, or have experienced higher cladding temperatures.

This letter contains only the Board's most important comments to ensure that you receive them before your June 6th meeting to review the sister rod PIE plan. The Board looks forward to receiving the next revision of the plan in sufficient time to review it prior to the upcoming technical fact-finding meeting with DOE and its technical experts on July 12–14, 2016.

Sincerely,

Rodney C. Ewing
Chairman

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

Department of Energy
Washington, DC 20585

RECEIVED JUN 1 3 2016

June 9, 2016

Rodney C. Ewing, Ph.D.
Chairman
U.S. Nuclear Waste Technical Review Board
2300 Clarendon Blvd.
Suite 1300
Arlington, VA 22201

Dear Dr. Ewing:

The Department of Energy (Department) appreciates our meeting with you and staff of the U.S. Nuclear Waste Technical Review Board (the Board) to discuss the recent report, *Technical Evaluation of the U.S. Department of Energy Deep Borehole Disposal Research and Development Program*. The Department has carefully reviewed the report to understand the insights and conclusions.

I'm pleased to report that many of the Board's suggestions have already been included in the plans for the Deep Borehole Field Test (DBFT), a program designed to evaluate the technical and programmatic feasibility of the deep borehole disposal concept. A general response to the Board's report is presented in the context of the DBFT as Enclosure 1. The Board's report identified four findings and made nine specific recommendations; our detailed responses to these are included in Enclosure 2. I should note that we find the report potentially misleading and open to interpretation regarding our plans for the DBFT. I should also note that while many of the experts expressed their opinions regarding borehole disposal at the workshop, few made the clear distinction between what was appropriate for the DBFT (which does not involve radioactive waste) and an actual waste disposal facility based on the borehole concept. We are incorporating into our plans the Board recommendations that are consistent with both the research focus of the DBFT and DOE's budget and schedule considerations that constrain the DBFT.

The Department recognizes that there is much work to do to bring about disposal of high-level radioactive waste and spent nuclear fuel, and we acknowledge the Board's many contributions in helping us to evaluate various disposal concepts, including the deep borehole. If you have any question about our responses, please contact Andrew Griffith at (202) 586-3715.

Respectfully,

John F. Kotek
Acting Assistant Secretary
for Nuclear Energy

Enclosures

Printed with soy ink on recycled paper

Enclosure 1

DOE's Summarized Response to the NWTRB Report on the DOE Deep Borehole Disposal Research and Development Program

The overall objective of the Deep Borehole Field Test (DBFT) is to demonstrate and evaluate technologies necessary for determining the feasibility and safety of deep borehole disposal for practical and safe disposal of smaller DOE-managed waste forms. In October 2015, at the Nuclear Waste Technical Review Board (NWTRB) International Technical Workshop on Deep Borehole Disposal of Radioactive Waste, and in prior DOE reports and presentations, DOE described planned DBFT activities to achieve this overall objective (see the References section at the end of this summary). These activities are for the most part consistent with those recommended by the NWTRB in their recent report, *Technical Evaluation of the U.S. Department of Energy Deep Borehole Disposal Research and Development Program*, January 2016. The DBFT is not intended to characterize a specific location as a potential disposal site. DOE will limit the scope of its research and demonstration activities and DBFT data collection to what is needed to evaluate the technical feasibility of the deep borehole disposal concept.

The DBFT scope is focused on achieving the following field test objectives (MacKinnon, 2015 and Sassani and Hardin, 2015):

1. Obtain a suitable test site
2. Design, drill and construct the Characterization Borehole (CB) to requirements
3. Collect data in the CB on geological, geomechanical, geochemical, and hydrologic conditions in the crystalline basement
4. Design, drill and construct the Field Test Borehole (FTB) to requirements
5. Design, develop, and demonstrate surface handling and emplacement equipment systems, test packages, and operational methods for safe canister/ package handling and emplacement with analyses of associated risks
6. Conduct generic post-closure safety analyses, utilizing DBFT data sets
7. Evaluate the feasibility and safety of the deep borehole disposal concept for disposal of smaller DOE-managed waste forms

These objectives will be accomplished by a DBFT team of recognized US and international experts with extensive experience in drilling, down-hole operations and testing, site characterization, safety assessment, and project management. This team includes the DBFT Contractor Team (Battelle Memorial Institute, Schlumberger, Solexperts AG), DOE, and technical experts from DOE National Laboratories (SNL, LANL, LBNL, ORNL, PNNL). A Technical Advisory Committee (TAC) will be established to monitor field test activities, especially during drilling and testing, and ensure the necessary data and information is collected. The membership of the TAC shall include key members of the DBFT team, and/or other external experts as necessary. *DOE does not believe, as recommended by the NWTRB, that it is necessary to have an additional group of experts review the drilling program design and implementation, nor is it necessary for an independent group to report on the field test to the Secretary of Energy.*

Descriptions of how each of these objectives will be accomplished are summarized below. Contrasts between the DBFT and actual disposal activities are included in the following

2

summary along with remarks (noted in italics) related to recommendations made by the NWTRB.

Field Test Objective 1: Obtain a suitable test site

A number of geological, hydrogeological, and geophysical characteristics have been evaluated that are relevant to successfully completing the DBFT, and are derived from those delineated for post-closure safety for a deep borehole disposal system. This evaluation has produced guidelines for selecting a suitable site based on existing geologic information (see Arnold et al., 2014 and Sassani and Perry, 2015). These guidelines were developed with the primary goal of identifying potential favorable sites that appear to have a crystalline basement geology relatively isolated from the associated subsurface hydrogeologic system and biosphere. DBFT site selection will be based on existing geologic information and an evaluation of how well the site meets the guidelines. *In addition, DOE has concluded that for the specific purposes of the DBFT, the likely value of information gained at depths of 3-5 km from surface-based techniques does not warrant the expense of surface-based geophysical investigations at the scale the NWTRB envisions or recommends.* The need for and use of geophysical investigations in the context of the DBFT and deep borehole disposal are discussed further in the following paragraph.

Note that the DBFT has the objective of specifically addressing key data necessary to evaluate the feasibility of the deep borehole disposal concept, particularly unproven or especially critical components (e.g., collecting diagnostic geochemical and environmental tracer profiles from deep low-permeability crystalline rocks – See Field Test Objective 3), but does not address broader objectives that would be required for site characterization supporting actual implementation of a deep borehole disposal facility. For example, selection of a site suitable for an actual disposal facility would potentially involve site characterization investigations prior to drilling (e.g., surface-based and/or airborne geophysical surveys), but a decision to conduct such investigations would depend on the geologic information already available (e.g., indications of through-going faults or fracture zones), on the disposal safety case for that site, and on the needs of particular stakeholders.

To summarize, the DBFT will include sampling and testing of formations in the crystalline basement to detect and characterize discontinuities that intersect the borehole if they are present. However, surface-based geophysics, multi-borehole studies, and extensive downhole testing to characterize larger-scale, distal discontinuities that may be present, are not planned. If data from the crystalline basement hydrogeologic system (see Field Test Objective 3) indicate that it has direct/active connection to shallow meteoric groundwater aquifers and/or the biosphere, then additional activities could focus on identifying the transport pathway. For a potential disposal site, identification and characterization of potentially significant transport pathways could be carried out using conventional approaches such as: additional boreholes; surface, downhole, and cross-hole geophysical techniques; and borehole tracer and pressure tests. *DOE does not currently plan to use the characterization and field test boreholes to conduct cross-hole monitoring to provide information on the characteristics of the rock volume surrounding the boreholes*. However, if the deep borehole disposal concept is determined to be feasible, DOE may choose to conduct such a study in the future.

Field Test Objective 2: Design, drill and construct the Characterization Borehole to requirements

This objective is to demonstrate, using existing technology, that a borehole having a bottom-hole diameter of 8.5 inches, with a specified maximum deviation, can be drilled to a depth of 5 km (with the last ~ 3 km in the basement), cased, and cemented to requirements. A preliminary design for the CB has been developed and documented (Kuhlman et al., 2015). Kuhlman et al. (2015) focuses on the conceptual design requirements of the DBFT, specifically the construction and completion of the CB and the FTB, as well as the characterization activities to be performed in the CB. The final design for the drilling and construction of the CB is being developed by a team including Battelle Memorial Institute, Schlumberger, Solexperts AG, DOE, and National Laboratory personnel and will be described in detail in the final Drilling and Test Plan (D&TP).

Field Test Objective 3: Collect data in the Characterization Borehole on geological, geomechanical, geochemical, and hydrologic conditions in the crystalline basement

The primary focus of this objective is to identify and evaluate key characteristics of the basement that are important to the safety of the concept and long-term waste isolation (MacKinnon, 2015 and Sassani and Hardin, 2015). *This objective is consistent with the NWTRB recommendation that the project team carefully consider the key parameters for the safety case that need to be measured during sampling and testing in the 2- to 5-km (1.2- to 3.1-mi) depth range encompassing the seal and disposal zones.* These characteristics include: ancient age of formation fluids that would indicate a system that has been isolated hydrologically from the biosphere (i.e., local, rock-dominated conditions) for millions of years; geochemically reducing conditions in the rock-brine system that would substantially inhibit mobilization of many important radionuclides; increasing brine density with depth that would act counter to any thermally-driven buoyancy flow that may enhance transport of radionuclides to the biosphere during the short-lived thermal period; and very low basement rock permeability. These key characteristics have been observed in previous studies of crystalline basement formations in the US, Canada, and Europe and are expected to exist at the suitable DBFT site. Data will be collected to evaluate:

- Deep groundwater in the crystalline basement to assess if it is very old, saline, dominated by rock reactions (i.e., rock equilibrated), and reduced/reducing;
- Formation fluid pressure, to check whether an ambient fluid potential gradient exists to drive flow from the deep disposal zone to the shallow subsurface (i.e., over-pressured conditions present at depth), or conversely, if under-pressured conditions exist in the crystalline basement hydrology (which would be favorable for isolation);
- Bulk permeability properties of the host rock and of the borehole disturbed rock zone (DRZ), if one exists, to assess disturbed transport properties (i.e., permeability at the borehole scale, rather than the core scale); and
- Uncertainty and variability in data, to assess data transferability and to support site-specific numerical models of waste isolation performance (i.e., geochemical, thermal, geomechanical, geohydrological properties and constitutive laws) and post-closure safety.

The types of data and the technologies needed to collect them (as the borehole is being drilled and after borehole completion) have been identified and described by Kuhlman et al. (2015). The types of data to be collected as a function of depth will focus on providing data *for key parameters for the safety case* and include:

- Crystalline basement faults and fractures near the borehole
- Lithology and stratigraphy
- Physical and transport parameters
- Geochemical parameters
    - Fluid composition
    - Stable isotope ratios (e.g., ^{2}H, ^{18}O)
    - Uranium decay series isotope ratios
    - Strontium isotope ratios
- Geomechanical parameters
- Environmental tracer transport parameters

The subsurface geology and variable in situ conditions at depth will be developed from existing data and from new characterization data from the DBFT, and will be organized and synthesized in the form of a three-dimensional site geologic framework model. This model will include heterogeneity and variability in geologic properties consistent with the collected and available information and will provide data transparency and facilitate data access. Key geologic inputs for the geologic framework model include the stratigraphy and any known structures of the selected area, with a focus on the depth to the crystalline basement, mineralogy and rock fabric/texture, identified aquifers and permeable zones, stress regime, physical rock properties, and the scale of heterogeneity within rock units. *The data will be used to provide key inputs for post-closure safety assessment modeling efforts and to address technical and scientific issues related to the potential heterogeneity of the subsurface geology and complex in situ conditions a depth.*

As summarized above, the focus of DOE's field test will be to collect data and conduct analyses that are in large part consistent with that recommended by the NWTRB. However, again it is emphasized that DOE will limit the scope of its DBFT data collection to that needed to evaluate the feasibility of the deep borehole disposal concept, which is a lesser scope than would be needed to fully characterize a disposal site.

<u>Field Test Objective 4: Design, drill and construct the Field Test Borehole to requirements</u>

The primary goal of this objective is to evaluate whether, using existing technology, a borehole having a bottom-hole diameter of 17 inches, with specified maximum deviation and dogleg severity, can be drilled to a depth of 5 km (with the last ~ 3 km in the basement), and completed to requirements that allow safe emplacement of surrogate waste packages to depths between 3 and 5 km. A preliminary design for the FTB has been developed and documented (Kuhlman et al., 2015). The process for developing the final design and the drilling and test plan (D&TP) for the FTB will use experts from contractors, National Laboratories, and DOE similar to that described above for the CB.

Limited subsurface characterization is planned for the FTB, and planned characterization will focus on evaluating the quality of the FTB construction. Note that in an actual disposal facility some downhole characterization might be included depending on the distance from other boreholes, and geologic characteristics of the site. *In addition, DOE does not currently plan to conduct on-going subsurface monitoring in the FTB after emplacement testing, as was*

5

recommended by the NWTRB, primarily because of the limited value of information that could be collected within the time frame of the DBFT as currently planned. However, if the deep borehole disposal concept is determined to be feasible and the FTB is not closed at the end of the DBFT, DOE may choose to conduct a monitoring study in the future.

Field Test Objective 5: Design, develop, and demonstrate surface handling and emplacement equipment systems, test packages, and operational methods for safe canister/package handling and emplacement with analyses of associated risks

The scope of this objective is to design, build, and operate a system that represents what could be used for an actual disposal system and radiological operations involving radioactive waste. The extent of this system and the field test is limited to evaluating and demonstrating system elements and safe handling operations that are unique to deep borehole disposal, such those involving the interface between cask unloading, borehole emplacement of test packages, and retrieval of test packages. Wireline emplacement of test packages will be demonstrated in the field test. This mode of emplacement was selected based on the evaluation of cost and risk described in SNL (2015). An evaluation of this work is documented in a report by AREVA (2016). DOE will develop a description of the handling operations and system elements that will be utilized in the DBFT prior to implementation. *Risk analyses will be conducted for handling and emplacement operations and important potential accident scenarios, but these analyses will be limited to operations unique to deep borehole disposal and wireline emplacement. DOE does not plan to conduct a comprehensive assessment of other modes of emplacement as recommended by the NWTRB but may consider doing such assessments in the future if the concept of deep borehole disposal is determined to be feasible.* Safe handling of nuclear materials under a variety of handling and transportation conditions is a well-developed discipline and DOE and its interdisciplinary team have high confidence that safe engineering solutions for a complete transportation, surface handling, and emplacement system can be developed if the deep borehole disposal concept is determined to be feasible and DOE decides to pursue disposal of DOE-managed waste forms in deep boreholes. DOE does plan to develop a description of upstream system components and operations for smaller DOE-managed waste forms (Price et al., 2015).

To support the design of a seal system for potential future disposal boreholes, the DBFT will include laboratory studies to evaluate sealing materials at representative temperature, pressure, salinity, and geochemical conditions. *The current field test plan does not include field testing of borehole seals or sealing methods as recommended by the NWTRB. However, DOE will consider such testing if it is determined that field testing is required to complete the evaluation of feasibility. This determination and the design of field testing will require data and analysis and therefore borehole sealing materials and emplacement configurations will be examined in parallel with DBFT field operations, starting from the reference seal design in Arnold et al. (2011) and Hardin (2015).*

Key components of the DBFT seals effort will include:

- Review of borehole seal practices in other borehole-related disciplines such as CO2 sequestration, deep well injection of hazardous wastes, and oil and gas production
- Development of sealing requirements and seal emplacement methods
- Experimental analysis of bentonite alteration and steel corrosion under borehole conditions

6

- Evaluation of seal-DRZ interface properties for conventional sealing materials
- Consideration of new sealing approaches including novel cements and thermite plugs
- Laboratory verification of rock weld properties

Eventually, the DBFT boreholes may be made available to the scientific and engineering R&D community as a deep borehole underground laboratory. *If the deep borehole disposal concept is determined to be feasible, in situ tests of seal emplacement and performance can be conducted when planned DBFT activities have concluded.*

Field Test Objective 6: Conduct post-closure safety analyses

The post-closure safety case for deep borehole disposal relies primarily on the long-term isolation of the deep geologic environment of the crystalline basement. A key element of the safety case is the demonstration that deep groundwater is very old and has been isolated from the surface or near-surface for very long periods of time (on the order of 10^6 years or longer). The DBFT will evaluate deep groundwater age from geochemical indicators such as salinity, and from isotopic indicators using environmental tracers such as noble gases. High salinity at depth also indicates old groundwater and precludes use of deep groundwater as a drinking water source. Increasing salinity with depth promotes stable stratification based on fluid density, and tends to oppose upward thermal convection from waste heat. Absence of over-pressured conditions at depth is expected at favorable locations for deep borehole disposal. The bulk permeability of deep crystalline rocks is generally very low and decreases with depth. The effectiveness and durability of borehole seals through the period of upward thermal convection are also elements of the safety case and are addressed through a borehole disposal concept that includes multiple barrier seal materials in the borehole above the waste disposal zone. *The post-closure safety case does not rely on waste form and waste package performance because of the isolation capabilities of the deep geologic environment of the crystalline basement.*

Post-closure safety of the deep borehole disposal concept will be evaluated with a comprehensive three-dimensional probabilistic post-closure safety assessment model using the geologic framework model and characterization data developed under Field Test Objective 3. A Features, Event, and Process (FEP) screening approach (Freeze, 2015) will be conducted to determine those FEPs that will be included in the safety assessment model. *DOE does plan to adequately assess coupled processes and the impact of drilling on the natural geologic system, and this FEPs screening process will include evaluation of coupled processes, system heterogeneities, and the impact of drilling on the natural geologic system.* A suite of safety analyses will be conducted to evaluate the long-term performance of a hypothetical deep borehole disposal facility having a geologic system consistent with the DBFT site. Smaller DOE-managed waste forms will be considered as candidate waste forms for disposal. *Alternative scenarios will be considered for accidents such as stuck and abandoned waste packages and geologic conditions that include possible enhanced/additional transport pathways in crystalline basement discontinuities such as fractures and faults. In addition, , if the deep borehole disposal concept is found to be feasible the DOE may evaluate the potential safety benefits of robust waste forms and waste packages in its suite of planned safety analyses.*

Field Test Objective 7: Evaluate the feasibility and safety of the deep borehole disposal concept

This objective will be achieved by synthesizing field test activities, test results, and safety analyses into a comprehensive evaluation of concept feasibility. Data and experience that will be evaluated include data gathered during site characterization, experience gathered during drilling and borehole construction, data gathered during physical demonstration of surface handling and borehole emplacement and retrieval operations, pre-closure safety analyses, and post-closure safety analyses.

References

Reports

AREVA Federal Services, LLC, 2016. *Task Order 22 - Engineering and Technical Support, Deep Borehole Field Test: AREVA Summary Review Report*. RPT-3014934-000. January.

Arnold, B.W. *et al.* 2011. *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2011-6749. October.

Arnold, B.W. *et al.* 2012. *Research, Development, and Demonstration Roadmap for Deep Borehole Disposal*. SAND2012-8527P. August 31.

Arnold, B.W. et al., 2014. *Deep Borehole Disposal Research: Geological Data Evaluation, Alternative Waste Forms, and Borehole Seals*. FCRD-USED-2014-000332. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition.

Cochran, J. and E. Hardin, 2015. *Handling and Emplacement Options for Deep Borehole Disposal Conceptual Design.* SAND2015-6218

Hardin, E.L., 2015. *Deep Borehole Field Test Specifications*, FCRD-UFD-2015-000132. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition.

Hardin, E. 2015, *Deep Borehole Field Test Requirements and Controlled Assumptions*. SAND2015-6009, July.

Kuhlman, K. et al., 2015. *Conceptual Design and Requirements for Characterization and Field Test Boreholes.* FCRD-UFD-2015-000131. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition.

Price, L., et al, 2015. *Groundwork for Universal Canister System Development*, Sandia Report, SAND2015-8332. September.

Su, J. and E. Hardin. 2015. *Conceptual Waste Packaging Options for Deep Borehole Disposal*. SAND2015-6335. July.

Presentations

October 20, 2016

Sassani, D.C. and E. Hardin. 2015. "DOE Deep Borehole Field Test: Site Characterization and Design Requirements." U.S. Nuclear Waste Technical Review Board Deep Borehole Workshop, Washington, DC. October 20–21.

Gunter, T.C. 2015. "Deep Borehole Disposal Research and Development Program." U.S. Nuclear Waste Technical Review Board Deep Borehole Workshop, Washington, DC, October 20–21.

July 16, 2016

Freeze, G. 2015. "Deep Borehole Disposal (DBD): Licensing and Post-Closure Safety Assessment." U.S. Nuclear Waste Technical Review Board Briefing, Albuquerque, New Mexico. July 16.

Hardin, E. 2015. "Deep Borehole Field Test Waste Packaging, Emplacement and Seals Testing." U.S. Nuclear Waste Technical Review Board Briefing, Albuquerque, New Mexico. July 16.

Kuhlman, K.L. 2015. "Deep Borehole Field Test Site Characterization." U.S. Nuclear Waste Technical Review Board Briefing, Albuquerque, New Mexico. July 16.

MacKinnon, R.J. 2015. "Overview of the Deep Borehole Field Test." U.S. Nuclear Waste Technical Review Board Briefing, Albuquerque, New Mexico. July 16.

Sassani, D.C. and F. Perry. 2015. "Deep Borehole Field Test (DBFT) FY15 Site Evaluation Overview." U.S. Nuclear Waste Technical Review Board Briefing, Albuquerque, New Mexico. July 16.

Sevougian, S.D. 2015. "Deep Borehole Emplacement Mode Hazard Analysis (DBEMHA)." U.S. Nuclear Waste Technical Review Board Briefing, Albuquerque, New Mexico. July 16.

Enclosure 2

DOE Responses to the NWTRB's Specific Findings and Recommendations

Findings

Even if disposal of some radioactive waste in deep boreholes is determined to be feasible, the need for a mined, geologic repository is not eliminated.

The Board's finding supports DOE's position that a mined geologic repository will be required even if deep borehole disposal is implemented. (No additional action)

Establishing a regulatory framework, identifying an acceptable site, and characterizing a deep borehole at depths down to 5 km (3.1 mi) are challenging and time consuming activities, suggesting that the time required for completing a deep borehole disposal facility might be comparable to that of a mined, geologic repository.

The Board's finding identifies some of the unknown factors regarding the deep borehole concept, including schedule uncertainty. The DBFT is limited to analyzing technical feasibility of the concept. (No additional action)

The Deep Borehole Field Test will provide only limited information on which to base an evaluation of the feasibility of the deep borehole disposal concept and the selection of a deep borehole disposal site.

The Deep Borehole Field Test (DBFT) is not intended to collect data to consider a specific site for disposal of radioactive waste. The DBFT should provide significant information to evaluate the engineering feasibility of the disposal concept and aspects of operational and post closure safety. The Department believes this information will inform a site selection process in much the same way the proven deep geologic repository concept informs the site selection process.

The operational implications and limitations of handling and emplacing highly radioactive waste at depth are very different from those for operations involving non-radioactive material; however, evaluating and understanding those implications and limitations are of utmost importance for the design of a deep borehole disposal facility and for the feasibility assessment of the deep borehole disposal concept.

The second phase of the DBFT will demonstrate surface handling and downhole emplacement of surrogate waste packages in the full-diameter field test borehole. This demonstration will be representative of actual operations needed for radioactive waste disposal. (No additional action)

10

Recommendations

Independent expert review—The Board recommends that DOE ensure the drilling program design and implementation are reviewed by experts with extensive experience in drilling and down-hole operations (e.g., logging, testing, well completion) and in designing and operating equipment for handling highly radioactive material. These experts should be independent of the Deep Borehole Field Test contractor and of the lead national laboratory on the project, and should be able to monitor the progress of the project and report on it to the Secretary of Energy.

> DOE's interdisciplinary team of contractors and national laboratories that will plan and conduct the field test are leading experts in project management, drilling subsurface characterization and testing, nuclear materials handling, and risk and safety assessment. The DOE team is fully capable of presenting to the DOE Secretary, independent experts, review committees, and stakeholders the status and findings of the deep borehole field test as it progresses through its planning and implementation.
>
> A Technical Advisory Committee (TAC) will be established to monitor field test activities, especially during drilling and testing, and ensure the necessary data and information is collected. The membership of the TAC shall include key members of the DBFT team, and/or other external experts as necessary. DOE does not believe, as recommended by the NWTRB, that it is necessary to have an additional group of experts review the drilling program design and implementation, nor is it necessary for an independent group to report on the field test to the Secretary of Energy. (No additional action)

Comprehensive risk analysis—The Board recommends that a more comprehensive risk analysis be completed for all aspects of the drilling and emplacement program as part of assessing the feasibility of deep borehole disposal of radioactive waste. In particular, an analysis should be conducted of what options will be available in the event of an accident during waste emplacement and the implications of such an accident for the safety of recovery operations and the isolation of waste. A transparent and comprehensive assessment of the five possible emplacement modes for deep borehole disposal, including their absolute and relative risks for having and recovering from an accident, also should be completed.

> The Department plans to conduct risk analyses for handling and emplacement operations and important potential accident scenarios, but these analyses will be limited to handling operations unique to deep borehole disposal and wireline emplacement. The Department does not plan to conduct a comprehensive assessment of all other modes of emplacement as recommended by the NWTRB, but may consider doing such assessments in the future if the concept of deep borehole disposal is determined to be feasible. (No additional action)

Heterogeneity of subsurface geology and transferability of data and results of analysis—The Board recommends that DOE strengthen its assessment of the feasibility of the deep borehole disposal option by addressing the technical and scientific issues related to the

11

potential heterogeneity of the subsurface geology and the complex *in situ* conditions at depth. DOE should take into consideration the potential implications, with a focus on conducting a defensible safety analysis and demonstrating the transferability of the data and results of analysis to other sites. DOE should address these issues in the guidance it provides to the contractor for developing the drilling and test plan. Specifically, the project team should carefully consider the key parameters for the safety case that need to be measured during sampling and testing in the 2- to 5-km (1.2- to 3.1-mi) depth range encompassing the seal and disposal zones. For example, DOE should identify down-hole logs, tests, and monitoring techniques that could lead to a better understanding for the potential development of a free gas phase (*e.g.*, hydrogen from the rapid corrosion of steel components) and its implications for disposal system behavior. The goal for characterization should be obtaining relatively continuous down-hole profiles based on multiple measurements, rather than relying on, and interpolating between, a limited set of measurements. DOE also should consider using the characterization and field test boreholes to conduct cross-hole monitoring to provide information on the characteristics of the rock volume surrounding the boreholes. Moreover, on-going subsurface monitoring after the emplacement testing, to continue to test and evaluate starting assumptions, should be included in the drilling and test plan.

The Department agrees with the Board that these are topics that need to be considered in developing the drilling and test plan (D&TP); the DOE also agrees with the Board's observation that subsurface geology is heterogeneous and site-specific geologic information obtained during the DBFT will have limited transferability to other locations. Future disposal boreholes, if any, will need individual characterization. The Department believes that the DBFT will provide valuable information about the feasibility of the disposal concept in a generic sense in multiple ways: e.g., by informing preliminary site screening criteria, by demonstrating construction of boreholes to requirements, by providing the opportunity to evaluate down-hole characterization techniques, and by providing a test of operational engineering techniques. (No additional action)

Pre-drilling geophysical subsurface characterization—The Board recommends that the Deep Borehole Field Test include surface-based geophysical surveys to delineate subsurface structure and physical conditions prior to drilling (*e.g.*, detailed gravity, magnetic, seismic, or electrical data). These measurements could help in the design of the Deep Borehole Field Test drilling and test plan and provide knowledge for using surface-based measurements to evaluate the subsurface characteristics of potential deep borehole sites prior to drilling.

The Department appreciates the Board's suggestion for surface-based geophysical characterization prior to drilling, and intends to use available information. However, the Department has concluded that for the specific purposes of the DBFT, the value of information gained at depths of 3-5 km from surface-based techniques is unlikely to warrant the expense of surface-based geophysical investigations at the scale the Board envisions. (No action)

Robust waste forms, waste packages, and seals—The Board recommends that DOE explicitly analyze the potential safety benefits of using more robust waste forms and waste packages as part of assessing the feasibility of the deep borehole disposal concept and in developing the associated safety case. The Board also recommends that the Deep Borehole

Field Test be used to demonstrate emplacement of potential seals and to test the efficacy of seal materials in dealing with breakouts and evolving damage zones around the borehole when exposed to *in situ* thermal, hydrogeologic, geomechanical, microbiological, and chemical conditions. Geophysical techniques (*e.g.*, acoustic sonic and ultrasonic tools) should be used to verify the seals between the casing and rock where the casing remains in the borehole.

> If deep borehole disposal is found to be feasible, the DOE may evaluate the potential safety benefits of robust waste forms and waste packages in follow-on studies. DOE does plan to investigate the behavior of different seal materials in the laboratory under representative downhole temperature, pressure, and chemical conditions to inform our effort to design a seal system. This information will be used to evaluate opportunities for in-situ testing of sealing technologies during the course of the DBFT, however, sealing experiments are generally incompatible with future non-nuclear R&D uses of the hole. (No additional action)

Developing an operational safety strategy—The Board recommends that DOE develop an operational safety strategy for the Deep Borehole Field Test that integrates conventional borehole operations and remote handling of highly radioactive materials. This might include emphasizing the use of engineering controls (*e.g.*, automated equipment to protect workers) over administrative controls (*i.e.*, processes that rely on personnel actions and procedures). The Deep Borehole Field Test should simulate implementation of deep borehole disposal as if radioactive wastes were being emplaced in order to test the features of an operational safety strategy that can be applied to a future borehole disposal site and to provide the basis for ensuring safe operations, limiting exposure of workers to hazards or release of radioactive material to the environment, and mitigating waste emplacement risks.

> The Department plan incorporates the Board's recommendation. The Department plans to design, build, and operate a system that represents what could be used for an actual disposal system and radiological operations involving radioactive waste. This system and operations will be demonstrated at the 2nd field test borehole (FTB). Demonstration activities will be limited to evaluating and demonstrating system elements and safe handling operations that are unique to deep borehole disposal, such those involving the interface between cask unloading, borehole emplacement of surrogate test packages, and retrieval of test packages. (No additional action)

Engaging regulators to define retrievability requirements—The Board recommends that, as part of its assessment of the feasibility of deep borehole disposal of radioactive waste, DOE place a high priority on engaging regulators to define retrievability requirements in the context of deep borehole disposal of radioactive waste. DOE should begin defining and clarifying the types of technical information that may be needed to address regulatory issues and then collect that information to the extent practicable as part of the Deep Borehole Field Test.

The Department agrees that regulatory clarity is necessary before any decisions can be made regarding deep borehole disposal of radioactive wastes and will incorporate interactions with the regulators into the project schedule as appropriate. (Pending)

A transparent pathway from the Deep Borehole Field Test to siting—The Board recommends that DOE use the Deep Borehole Field Test to gain experience related to its siting approach. DOE should begin to incorporate new standards of transparency and data access, and should explore avenues to engage stakeholders.

The Department has initiated a process to obtain public feedback to help design a consent-based process. The process will be used to site future nuclear waste facilities - which could include a deep borehole. The consent-based process will be transparent, phased and adaptive. (No additional action)

Chief scientist in charge of the Deep Borehole Field Test program—The Board recommends that the DOE Deep Borehole Field Test program have a chief scientist responsible for integrating the engineering activities (i.e., drilling the characterization and field test boreholes, emplacing and retrieving the simulated waste) and the site characterization activities. The chief scientist should have the scientific understanding required to ensure the technical integrity of information gathered in the Deep Borehole Field Test and its use for developing the safety case for deep borehole disposal of radioactive waste.

In lieu of a chief scientist as envisioned by the Board, the Department will establish a Technical Advisory Committee (TAC) to monitor field test activities. The membership of the TAC includes members of the DBFT Contractor team (Battelle Memorial Institute, Schlumberger, Solexperts AG), DOE, technical experts from DOE National Laboratories (Sandia National Laboratories, Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory), and/or other external experts as necessary. (No additional action)

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

July 7, 2016

Mr. John Kotek
Acting Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Re: DOE Response to Board Report titled *Technical Evaluation of the U.S. Department of Energy Deep Borehole Disposal Research and Development Program.*

Dear Mr. Kotek:

Thank you for your letter dated June 9, 2016, that presents DOE's responses to the findings, conclusions, and recommendations presented in the Board's report on its technical evaluation of the DOE deep borehole disposal research and development program.

While the Board recognizes that budget and schedule limitations will necessarily constrain the scope of the Deep Borehole Field Test program (DBFT), the Board remains concerned that the DBFT be designed to take advantage of the opportunity to develop a solid technical and operational basis for deep borehole disposal.

The Board looks forward to reviewing the draft drilling and test plan for the DBFT. I would be grateful if you would provide a copy of the draft plan for the Board to review as soon as it is available.

Sincerely,

Rodney C. Ewing
Chairman

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

Department of Energy
Washington, DC 20585

July 13, 2016

RECEIVED JUL 2 5 2016

Rodney C. Ewing
Chair, United States Nuclear Waste Technical Review Board
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201-3367

Dear Dr. Ewing,

Thank you for the May 23, 2016 NWTRB letter detailing the Board's review and associated recommendations resulting from the 2016 Board Winter Meeting in Knoxville, TN. In addition, the teleconference between the Board and DOE on May 26, 2016, to further discuss details of the Board letter was helpful.

This letter provides specific DOE responses to each of the three recommendations proposed by the Board in the May 23rd letter. We hope that this letter, coupled with the planned follow-on technical meeting in July, will provide the Board sufficient information to assess the status of the DOE R&D program associated with the degradation characteristics of commercial spent nuclear fuel in extended storage and transportation.

> *Recommendation 1 – The Board recommends that the research program be structured such that the focus is on the likelihood and consequences of cladding failure during interim storage, transportation, possible repackaging, and eventual disposal of HBF in a repository.*

We agree that the risk posed by cladding failure is important to understand, but we have chosen to evaluate this risk as a part of a more comprehensive systems engineering approach.

The DOE R&D program in this area began in earnest in 2009. The first task we focused on was the development of a technical gap analysis to identify data that was needed to sufficiently develop the right level of understanding of how various parameters affect the degradation mechanisms of spent fuel and the resultant ability of the spent fuel to withstand extended storage and transportation loading environments. Rather than use a risk based approach, the DOE has taken a systems engineering approach to identify and prioritize these gaps. The systems engineering approach includes risk based evaluation that includes likelihood and consequence factors. In one of our early reports, Gap Analysis to Support Extended Storage of Used Nuclear Fuel Rev. 0, FCRD-USED-2011-000136, PNNL-20509, January 2012, it states:

> *"Based upon the importance of the SSC to licensing a dry storage system or an independent spent fuel storage installation (ISFSI), the potential effects of extended storage or high burnup on the degradation mechanism, and a combination of the data needs, regulatory considerations, likelihood of occurrence, the consequence of degradation, the means to remediate the degradation, and the impact of degradation on*

cost, operations, and future waste management strategies, a research and development (R&D) priority (Low, Medium, or High) is assigned."

We believe that the systems engineering approach provides a more comprehensive evaluation of prioritization by including other factors into the evaluation than just risk. It is felt that this prioritization is crucial to properly manage the acquisition of data with the greatest resultant impact in light of a limited R&D budget. Prior to the issuance of this report, it was externally reviewed by a wide range of external groups, including the NWTRB, NRC, NEI, EPRI, as well as several cognizant international organizations. The DOE continues to work with NRC and NEI to get information to ensure that our research priorities are consistent with the concerns of others. Through this process, the issue of cladding behavior during extended storage and transportation has been a recognized top priority. Focused work over the past six years has resulted in major progress, to the point that the NRC has stated that long term storage and transportation of high burnup spent fuel is safe.

Recommendation 2 – The Board recommends that DOE develop a physical-chemical model that relates the behavior of unirradiated cladding to the behavior of irradiated cladding. This work should also include experimental work to test the model's predictions and evaluate the associated uncertainties.

The idea behind this recommendation has been discussed and several efforts in modeling and early experimental work have been conducted to develop the important parameter associations between irradiated cladding and unirradicated cladding. It is believed that correlating factors for this would be intensely subtle or non-existent, so a full development of this recommendation would be multi-year in scope and would need a sustained high level of funding. Modeling validation to the data, development of statistical confidence of important parameters, and understanding of how important parameter effects transfer from one cladding type to another and one duty cycle to another must be fully understood before modeling predictions can be done with any degree of confidence.

Further, a comprehensive journal article was published by leading U.S. scientists in this area; "Ductile-to-brittle transition temperature for high-burnup cladding alloys exposed to simulated drying-storage conditions", Billone, Burtseva, Einziger, Journal of Nuclear Materials, Vol 433, 2013. The last sentence in the abstract from this article is important to highlight.

"It was also observed that uniformly pre-hydrided, non-irradiated cladding was not a good surrogate for high-burnup cladding because of the high density of circumferential hydrides across the wall and the high metal-matrix ductility for pre-hydrided cladding."

Dr. Billone continues to believe that there are major issues regarding the cost-benefit of launching a significant effort to develop these correlations as recommended. For this reason, as well as a potential host of parameter interactions that have not been addressed regarding the behavior of irradiated cladding v. unirradiated hydrided cladding, the NRC has also expressed skepticism in pursuing this path.

While the DOE is still investigating this approach experimentally at a low level of funding, other high priority issues (e.g., stress corrosion cracking of SS canisters), the current experimental work on irradiated cladding focused on closing this technical gap, and the planned experimental work for the sister pins make this an area that does not rise to a priority level that would warrant the type of funding that is required.

> *Recommendation 3 – The Board recommends that DOE make transparent how it integrates the results from Nuclear Energy University Programs, and other relevant U.S. and foreign research activities into its overall research program on HBF degradation.*

We agree with the need to provide increased clarity regarding how NEUP work is integrated to achieve the desired results. As you have noted, DOE is funding a significant amount of work in this area through its NEUP programs. We are working to better integrate the work going on at these universities into the fabric of our internal R&D program. This is done mainly through assigning DOE Laboratory Technical Points of Contact to provide technical input to the university and communication back to the DOE program. In some cases, the integration is high and the work just hasn't been communicated in a way that has been apparent to the NWTRB. With regard to other relevant U.S. and foreign research programs, the DOE has worked closely with the U.S and international communities in this area. This work has been published and has been submitted to the NWTRB.

Please let me know if you have any questions regarding this letter. We look forward to further technical exchanges with the Board.

Sincerely,

John F. Kotek
Acting Assistant Secretary
for Nuclear Energy

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

December 7, 2016

Mr. John Kotek
Acting Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Mr. Kotek:

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 two recent technical fact-finding meetings related to the performance of high-burnup spent nuclear fuel (SNF) during extended storage and transportation.

On February 17, 2016, the Board held a public meeting in Knoxville, TN, to review the Department of Energy's (DOE) research and development program on high-burnup SNF performance. During that meeting, there was not sufficient time for full discussion of some of the technical issues raised by the Board, so the two fact-finding meetings were held to allow additional discussion of these issues. In each case, three Board members and two members of the Board's Senior Professional Staff participated in the meeting.

The first fact-finding meeting was held on July 11–14, 2016, in Las Vegas to discuss research being performed to obtain the data needed to characterize high-burnup SNF, including the degradation that may occur during extended storage and transportation. The second meeting was held on October 4–6, 2016, at the Idaho National Laboratory to discuss how data from this research can be used with computer models being developed by DOE and the National Laboratories to understand the potential degradation of high-burnup SNF during extended storage and transportation. The Board commends DOE for undertaking this work.

The meetings were very productive and provided additional clarity to the discussions on high-burnup SNF that took place at the Board's open public meeting in Knoxville. The Board is preparing a report on high-burnup SNF, drawing on information from the public meeting and the two fact-finding meetings, and I would be grateful if you would pass on the Board's thanks to the DOE staff and the staff from the National Laboratories for preparing their presentations and participating in these fact finding meetings.

Sincerely,

Rodney C. Ewing
Chairman

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

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

December 8, 2016

Dr. Monica Regalbuto
Assistant Secretary for Environmental Management
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Mr. John Kotek
Acting Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Dr. Regalbuto and Mr. Kotek:

The U.S. Nuclear Waste Technical Review Board (Board) held its 2016 Summer Meeting in Washington, D.C., on August 24, 2016, to review progress in U.S. Department of Energy (DOE) activities to develop an integrated program for transporting and disposing of spent nuclear fuel (SNF) and high-level radioactive waste (HLW). DOE's early planning for the development of a separate repository for defense wastes was also discussed briefly. The meeting included presentations by representatives of the DOE Office of Nuclear Energy (DOE-NE), the DOE Office of Environmental Management (DOE-EM), two DOE national laboratories, the Naval Nuclear Propulsion Program, and the Nuclear Energy Institute. Following the discussions at the meeting, the Board considered the information presented in the context of the need to develop an integrated program for managing and disposing of SNF and HLW.

The Board extends its gratitude to your staff members who worked with Board staff to plan the meeting, to Mr. Kotek for making the opening presentation, and to Mr. Mark Whitney for representing Dr. Regalbuto. We also appreciate the investment of time and effort by DOE and national laboratory personnel who presented posters following the public meeting. The meeting agenda is attached to this letter, while the presentations, transcript, and an archived recording of the webcast are available on the Board's website at http://www.nwtrb.gov/meetings/meetings.html.

Integration of a Nuclear Waste Management and Disposal Program

The meeting agenda was crafted to guide discussion on the development and implementation of an *integrated system* for the management and disposal of SNF and HLW managed by three organizations: DOE-NE (SNF and HLW managed by DOE-NE plus SNF produced by the commercial nuclear power industry), DOE-EM (mainly wastes associated with the production of nuclear weapons), and the Naval Nuclear Propulsion Program (naval SNF). In an integrated

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

system, the component sub-systems are brought together into a functional framework in which the sub-systems work together safely and efficiently. The major sub-systems in the planned U.S. waste management system include waste treatment, packaging, and storage at the sites generating wastes; transfer to and disposal at one or more repository sites; and transportation of waste between sites. The system may also include one or more consolidated interim storage facilities and one or more SNF repackaging facilities. Safe and efficient operation of the integrated system can best be achieved if the system is managed using an "end-to-end" process—*i.e.*, a process that optimizes (improves cost efficiency, timeliness, etc.) the complete system from beginning to end.

A key aspect of developing and integrating a waste management system is analyzing the interfaces between the different sub-systems (system analysis) to determine whether the wastes from one sub-system can be feasibly (*e.g.*, meet size, weight, and heat load criteria), efficiently (*e.g.*, require minimal repackaging), and safely (*e.g.*, are not unacceptably degraded) managed by subsequent sub-systems. These attributes can be analyzed with the aid of computer simulation, which projects, as a function of time, the movement and characteristics of SNF and HLW, indicating characteristics such as location, age, quantity, size, composition, radiation dose, heat load, and packaging. By imposing constraints on the simulation (*e.g.*, maximum heat load for transportation), realistic assessments of the attributes can be completed for different scenarios, which the system integrator utilizes to identify corrective actions as needed and preferred scenarios.

The starting point for analyzing an integrated system is to define the required outcomes (*e.g.*, all naval and commercial SNF plus some HLW emplaced in a deep geologic repository; all other SNF and HLW emplaced in a separate repository for only DOE wastes) and the sub-systems that will be needed to achieve the outcomes. Defining the outcomes is influenced by other factors such as clearly identifying:

- Decision-makers and their roles and responsibilities
- The changing condition of the wastes over time (*e.g.*, corrosion, reduced heat load)
- National policies related to radioactive waste management
- Federal regulations that apply to sub-system design and operation
- State and tribal regulations and agreements that DOE must meet.

DOE is not new to developing integrated systems and system analyses. For example, DOE's now disbanded Office of Civilian Radioactive Waste Management employed the Total System Model to analyze integration of the U.S. SNF and HLW management program in the early 2000s in support of the Yucca Mountain repository project. In addition, other organizations have considered integration of radioactive waste systems, and these efforts can provide valuable insights and lessons learned. In this regard, the International Atomic Energy Agency (IAEA) review of interface issues in SNF management[1] (TECDOC-1774) is particularly relevant. TECDOC-1774 results from an international effort to provide support to entities developing integrated systems for managing radioactive waste and offers valuable examples, observations, and recommendations from the international community that should be considered when

[1] IAEA TECDOC SERIES, *Potential Interface Issues in Spent Fuel Management*, IAEA TECDOC No. 1774, 2015.

developing an integrated waste management system. TECDOC-1774 also reinforces the points noted above by recommending that key elements of a system, including regulatory and decision-making elements, need to be identified, and then the interfaces between the elements need to be characterized and carefully managed. Specific examples of preferred practices found in TECDOC-1774 that are relevant to integration in DOE's waste management program include the following:

- Ensure the compatibility of schedules, equipment, and acceptance criteria at each interface within the waste management system. (TECDOC-1774, §6.)

- Establish radioactive waste policies that are stable over long time frames. The IAEA report elaborates: "Availability of an endpoint (… disposal) affects the need for storage capacity and its duration. Duration of [the] storage period affects condition of fuel and fuel package – which may limit and/or add costs/constraints to future options. The length of the storage period and associated requirements depends upon the availability and actual implementation of national policy relative to closure of the nuclear fuel cycle." (TECDOC-1774, §4.3.2.)

- Exercise early integration: "Effective integration begins early in the planning process. Opportunities are lost if interfaces are not identified and addressed in the early stages of each of the [back end of the fuel cycle] phases." (TECDOC-1774, §6.)

- Establish integrated decision-making. For example, "The various phases and operational steps in the [back end of the fuel cycle] may be performed by a number of different entities that require close coordination. To assure safe and effective operations, interactions among [entities] are necessary to address issues related to contractual arrangements, schedule coordination, records management, transfer of ownership, assuring compatibility (tooling, physical geometry, acceptance criteria, *etc*.), specifying performance requirements, as well as numerous other transfers of information and materials needed." (TECDOC-1774, §4.3.7.)

The Board recognizes that the IAEA report reflects experiences gained during the development of waste management systems in other countries, and that not all of the conclusions and recommendations in the report will apply in the United States. Moreover, given the uncertainties that exist with respect to the timing, location, and design of the repository or repositories that will be constructed for final disposal of SNF and HLW in the United States, it is clear that DOE will need to retain flexibility in developing an integrated system for managing and disposing of HLW and SNF in a manner that was not foreseen in the IAEA report. Nevertheless, the Board views the insights offered by TECDOC-1774 as relevant to the development of an integrated waste management system in the United States.

DOE is in the process of developing a radioactive waste management system and the analysis tools to evaluate it. Discussion of these efforts was a point of particular focus of the Board meeting. In the sections that follow, the Board provides observations about DOE's system analysis tools and DOE's progress in integrating a waste management system in the United States.

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

DOE's Program for the Management of SNF and HLW

DOE's Waste Management System. In his opening presentation, Mr. Kotek described DOE's "Integrated Waste Management System." As planned and presented by DOE at the meeting, the Integrated Waste Management System includes the following sub-systems: a pilot consolidated interim storage facility for commercial SNF; a larger consolidated interim storage facility for commercial and DOE SNF and possibly HLW; a deep geologic repository that could accept all types of SNF and HLW; possibly separate disposal options for defense-related SNF, HLW, and some naval SNF; and a transportation system to move the waste materials between sub-systems. The waste management system may also include a repackaging facility.

Mr. Kotek stated his office is responsible for leading the overall integration effort for coordinating with other organizations involved in the management, possible interim storage, transportation, and disposal of SNF and HLW. He also noted that he is taking action to consolidate into one office within DOE-NE the sub-organizations that have responsibilities related to the development of DOE-NE's Integrated Waste Management System. *The Board believes this reorganization, which was completed in October 2016, could strengthen sub-system integration within DOE-NE, and help DOE-NE as it works to improve organizational interfaces with DOE-EM, the commercial nuclear industry, and the Naval Nuclear Propulsion Program.*

Integration in Packaging for SNF and HLW. From the presentations and discussions of SNF casks and canisters and HLW canisters at the meeting, it is clear that DOE-NE, DOE-EM, and the Naval Nuclear Propulsion Program use a wide variety of waste canister designs. It is also clear that the transportation, storage, and disposal of all of them will need to be managed as part of the Integrated Waste Management System.

Mr. Joe Carter, Savannah River National Laboratory, presented information on the casks and canisters currently in use, and new designs being introduced, for storage and transportation of commercial SNF. Mr. Carter highlighted the large variations in canister lengths, diameters, and SNF capacities. He also noted a wide range of other design constraints for the canisters, such as thermal (heat) limits, dose rate limits, and limited capacity for damaged SNF.

Mr. Carter also identified an additional complexity presented by some commercial SNF canisters having an NRC-approved thermal limit for storage that is significantly higher than the thermal limit approved for transportation. As a consequence, unless the transportation thermal limit can be increased, these canisters will have to remain in storage at the nuclear power plant sites until the SNF they contain has cooled sufficiently to meet the thermal limit for transportation. In some cases, this may impact the schedule for final decommissioning of the site. An alternative course of action for SNF canisters with high heat loads is to repackage the SNF into smaller canisters in order to meet the thermal limit for transportation earlier. This example highlights the recommendation in TECDOC-1774 for integration to begin early in developing a waste management system so that the implications of operations in one sub-system on the interface with another sub-system can be identified and taken into account.

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

Mr. Ken Picha, DOE-EM, presented information about the packaging of SNF and HLW managed by DOE-EM, which similarly includes a number of different canister types and sizes. Furthermore, DOE-EM also has a number of waste types that still need to be packaged or treated and packaged, including more than 250 types of SNF, 90 million gallons (340,000 cubic meters) of HLW stored in underground tanks, and HLW in glass and granular forms. This represents an opportunity for DOE-EM to consider the impact of how these wastes are packaged on operations at the interfaces between sub-systems of an integrated waste management system.

As an example, Mr. Picha indicated that the canister designed for packaging the sodium-bearing waste to be processed at the Idaho National Laboratory (INL) is 26 inches in diameter and 10 feet long. A canister with these dimensions should fit in the RH-72B cask used to transport certain transuranic wastes to the Waste Isolation Pilot Plant (WIPP), which would be appropriate if this waste can be disposed of as transuranic waste. However, the final waste classification of the sodium-bearing waste has not yet been determined, with the possibility that this waste will need to be disposed of as HLW. By comparison, the canisters being used for HLW are all 24 inches in diameter and, from the discussion at the meeting, it was not clear whether consideration had been given to the consequences of using 26-inch diameter canisters for the processed sodium-bearing waste, if it is subsequently determined that this waste needs to be disposed of as HLW. It was for this reason that the Board recorded in a letter to DOE in 2012[2] that "it would be prudent to formalize the classification of this material prior to processing to ensure that it meets the applicable final disposal requirements." Similarly, IAEA TECDOC-1774 points to the need for early coordination to define the interfaces between sub-systems and ensure efficient operations.

In an attempt to limit the number of additional variations in canister designs that may be introduced in the future, DOE has initiated the development of "standardized" canister designs for different applications. Mr. Carter discussed the Standardized Transportation, Aging, and Disposal Canister concept that could be used for commercial SNF and Mr. Picha discussed the DOE SNF Standardized Canister intended for DOE-managed SNF. However, neither DOE-NE nor DOE-EM is actively pursuing implementation of these systems. *The introduction of standardized canister systems may offer significant benefits for the development of an integrated waste management system, although the Board notes that, even if they were introduced today, the interfaces between waste management sub-systems would have to be designed to accommodate many different designs of casks and canisters for SNF and HLW.*

<u>Integration in System Analysis</u>. As indicated above, a key element in integrating the waste management system is the use of system analysis tools. DOE-NE is developing system analysis tools although, based on discussions at the meeting, the Board understands that these efforts are focused almost exclusively on transportation of commercial SNF and are not currently being applied in an integrated fashion to include wastes from DOE-EM or the Naval Nuclear Propulsion Program.

Dr. Josh Jarrell of the Oak Ridge National Laboratory presented information on the system analysis tools DOE-NE is developing and using, such as the Next Generation System Analysis Model (NGSAM). Using output from NGSAM, he showed the impact of setting different

[2] Ewing, R. C., to Huizenga, D., December 11, 2012.

priorities for the removal of commercial SNF from nuclear power plant sites. If DOE were to remove SNF in the order of oldest fuel first, which is the current plan, rather than in the order of shutdown sites first, the analysis predicted that the cumulative amount of time the SNF would remain at shutdown sites would be significantly extended, potentially delaying the final cleanup at the sites. Dr. Jarrell noted that the new tools, like NGSAM, have the capability to include detailed SNF and cask information, such as where specific SNF assemblies are loaded in dry-storage canisters for commercial SNF, which will be needed to support approving the canisters for transportation. Including this type of information is consistent with the need to analyze the interfaces between sub-systems in support of developing an integrated waste management system, as discussed above.

The Board commends DOE-NE for continuing to develop and improve its system analysis tools, such as NGSAM, which allow DOE to identify and address the challenges that will be faced in designing and implementing an integrated waste management system for commercial SNF. *The Board encourages DOE-NE to expand the use of its system analysis tools so that it has the capability to include SNF managed by DOE-EM, all HLW, and SNF from the Naval Nuclear Propulsion Program in its analyses.*

Integration in Planning the Transportation of SNF and HLW. The Board heard from DOE-NE, DOE-EM, and the Naval Nuclear Propulsion Program about plans and equipment for the transportation of radioactive waste. *Based on the presentations, it is not clear to the Board how DOE-NE responsibilities for planning the transportation of commercial SNF are integrated with DOE-EM responsibilities in the areas of packaging certification and transportation of wastes or with Naval Nuclear Propulsion Program transportation of naval SNF.*

Mr. Mike Wangler, DOE-EM, presented information on DOE-EM's packaging and transportation program for hazardous and non-hazardous materials. He pointed out that DOE-EM's Office of Packaging and Transportation administers the policies and procedures for the DOE packaging certification program that applies to all offices of DOE. However, the Board understands that the Naval Nuclear Propulsion Program conducts its own packaging certification and that the DOE-EM packaging certification program does not apply to packaging of SNF and HLW that is now assigned to DOE-NE. In response to a Board question about senior-level coordination of transportation responsibilities between DOE-EM and DOE-NE, Mr. Wangler stated that there was formerly a Senior Executive Transportation Forum, with coordination of transportation issues as its main charge, but it was no longer active.

Mr. Wangler described and demonstrated the Web-based Transportation Geographic Interface System (WebTRAGIS), highlighting its routing analysis capabilities and showing how it can link to a computer program that estimates radiation doses along transportation routes. Given the capabilities of WebTRAGIS, the Board asked why DOE-NE had not adopted it, rather than developing the Stakeholder Tool for Assessing Radioactive Transportation (START) as a separate routing analysis tool. A representative of DOE-NE stated that, following an assessment of the capabilities of WebTRAGIS, DOE-NE had decided to develop the START program using commercially-available software. *It is not clear to the Board why this approach was preferable to one of coordinating with DOE-EM to take advantage of a well-developed tool like WebTRAGIS.*

At the meeting, Mr. Barry Miles of the Naval Nuclear Propulsion Program presented the history and current status of its SNF management program. This program includes loading canistered or bare (uncanistered) naval SNF into casks at the shipyards, transporting the SNF to the Naval Reactor Facility at the Idaho National Laboratory (INL), and packaging or repackaging the SNF into welded canisters for dry-storage. Following storage, the canisters are also intended for direct disposal of the naval SNF in a repository. Mr. Miles noted that the Naval Nuclear Propulsion Program had recently introduced into service a new transportation cask and a new railcar, which have been designed to be used both for the transportation of canistered or bare naval SNF to INL and for transportation of canisters of SNF from INL to a deep geologic repository for disposal. He also showed, in his presentation, that the newest naval SNF canister is similar in size and weight to the largest SNF dry storage canisters being used today in the commercial nuclear power industry.

Mr. Miles highlighted the integrated operational nature of the Navy's transportation and storage program, specifically pointing out the operational interfaces between the Naval Nuclear Propulsion Program and INL, the railroads, emergency responders along the transportation routes, and the State of Idaho. *The Board notes that, while the management of naval SNF is integrated as a self-contained program, it is not integrated with transportation of commercial SNF or DOE-managed SNF or HLW.*

Integration between DOE and the Commercial Nuclear Industry. During the meeting, the Board heard presentations from representatives of DOE-NE and the commercial nuclear industry concerning the dry-storage of commercial SNF in large canisters at nuclear power plant sites and the implications of this for the development of an integrated waste management system. Indicative of the challenges that will need to be addressed in developing an integrated waste management system, the presentations by DOE representatives included the disclaimer: "Under the provisions of the Standard Contract[3], DOE does not consider spent nuclear fuel in canisters to be an acceptable waste form, absent a mutually agreed to contract modification."

Mr. Kris Cummings, of the Nuclear Energy Institute, presented the nuclear industry's perspectives on the storage and future management of commercial SNF. He indicated that the nuclear industry is now using larger canisters for dry-storage of SNF in the interests of improving the efficiency of plant operations. Although these large canisters may not meet the requirements for disposal in all geologic repositories, Mr. Cummings referred to a study by the Electric Power Research Institute (*Feasibility of Direct Disposal of Dual-Purpose Canisters in a High-Level Waste Repository*, Report 1018051, August 2008) and noted that it concluded direct-disposal of large dry-storage canisters is feasible in certain repository designs. Mr. Cummings suggested that DOE should recognize that utility management of commercial SNF today is based on the use of large canisters, and the Integrated Waste Management System, including the repository, should be designed to accept direct disposal of commercial SNF in large dry-storage canisters.

---

[3] Title 10, Code of Federal Regulations, Part 961, SUBPART B—*Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste.*

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

Mr. Cummings acknowledged, however, that in some cases, there are storage-only canisters that may need to be repackaged at the nuclear utility sites prior to transportation. Based on information available from the nuclear industry and DOE as of August 2016, approximately 780 (36 percent) of all loaded commercial SNF dry storage canisters are not currently approved by the NRC for transportation. Of these, approximately 380 canisters are designed as dual-purpose canisters (*i.e.*, designed for storage and transportation) and the nuclear industry expects the canisters will receive NRC approval for transportation when needed. Approximately 400 canisters are of types that were not designed with transportation in mind, and may need additional analyses by the licensees or exemptions from the NRC (or both) to receive approval for transportation. If the canisters cannot be approved for transportation, the SNF in the canisters would have to be repackaged into transportable SNF canisters or into bare-fuel transportation casks at the utility sites.

There are also other issues that may result in the need for repackaging, beyond the need to meet transportation safety regulations as noted by Mr. Cummings. Repackaging might also be necessary because SNF storage casks or canisters do not meet the criticality safety requirements or heat load limits for some designs of a geologic repository. Whatever the cause, repackaging SNF at utility sites, which typically do not have facilities for this activity, would have significant adverse impacts on cost, worker dose, and schedule.

Conclusions and Recommendations Regarding Integration

Based on the presentations and other materials provided by DOE-NE, DOE-EM, and the Navy Nuclear Propulsion Program, DOE will face integration challenges on three levels: the national level, the DOE level, and the DOE-office level.

At the national level, DOE is challenged by issues that limit its ability to develop an integrated waste management program. Uncertainties such as the location and geology of a waste repository, the outcome of negotiations concerning the Standard Contract, and potential changes to federal waste policies create a challenge for the implementer (DOE) in finalizing waste package designs that are best suited for the geochemical and hydrogeologic conditions in the repository.

Within DOE, DOE-NE, DOE-EM, and the Naval Nuclear Propulsion Program each keep their own databases and records of waste inventories, conduct their own analyses of waste management systems, and arrange for transportation of their own wastes. Based on the presentations at the meeting, there appears to be little interaction between the separate programs. Indicative of this is the development of the START program in DOE-NE, even though a similar program, WebTRAGIS, was already fully-developed and in use in DOE-EM. The Board suggests that much could be done now to further coordination within DOE in the interests of integrating the various radioactive waste management sub-systems. More generally, the Board notes that having three separate offices involved in managing SNF and HLW complicates system integration by creating more interfaces, which require additional communications and concurrence to reach and implement technical decisions involving parallel decision-making authorities when the first common management authority is the Secretary of Energy. The Board concludes that system integration efforts would be facilitated if the number of interfaces among

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

offices can be reduced, perhaps by using the DOE-Navy collaboration in the Naval Nuclear Propulsion Program as a model, or at least continuously coordinated by an appropriate group.

Within DOE offices, there are additional challenges, most notably within DOE-EM. DOE-EM needs to complete the treatment and packaging of much of its SNF and HLW, and needs to do so in a manner that takes account of the need for the transportation and disposal of all of its wastes in the integrated waste management system. DOE-EM is also constrained by legal agreements with host states and contractual requirements that vary by site. For example, the Idaho Settlement Agreement between the State of Idaho, DOE, and the Navy requires that all DOE SNF and most naval SNF be removed from Idaho by 2035, although the timescale for developing a facility outside Idaho to accept SNF from INL is uncertain.

In order to address the need to develop an integrated system for the management and disposal of SNF and HLW in the United States, the Board recommends that DOE, as a matter of priority:

1. *<u>Establish a comprehensive database of SNF and HLW</u>: Develop a single database containing all of the information on SNF and HLW necessary to support developing an integrated management and disposal system, or the software necessary to successfully integrate the separate databases that contain the necessary information.*

2. *<u>Develop an integrated (end-to-end) system analysis tool for waste management</u>: Develop new, or modify existing, system analysis tools, as described earlier, to allow successful analysis of the full scope of the integrated waste management system.*

3. *<u>Optimize the system using an end-to-end approach</u>: Complete the necessary system analyses to identify actions that can be taken to (i) optimize the complete system against key program objectives (schedule, cost, operator doses, etc.) and (ii) avoid introducing additional complexities by decisions made independently at the facility, site, office or other level.*

4. *<u>Assess and optimize new canister designs for end-to-end compatibility</u>: Avoid the introduction of new canister designs for packaging SNF and HLW unless absolutely necessary. If new designs need to be used, ensure that, as far as possible, they are compatible with the handling, storage and transportation facilities, systems, and equipment already in service or necessary to support the management and disposal of canisters already in use or licensed for use.*

In making these recommendations, the Board understands that DOE cannot require the commercial nuclear utilities to provide information on their activities considered sensitive or proprietary. To the extent the information necessary for developing an integrated system is not available from the utilities, however, the Board considers that sufficient information is publicly available to allow DOE to adopt and act on these recommendations.

Thank you again for the participation of DOE-NE and DOE-EM staff and technical experts from the national laboratories at our August meeting. In particular, we thank Mr. Jack Wheeler of DOE-NE and Mr. Hitesh Nigam of DOE-EM for their efforts in coordinating DOE speakers and

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

presentations. We look forward to continuing our ongoing review of DOE's technical activities related to the management and disposal of SNF and HLW.

Sincerely,

Rodney C. Ewing
Chairman

Attachment

10

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

Attachment

AGENDA

SUMMER BOARD MEETING

WEDNESDAY, AUGUST 24, 2016

THE WESTIN WASHINGTON, DC CITY CENTER HOTEL
1400 M STREET, NW
WASHINGTON, DC 20005
202-429-1700
[NATIONAL BALLROOM AB]

8:00 a.m. **Call to Order and Introductory Statement**
Rod Ewing, Board Chairman

8:15 a.m. **Department of Energy (DOE) Opening Remarks – DOE's Integrated Program for the Management and Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste**[4]
John Kotek, DOE, Office of Nuclear Energy (DOE-NE)

i. Describe the objectives and status of DOE's Integrated Waste Management System directed by the DOE-NE Office of Fuel Cycle Research and Development.

ii. How does DOE-NE coordinate its commercial SNF activities with DOE Office of Environmental Management (DOE-EM) activities to store, process, and prepare DOE-managed spent nuclear fuel (SNF) and high-level radioactive waste (HLW) for disposal?
   a. Do the DOE SNF Working Group and the DOE Tank Waste Corporate Board consider integration issues among DOE-NE, DOE-EM, and Naval Reactors? If so, please provide examples.

iii. What are the priorities in fiscal years 2017 and 2018 for the DOE Integrated Waste Management System?

iv. Generally, how does DOE-NE address recommendations from the Board? More specifically, how has DOE-NE addressed the Board's recommendations on storing and transporting casks and canisters for commercial SNF? See the Board letters to DOE-NE dated:
   a. January 29, 2014 (re Board Meeting of Nov. 20, 2013, on DOE-NE research and development programs).
   b. October 10, 2014 (re Board Meeting of Aug. 6, 2014, on DOE SNF management).
   c. August 31, 2015 (re Board Meeting of Jun. 24, 2015, on commercial SNF transportation).

---

[4] Note: Questions were provided to the speakers in advance to convey the Board's primary interests in the agenda topics and to aid in focusing their presentations.

A-1

8:45 a.m. **Questions/Discussion**

9:00 a.m. **Containers for Commercial Spent Nuclear Fuel**[5]
("container" is used generically to mean canister, cask, or overpack)
Joseph Carter, Savannah River National Laboratory

i. The commercial nuclear power industry uses more than 25 types of dry-storage casks and canisters for commercial SNF, and the number is growing. In addition, DOE is evaluating several options for "standardized" containers that may be used for storing, transporting, or disposing of commercial SNF. The standardized containers include small, medium, and large Standardized Transportation, Aging, and Disposal (STAD) canisters. Reusable, bolted-lid transportation-only cask concepts were also recently developed (designs by AREVA and EnergySolutions). Briefly describe the in-use containers and recently proposed container concepts. Discuss the integration issues known or anticipated—in particular, focus on:

   a. Challenges presented by the physical dimensions and capacity of the containers.
   b. The scope of commercial SNF types that can be loaded.
   c. The ability to accommodate damaged SNF (in "damaged fuel cans").
   d. Challenges for licensing for storage and transportation.
   e. Limitations for the transportation casks and trailers/railcars to be used (if applicable) and the status of design and procurement of the transportation casks.

ii. Explain whether any of the SNF containers may exceed storage or transportation limits for temperature, criticality safety, radiation dose, or weight. If the limits are challenged or exceeded, how will containers be managed and what is being done to mitigate the problems in the future?

9:30 a.m. **Questions/Discussion**

9:50 a.m. **System Analysis Tools used to Evaluate the Integrated Waste Management System**
Josh Jarrell, Oak Ridge National Laboratory

i. What is the status of the development and implementation of DOE's system analysis tools for evaluating options for commercial SNF management?

   a. Explain how these tools can be used to examine the pros and cons of using different types and sizes of SNF canisters at different points in the back end of the fuel cycle (*e.g.*, storage, transportation, and disposal).

[5] This and the following presentations will consider containers for nuclear waste storage and transportation, but will not include disposal overpacks that may be used when disposing of wastes in a deep geologic repository.

A-2

b. Has DOE-NE assessed the time, cost, dose, and radioactive waste implications of repackaging SNF at different locations? If so, what are the results of the assessment?
c. Did DOE-NE coordinate with DOE-EM in developing START (the Stakeholder Tool for Assessing Radioactive Transportation) and use lessons learned from DOE-EM's Web-based Transportation Geographic Interface System (WebTRAGIS)?
d. In the early application of these tools, has DOE learned anything significant about the projected integration and management of SNF storage and transportation systems?

10:15 a.m. **Questions/Discussion**

10:30 a.m. **Break**

10:45 a.m. **Nuclear Industry Perspective on Commercial SNF Management and Transportation**
Kris Cummings, Nuclear Energy Institute

i. Discuss the nuclear industry's perspective on DOE efforts to integrate commercial SNF and DOE waste management and transportation. What are the perceived impacts to the nuclear industry of integrating defense and non-defense wastes? In particular, what is the impact on the industry's ongoing efforts to package and store commercial SNF?

ii. If DOE introduces relatively small standardized canisters for commercial SNF to gain efficiencies in the waste management system, how will this action be received by industry?

iii. It may not be possible to dispose of SNF in the large canisters being used by utilities today and DOE has developed the initial concepts for a range of smaller canister designs. What could be done to minimize or offset the impact of loading smaller canisters at nuclear power plant sites to avoid the need for repackaging later?

11:15 a.m. **Questions/Discussion**

11:35 a.m. **Public Comment**

12:00 p.m. **Lunch Break**

1:00 p.m. **DOE-EM Program Overview; Integration of DOE-managed SNF and HLW**
Mark Whitney, DOE, Office of Environmental Management

i. Cleanup Mission.
   a. What is DOE-EM's legacy cleanup mission?
   b. How does management of DOE-EM's SNF and HLW help DOE-EM achieve cleanup success?
   c. What is the current status and key milestones relevant to DOE-EM's tank waste management and SNF management activities?

ii. Office of Environmental Management Reorganization.
   a. How does the recent DOE-EM reorganization impact oversight and implementation of its key SNF and HLW mission and functions?

iii. Current plans for packaging DOE-managed SNF and HLW.
   a. What are DOE-EM's current plans for packaging its SNF and HLW following termination of the Yucca Mountain project and start of a new consent-based siting process?

1:15 p.m. **DOE-EM Transportation Overview and Integration**
Mike Wangler, DOE, Office of Environmental Management

i. Transportation Office Overview & Integration.
   a. What is the overall scope and responsibilities of DOE-EM's packaging and transportation activities?
   b. What organizations within and external to the Department integrate with DOE-EM on packaging and transportation activities?
   c. What shipments of SNF and HLW have occurred or are planned?
   d. What integration occurs for such shipments?
   e. What factors, based on DOE-EM's past operational experience, are important to consider in meeting future needs for transport of DOE-managed SNF and HLW as part of an integrated waste management system?

ii. WebTRAGIS demonstration and discussion of its capabilities and usage.

1:45 p.m. **DOE-Managed SNF Integration**
Ken Picha, DOE, Office of Environmental Management

i. DOE-EM Complex-wide SNF Overview.
   a. What current activities related to DOE-managed SNF management are occurring at DOE-EM sites?

ii. Integration of Near-Term Activities at Idaho.
   a. How are SNF-related activities at DOE sites being integrated? Focus on how SNF activities at DOE-Idaho demonstrate integration between DOE-EM, DOE-NE, and the Navy.

iii. Planning for and Integration Supporting DOE-managed SNF Disposition.
   a. What are the different canister designs and characteristics for packaging DOE-managed SNF for disposal in an integrated, commercial/defense waste management system developed by the previous repository organization?
   b. What are DOE's plans for packaging SNF for transportation and disposal in a future repository?
   c. What continuing or new integrating activities and tools are available to support future disposition of SNF?
   d.

A-4

2:10 p.m. **HLW Integration**
Ken Picha, DOE, Office of Environmental Management

i. DOE-managed HLW Overview.
   a. What current activities related to tank waste management are occurring at DOE-EM sites?
   b. What are the different canister designs and characteristics for disposal of immobilized HLW for disposal?

ii. Tank Waste Integration among DOE sites.
   a. How are HLW-related activities at DOE sites being integrated?

2:35 p.m. **Questions/Discussion**

2:55 p.m. **Break**

3:10 p.m. **U.S. Navy Spent Nuclear Fuel Transportation**
Barry Miles, U.S. Navy

i. Describe the U.S. navy program for transporting Naval SNF.
   a. What are the primary organizations with which the Navy integrates?
   b. What are the biggest challenges to transporting Naval SNF?
   c. What lessons learned can the Navy offer DOE?

3:35 p.m. **Questions/Discussion**

3:50 p.m. **Planning for a Separate Repository for Defense Waste**
Andrew Griffith, DOE, Office of Nuclear Energy

i. Describe the plans, objectives, and status of the development of a separate repository for defense waste.

4:15 p.m. **Questions/Discussion**

4:35 p.m. **Public Comments**

5:00 p.m. **Adjourn Public Meeting**

5:00 – 6:00 p.m. **Poster Session** [NATIONAL BALLROOM C]
- Posters on the characteristics of canisters and casks for commercial SNF.
- Posters on the integrated system analysis tools being used by DOE-NE to evaluate the storage and transportation of commercial SNF.

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201-3369

August 16, 2017

Mr. James M. Owendoff
Acting Assistant Secretary for Environmental Management
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Mr. Edward McGinnis
Acting Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Mr. Owendoff and Mr. McGinnis:

The U.S. Nuclear Waste Technical Review Board (Board) held a meeting in Richland, Washington, on June 21, 2017, to review information on recent U.S. Department of Energy (DOE) research activities related to corrosion and long-term performance of borosilicate high-level radioactive waste (HLW) glass in a repository environment. The meeting included presentations by representatives of three DOE national laboratories and the Vitreous State Laboratory (VSL) of the Catholic University of America on DOE-funded research and development (R&D) activities. In addition, experts from other countries provided their perspectives on the current understanding and remaining challenges in measuring and modeling HLW glass performance. Immediately after the public meeting, a poster session was held during which scientists and engineers from the United States and other countries presented their research related to nuclear waste glass corrosion.

The Board extends its gratitude to your staff members who worked with Board staff to plan the meeting. We also appreciate the investment of time and effort by national laboratory personnel who made presentations or exhibited posters at the meeting. The meeting agenda is attached to this letter, while the presentations, poster abstracts, transcript, and an archived recording of the webcast are available on the Board's website at http://www.nwtrb.gov/meetings/meetings.html.

The Board also thanks your staff, as well as staff from the national laboratories, for supporting a technical fact-finding meeting that was held on May 15, 2017, in Washington, D.C. This fact-finding meeting allowed a more detailed presentation of technical issues related to HLW glass corrosion and long-term performance and enabled the Board to prepare for the June 21 public meeting. The presentations made at the May 15 fact-finding meeting also are available on the Board's website, at the same location as the other June 21, 2017, meeting materials. We also thank your staff, as well as staff from Pacific Northwest National Laboratory (PNNL), for supporting the Board's tour of HLW-related laboratories at PNNL on June 20, 2017.

Telephone: 703-235-4473 Fax: 703-235-4495 www.nwtrb.gov

Background

In the United States and in most other countries, vitrification into borosilicate glass is the technology being used to immobilize liquid HLW destined for disposal in a geologic repository. Borosilicate glass is the preferred waste form because it can accommodate a wide range of HLW compositions, has a structure considered to be less susceptible to radiation damage than crystalline materials, is relatively durable in many geologic disposal environments, and exhibits good thermal and mechanical stability properties. Also, vitrification is a well-demonstrated technology resulting from more than 40 years of industrial experience and is a processing method that can be applied to large volumes of HLW.

During the past few years, DOE has conducted R&D activities on corrosion of borosilicate HLW glass. The purpose of these activities is to improve understanding of glass waste form degradation and to develop a basis for reducing conservatisms in glass corrosion models that are used in disposal system performance assessments.[1] DOE's detailed plan for these R&D activities, which was developed in 2011, included experiments to measure glass corrosion as well as modeling at the atomic and larger scales to help interpret experimental results. The plan also included using the experimental results to develop an improved glass corrosion model and integrating the corrosion model with generic repository system performance assessment calculations. DOE has coordinated its research activities with those being conducted in other countries and also has funded R&D activities on glass corrosion at several U.S. universities through its Nuclear Energy University Program.

The meeting agenda was crafted to guide discussion on the current understanding of glass corrosion mechanisms and rates, the environmental factors that control these mechanisms and rates, the remaining uncertainties and challenges in measuring and modeling the long-term performance of borosilicate HLW glass, and the progress DOE, in collaboration with the international scientific community, has made in addressing those uncertainties and challenges. The meeting focused only on local-scale processes of glass corrosion along surfaces of glass particles or within fractures under conditions of water saturation. Although the long-term durability of glass in a repository environment also will depend on many other factors and interactions, including the transport of water or water vapor through engineered barriers to the waste glass, the extent of fracturing within the waste glass, and the various potential disposal geochemical environments, the limited duration of the meeting precluded discussion of these other factors.

The first technical presentation was by Dr. Bernd Grambow (SUBATECH, France), who discussed alternative approaches to modeling glass corrosion in repository environments and how different countries take account of glass corrosion and radionuclide release in repository performance assessments. In a following presentation, Dr. Carol Jantzen [Savannah River National Laboratory (SRNL)] described DOE's criteria for qualifying borosilicate glass waste forms as being acceptable for disposal in any geologic repository and the technical bases of those

[1] Dr. J.D. Vienna described the motivation for these activities in his May 15, 2017, presentation titled "Summary of Programs and Collaborations."

Telephone: 703-235-4473 Fax: 703-235-4495 www.nwtrb.gov

criteria, including standards, test methods, databases, and models. Then, Dr. Stéphane Gin (French Atomic Energy and Alternative Energies Commission) presented his assessment of the current scientific understanding of the processes responsible for glass corrosion and release of radionuclides into the environment, and the remaining technical challenges to measuring glass corrosion and modeling the long-term performance of borosilicate HLW glasses. Dr. Ian Pegg (VSL) followed with a presentation on glass formulation and durability studies at the VSL and how the results of those studies are used to understand glass corrosion mechanisms and long-term performance in disposal environments.[2] Dr. Joseph Ryan (PNNL) then made a presentation on DOE studies to improve understanding of rate-limiting mechanisms for glass corrosion under varying conditions. Dr. William Ebert (Argonne National Laboratory) followed with a presentation on the DOE HLW glass corrosion model and its implementation in repository post-closure safety analysis. Finally, Dr. Aurélie Verney-Carron (Interuniversity Laboratory of Atmospheric Systems, France) gave a presentation on studies of natural and archeological glasses and what can be learned from these natural and archeological analog studies about long-term HLW glass corrosion.

Board Observations

Borosilicate glass corrosion is a complex process, but there is general consensus that borosilicate glass corrosion follows three main stages: an initial (high) corrosion rate (Stage I) followed by a residual (low) corrosion rate (Stage II), and, under certain conditions, a resumption of a higher corrosion rate that is still less than the initial rate (Stage III).[3] Additional detail on glass corrosion, and its associated stages, is provided in an appendix to this letter.

DOE has used a "bounding" glass corrosion model in repository performance assessments, which was designed to not under-predict the rate of glass corrosion.[4] At the time DOE developed this bounding model in the early 2000s, the conditions triggering Stage III were not well understood. Dr. Ebert explained during his May 15, 2017, presentation that the model represents dependencies on solution composition by using a range of corrosion rates derived from tests conducted over a wide range of pH conditions. Potentially higher glass corrosion rates due to Stage III processes were bounded in the model by using a maximum value that is higher than the rates derived from experiments in which a Stage III resumption of alteration was observed.

Dr. Ebert explained that the model DOE is currently developing incorporates the effects of secondary phase nucleation and growth on glass corrosion rate (*i.e.*, Stage III) deterministically. As Dr. Ebert described, the new model represents DOE's improved understanding of the conditions required to trigger Stage III and provides confidence in using the Stage II (residual)

---

[2] Dr. Pegg also discussed the performance of low-activity waste glass that DOE plans to create at the Hanford site in Washington State. DOE plans to dispose of low-activity waste glass at the Integrated Disposal Facility, a near-surface disposal facility at the Hanford site.
[3] Based on all of the data that are in the ALTGLASS database, which DOE has developed, Stage III rates are always lower than the Stage I rate for the same glass composition and pH conditions.
[4] Dr. Ebert described the historical basis for the current HLW model in his May 15, 2017, presentation titled "DOE HLW Glass Degradation Model." The Board notes that DOE used this "bounding" model in its performance assessment for the Yucca Mountain repository.

Telephone: 703-235-4473 Fax: 703-235-4495 www.nwtrb.gov

rate if those conditions are not predicted to occur. As DOE continues this model development, and if the resulting model is used for future performance assessments, DOE should consider the following Board observations.

Substantial progress, but significant technical uncertainties remain

The presentations at the Board's public meeting indicate that the R&D activities DOE has conducted in the past few years in collaboration with international scientists have advanced the scientific understanding of HLW glass corrosion. Results are being used to develop mechanistic glass corrosion models for generic repository performance assessment calculations.

Nevertheless, technical uncertainties remain that could be reduced by additional research. For example, the focus of recent studies by DOE and the international community has been on what triggers the resumption of more rapid glass corrosion (Stage III). There has been progress in identifying the glass characteristics and environmental conditions associated with the initiation of Stage III, and DOE-funded researchers have developed a conceptual model of precipitation of secondary phases such as zeolites that drives enhanced corrosion of glass during Stage III. However, significant uncertainties remain, particularly related to the detailed causation mechanisms and timing of Stage III. Establishing what triggers Stage III and how it might be avoided is important because HLW glass will retain radionuclides for a very long time at Stage II corrosion rates whereas the HLW glass radionuclide retention under Stage III corrosion rates will be much shorter.

Effective utilization of state-of-the-art analytical equipment

The advancement of the scientific understanding of HLW glass corrosion mechanisms and rates has been facilitated by new and novel analytical and experimental methods (*e.g.*, cryogenic atom probe tomography, *in-situ* monitoring using Raman spectroscopy, energy-filtered transmission electron microscopy, and isotope tagging). These new analytical techniques have allowed a more detailed characterization of the gel and other alteration layers that form on glass surfaces during corrosion. These techniques have led to an improved understanding of glass corrosion mechanisms and have contributed to developing more mechanistic glass corrosion models. DOE's continued support for the development of and use of such techniques and equipment in making measurements to understand the mechanisms that control corrosion of waste repository glass, including examination of existing glass samples from long-term corrosion experiments, would further improve the fundamental understanding of HLW glass corrosion and the predictive capability of glass corrosion models.

Robust international collaboration

It is evident there is an international scientific community that collaborates in investigating HLW glass corrosion, exchanging information, and developing a consensus regarding the mechanisms of corrosion. In his presentation, Dr. Ryan stated that this community meets at least once a year in conjunction with the American Ceramic Society Glass and Optical Materials Division meeting, and at other venues, to exchange data and ideas on glass corrosion models and experiments, and to identify problems and the research needed to solve them. The Board lauds

Telephone: 703-235-4473 Fax: 703-235-4495 www.nwtrb.gov

DOE's support that enables DOE-funded researchers to participate at these mutually beneficial meetings. Dr. Grambow, in his presentation, mentioned that a new European Union-funded project, JOPRAD (Joint Programme on Radioactive Waste Management and Disposal) was initiated in April 2017 and that part of the project will focus on nuclear waste glass corrosion. The Board notes that DOE participation in this European Union initiative would foster increased interaction among the researchers and facilitate continued progress in the development of DOE's new model.

Database enhancement and data analysis

In the U.S. and internationally, there is an immense amount of experimental data on glass corrosion. Some of these data have been incorporated into the ALTGLASS database, discussed by Dr. Jantzen at the meeting. Dr. Jantzen's meta-analysis of the data has resulted in improved understanding of what triggers the resumption of accelerated corrosion in Stage III. Dr. Ebert has used the results of her analyses to develop a modeling approach that could incorporate the mechanisms indicated by her observations into radionuclide source term calculations for repository performance assessment models. These efforts are noteworthy, but as Drs. Pegg and Grambow indicated, there are additional data in the United States and other countries that have not yet been incorporated into the ALTGLASS database. A sustained effort to compile all available data and to develop data analysis tools and techniques, such as Bayesian inference, would enable metadata analysis by researchers in the international collaboration. That effort could be used to identify important empirical correlations between parameters and corrosion rates, reduce duplicative experiments, and identify additional experimental studies needed to reduce uncertainties in model parameters. These efforts could lead to more mechanistic understanding of glass corrosion.

Long-term experiments are important

Several speakers noted how difficult it can be to predict the timing of commencement of Stage III accelerated corrosion and commented that some experiments that were terminated might have entered into Stage III if the tests had continued for a longer time. Given this uncertainty in Stage III initiation, it is impressive that VSL has been able to sustain some tests for 36 years. Long-term experiments appear to have been crucial to providing needed data on Stage III initiation (seventy five percent of the data currently recorded in the ALTGLASS database come from VSL experiments). Additional long-term studies on a wider range of glass compositions could help identify glass formulations that have the potential for entering Stage III corrosion.

Considering model uncertainties

As DOE develops support for a more refined glass corrosion model and adopts a new "consensus" model, it is important to recognize the uncertainties related to these models. In particular, the models may not include phenomena that were deemed unimportant in developing the model, but which may lead to glass corrosion rates higher than the "best estimate" or "consensus" models. For example, the past decade has seen advances in understanding the role that micro-organisms and organic molecules play in mediating and enhancing inorganic chemical processes. The speakers at the meeting felt that micro-organisms would not significantly influence glass corrosion rates, but this conclusion appears to be based primarily on a few, older studies. Similarly, the impact of radiation emitted by radionuclides immobilized in the HLW glass on its exterior alteration layer and on the precipitation of secondary (*e.g.*, zeolite) phases that could trigger Stage III is not well understood. Since cracking, crack geometry, and surface roughness have been shown to influence glass corrosion rates, understanding glass corrosion dependencies on these factors is also warranted. More generally, it is important to identify and understand processes that may occur in repository environments that could lead to corrosion rates higher than "best estimates."

Natural analogs

Dr. Verney-Carron presented interesting work on archeological and natural glass samples. Characterization of alteration layers in natural analogs and attempts to simulate the observed levels of alteration using geochemical models developed for nuclear waste glasses can provide important tests of the conceptual and rate models that are being used to simulate glass corrosion in geologic repositories. However, using natural analogs to validate models for HLW glass corrosion is challenging because the conditions to which the natural analogs were exposed is poorly known in many cases and the compositions of the natural analog materials do not match the borosilicate compositional range of waste glasses.

Bounding estimates of glass durability

Dr. Jantzen explained that HLW glass is qualified for disposal in a geologic repository by comparing its short-term, laboratory-measured leach rate to that of a reference glass whose properties are utilized in the total system performance assessment. Confirmation that the reference glass corrosion rate is a bounding value is established via accelerated corrosion experiments of the as-manufactured glass using ASTM standard test procedures. A question deserving continued attention, as more becomes known about glass corrosion, is whether the ASTM standard test procedures assure that usage of the reference glass for comparison still provides bounding estimates of glass durability.

Effective integration of DOE program

At the meeting, the Board observed a notable integration within the DOE program and between the various groups working on the glass R&D program. The presentations and discussions at this Board meeting indicated there has been increasing collaboration among the different groups since the Board's meeting in 2013 on vitrifying HLW stored at the Hanford site. It was also apparent that the U.S. program is integrated with the international community working in this area. Additional coordination within DOE, with the Offices of Science, Environmental Management, and Nuclear Energy working together, is evidenced by the establishment of new Office of Science Energy Frontier Research Centers such as the Center for Performance and Design of Nuclear Waste Forms and Containers (WastePD) at the Ohio State University and the Interfacial Dynamics in Radioactive Environments and Materials (IDREAM) center at PNNL. The Board commends such integration which engenders internal critical review of results.

Telephone: 703-235-4473 Fax: 703-235-4495 www.nwtrb.gov

Thank you again for the participation of DOE staff and technical experts from the national laboratories at our June meeting. In particular, we thank Dr. Patricia Paviet and Ms. Kimberly Gray, both of DOE-NE, for their efforts in coordinating the national laboratory speakers and presentations. We look forward to continuing our ongoing review of DOE's technical activities related to the management and disposal of SNF and HLW.

Sincerely,

Jean M. Bahr
Chair

Attachment

Telephone: 703-235-4473 Fax: 703-235-4495 www.nwtrb.gov

APPENDIX
Glass Corrosion Mechanisms and Kinetics

Borosilicate glass corrosion in water has been studied extensively, resulting in a large database of experimental results. Based on these results, consensus has emerged that borosilicate glass corrosion follows three main stages corresponding to different rate-limiting mechanisms: the initial corrosion rate (Stage I), the residual rate (Stage II), and, under certain conditions, a resumption of increased corrosion (Stage III). Figure 1 illustrates these stages and the proposed rate-limiting mechanisms.

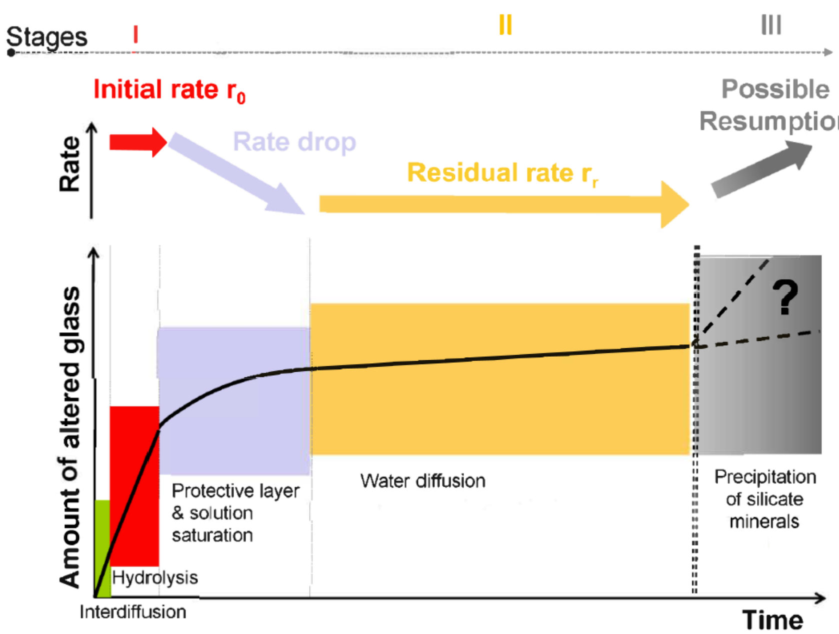

Figure 1. Glass corrosion stages and related rate-limiting mechanisms (modified after Gin *et al.* 2013)

During Stage I, glass corrosion is characterized by diffusion of water into the glass structure, ion exchange, and hydrolysis of the silicate network. Ion exchange, also called interdiffusion, occurs between protonated species in solution (H^+ or H_3O^+) and weakly bound, "glass network-modifier" alkali metal and alkaline earth elements[5] in the glass, which are released into solution as ions (*e.g.*, Na^+ and Ca^{2+}). Hydrolysis (or dissolution) of the glass network-forming elements

[5] In borosilicate glasses, silicon atoms, together with other "glass network-forming" elements (*e.g.*, aluminum, boron, and zirconium) that readily form bridging bonds with oxygen atoms, provide the highly cross-linked glass network. Alkali and alkaline earth elements alter the network structure ("glass network-modifiers"); they are usually present as ions (*e.g.*, Li^+, Na^+, K^+, and Ca^{2+}) and are charge compensated by nearby non-bridging oxygen atoms.

8

also occurs, which breaks the covalent bonds (Si–O–M, where M = silicon, aluminum, boron, zirconium, *etc.*) that form the glass network and releases into solution the elements constituting the glass (*e.g.*, silicon as H_4SiO_4) as well as radionuclides bound in the glass.

The initial corrosion rate reveals the "forward rate" of the reaction and is relatively high, but the corrosion rate drops as the reaction proceeds. Early studies on glass corrosion attributed this rate drop to an increase in dissolved silica concentration, which decreases the affinity (or driving force) for hydrolysis of the Si–O bonds. Later experiments using various techniques indicated the importance of transport limitation through an alteration layer. In the early 2000s, the European project GLAMOR[6] (Van Iseghem *et al.* 2006, 2007) concluded that two mechanisms must be taken into account to explain the rate drop: the onset of high silica concentration in solution slows down the dissolution of the silicate network (affinity effect) and the formation of a protective alteration layer limits the transport of aqueous species (passivation effect).

The corrosion rate drop does not last indefinitely—the rate tends to stabilize at a relatively constant value, called the residual rate, in Stage II. The residual rate is typically orders of magnitude lower than the Stage I initial rate. Stage II of glass corrosion generally begins once the solution becomes saturated with respect to amorphous silica (Gin *et al.* 2012). During that stage in a closed system, the dissolved silicon concentration reaches a steady state, but the aqueous concentrations of the more soluble glass components (*e.g.*, sodium, calcium, and boron) continue to increase, albeit at a low rate (Ferrand *et al.* 2006; Gin *et al.* 2015a, 2015b). Ion exchange and hydrolysis reactions still occur, but at a much reduced rate controlled by the reactive transport of water species through the alteration layer. This layer acts to diminish the accessibility of water to the unaltered glass. Stage II is considered the most important glass corrosion stage in most geologic disposal performance assessments because the residual rate is thought to be the rate that likely will determine the performance of HLW glasses in a repository at times before the HLW radioactivity decays to negligible levels. If the residual rate is maintained, the glass matrix could have lifetimes of at least several hundreds of millennia (ANDRA 2005).

Under certain conditions (*e.g.*, $T > 90$ °C and/or $pH > 10.5$), a sudden increase in glass corrosion rate (Stage III) can occur. The increased rate typically is associated with the precipitation of secondary silicate phases, such as phyllosilicates (*e.g.*, smectite clays), zeolites, phosphates, and calcium-silicate-hydrates. Precipitation of these phases removes dissolved silicon and other glass network-forming elements from the solution, which could increase the driving force for dissolution. Elements may also be removed from the passivating layer, which could result in a loss of its armoring properties.

[6] GLAMOR = A Critical Evaluation of the Dissolution Mechanisms of High-level Nuclear Waste Glasses in Conditions of Relevance for Geological Disposal (Van Iseghem *et al.* 2006).

References

ANDRA (Agence nationale pour la gestion des déchets radioactifs). 2005. *Dossier 2005 Argile: Synthesis—Evaluation of the feasibility of a geological repository in an argillaceous formation*. Paris, France: ANDRA.

Ferrand, K., A. Abdelouas, and B. Grambow. 2006. "Water Diffusion in the Simulated French Nuclear Waste Glass SON68 Contacting Silica Rich Solutions: Experimental and Modeling." *Journal of Nuclear Materials*, Vol. 355, pp. 54–67.

Gin, S., A. Abdelouas, L.J. Criscenti, W.L. Ebert, K. Ferrand, T. Geisler, M.T. Harrison, Y. Inagaki, S. Mitsui, K.T. Mueller, J.C. Marra, C.G. Pantano, E.M. Pierce, J.V. Ryan, J.M. Schofield, C.I. Steefel, and J.D. Vienna. 2013. "An International Initiative on Long-Term Behavior of High-Level Nuclear Waste Glass. *Materials Today*, Vol. 16, pp. 243–248.

Gin, S., X. Beaudoux, F. Angéli, C. Jégou, and N. Godon. 2012. "Effect of Composition on the Short-Term and Long-Term Dissolution Rates of Ten Borosilicate Glasses of Increasing Complexity From 3 to 30 Oxides." *Journal of Non-Crystalline Solids*, Vol. 358, pp. 2559–2570.

Gin, S., P. Jollivet, M. Fournier, F. Angeli, P. Frugier, and T. Charpentier. 2015a. "Origin and Consequences of Silicate Glass Passivation by Surface Layers." *Nature Communications*. Vol. 6, pp. 1–8.

Gin, S., P. Jollivet, M. Fournier, C. Berthon, Z. Wang, A. Mitroshkov, Z. Zhu, and J.V. Ryan. 2015b. "The Fate of Silicon During Glass Corrosion Under Alkaline Conditions: A Mechanistic and Kinetic Study with the International Simple Glass." *Geochimica et Cosmochimica Acta*, Vol. 151, pp. 68–85.

Van Iseghem, P., M. Aertsens, S. Gin, D. Deneele, B. Grambow, P. McGrail, D. Strachan, and G. Wicks. 2007. *A Critical Evaluation of the Dissolution Mechanisms of High-level Waste Glasses in Conditions of Relevance for Geological Disposal (GLAMOR)*. Contract No. FIKW-CT-2001-00140 Final report. European Commission.

Van Iseghem, P., K. Lemmens, M. Aertsens, and T. McMenamin. 2006. "Chemical Durability of High-level Waste Glass in Repository Environment: Main Conclusions and Remaining Uncertainties from the GLASTAB and GLAMOR Projects." *Materials Research Society Symposium Proceedings*, Vol. 932, pp. 293–304.

Attachment

AGENDA

Summer Board Meeting

Wednesday, June 21, 2017

Courtyard Richland Columbia Point
480 Columbia Point Drive
Richland, WA 99352
509-942-9400

8:00 a.m. **Call to Order and Introductory Statement**
Jean Bahr, Board Chair

8:15 a.m. **Welcoming Remarks**
Jud Virden, Associate Laboratory Director, Pacific Northwest National Laboratory

8:20 a.m. **Modeling of Glass Performance in Repository Environments—An International Perspective**[7]
Bernd Grambow, SUBATECH, France

i. What are the various approaches to modeling glass corrosion in repository environments and how do different countries take account of glass corrosion and radionuclide release in repository performance assessments?
ii. What are the remaining technical gaps or uncertainties in understanding and modeling of long-term glass performance in repository environments and how important is glass performance to the overall safety case for different repository designs?

8:55 a.m. *Questions, discussion*

9:15 a.m. **Break**

9:30 a.m. **DOE Strategy for Glass Waste Form Acceptance for Geologic Disposal**
Carol Jantzen, Savannah River National Laboratory

i. What are the technical bases, including standards, test methods, and use of databases and models, for DOE's criteria for qualifying borosilicate glass waste forms as acceptable for disposal in a geologic repository?
ii. What is DOE's technical basis for applying the results of short-term tests on reference glasses or glasses with simplified compositions to assessments of the long-term performance of more chemically complex HLW glasses in repository environments?

[7] Note: Questions were provided to the speakers in advance to convey the Board's primary interests in the agenda topics and to aid in focusing their presentations.

A-1

iii. What is known about the influence of glass chemistry on crystallite precipitation during glass production and on glass corrosion, and how are crystallites taken into account in DOE's approach to designing glass for disposal in a repository?
iv. Are data on natural and archeological glasses used to support DOE assessments of the long-term performance of HLW glass in a repository and, if so, how?

10:05 a.m. *Questions, discussion*

10:25 a.m. **Current Understanding and Remaining Challenges in Measuring and Modeling Long-term Performance of Borosilicate Nuclear Waste Glasses**
Stéphane Gin, French Atomic Energy and Alternative Energies Commission

i. What is the current understanding of the processes responsible for glass corrosion and release of radionuclides into the environment? What experimental data support this understanding? What are the key parameters affecting the rate of each of the processes and how have these been used in models?
ii. What are the remaining technical challenges to measuring glass corrosion and modeling the long-term performance of borosilicate nuclear waste glasses?

11:00 a.m. *Questions, discussion*

11:20 a.m. **Public Comments**

11:35 a.m. **Lunch Break (1 hour 10 minutes)**

12:45 p.m. **Glass Formulation and Durability Studies at the Vitreous State Laboratory**
Ian Pegg, Catholic University of America

i. Describe the results of studies the Vitreous State Laboratory has conducted for the U.S. program and for other countries and how these are shared and used to understand glass corrosion mechanisms and long-term performance in repository environments.

1:15 p.m. *Questions, discussion*

1:35 p.m. **DOE Studies to Improve Understanding of Rate-Limiting Mechanisms under Varying Conditions**
Joseph Ryan, Pacific Northwest National Laboratory

i. From DOE's perspective, what are the most important remaining technical uncertainties or gaps in data and understanding of the long-term performance of HLW glass? How is DOE addressing those uncertainties or gaps?
ii. What are the status and results of DOE R&D activities to understand and model the long-term performance of borosilicate HLW glass?
iii. Describe the results of recent DOE studies, if any, on natural and archeological analogs of nuclear waste glass. How are the results used to support assessments of the long-term performance of HLW glass?

iv. How is DOE integrating the results of international R&D activities and activities completed at different national laboratories in the U.S. on nuclear waste glass corrosion into its assessments of HLW glass long-term performance?

2:10 p.m. *Questions, discussion*

2:30 p.m. **Break**

2:45 p.m. **DOE High-Level Waste Glass Corrosion Model and Its Implementation in Safety Analysis**
William Ebert, Argonne National Laboratory

i. What are the recent improvements in DOE models for HLW glass corrosion? How are these improvements helpful to the DOE HLW geologic disposal program?
ii. How do the models take account of the important glass corrosion mechanisms and the range of environmental conditions expected for different repository host-rock types and near-field environments? How are environmental conditions such as dissolved organic matter and the presence of microbial life being investigated?
iii. How do the models take account of the wide range in DOE HLW glass compositions to be produced at the Waste Treatment and Immobilization Plant and the Defense Waste Processing Facility?
iv. How are the models and model parameters supported by experimental data, including the large database of glass dissolution experiments managed by DOE personnel?
v. What is DOE's technical basis for using the results of short-term, small-scale tests on glass corrosion to support assessments of long-term glass performance in a repository?
vi. How are the process-level models of glass corrosion and radionuclide release integrated into repository performance assessments? How important is glass performance to the overall safety case for different repository designs?

3:20 p.m. *Questions, discussion*

3:40 p.m. **Studies on Natural and Archeological Glasses—Opportunities to Learn About Long-term High-Level Waste Glass Corrosion**
Aurélie Verney-Carron, University Paris-Est Créteil

i. What have we learned from studies on natural and archeological glasses regarding the corrosion and long-term performance of nuclear waste glasses?
ii. Are the rate-limiting mechanisms the same for natural and for nuclear waste glasses? Have researchers found evidence that natural glasses alter in stages such as those observed for nuclear waste glasses? Is there evidence that corrosion rates increase at late stages in natural systems? What corrosion rates have been estimated for natural glasses?
iii. What causes the large discrepancies between silicate mineral dissolution rates measured in the laboratory and those measured in the field? Is this discrepancy also noted for glassy natural analogs?

A-3

iv. Are the kinetic models used for predicting nuclear waste glass corrosion able to take account of glass corrosion on a geological timescale?

4:10 p.m.	*Questions, discussion*
4:30 p.m.	**Quick Look at Poster Papers**
5:05 p.m.	**Public Comments**
5:20 p.m.	**Adjourn Public Meeting**
5:30 p.m.	**Poster Session: Research Related to Long-Term Performance of Nuclear Waste Glasses**

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

August 25, 2017

Mr. Edward McGinnis
Acting Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Mr. McGinnis:

In a meeting on February 8, 2017[1], Ned Larson of the Department of Energy (DOE), and Ken Sorenson of the Sandia National Laboratories (SNL) charged Sylvia Saltzstein of SNL with generating an overall integrated approach to the sister rod[2] testing plan to support the High Burnup Dry Cask Storage Research and Development Program (HDRP). On August 2, 2017, Ms. Saltzstein distributed[3] the revised test plan, "EPRI/DOE High Burnup Fuel Sister Pin Test Plan Simplification and Visualization" (SAND2017-7597, July 2017) to the participants in the February 8th meeting and others for review and comment. This letter transmits the comments generated by the Nuclear Waste Technical Review Board (Board) during its review of the test plan. The Board appreciates the opportunity to offer its comments.

The Board believes the simplified, phased approach defined in the plan improves its transparency and flexibility, and constitutes a prudent approach to this unique opportunity for destructive characterization of high-burnup fuel (HBF) rods. DOE clearly sought external input and reflected it in the technical content of the report.

The proposed tests appear appropriate and reasonable, and we agree with the recommendation to use ASTM or Nuclear Regulatory Commission (NRC) test methods such as ring compression testing and testing with the Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT). This action addresses one of our previous concerns. In addition, the Board believes it is prudent that other testing details will be decided in a stepwise approach. These details include which tests need to be conducted, how many tests will be conducted, and where the tests will be conducted. The plans to use sections near the top and bottom of the rods to get a range of burnups and to perform mechanical testing at room temperature and 200°C are appropriate.

[1] Dr. Lee Peddicord of the Board, and Dr. Einziger of the staff attended this meeting.
[2] A "sister rod" is a rod that has been determined to have very similar characteristics to one that will be stored in the HDRP Cask. There are two potential donor fuel assembly sources for sister rods: assemblies having similar operating histories to those assemblies that have been chosen for storage in the HDRP Cask and actual fuel assemblies selected for storage. Properties that must be similar in order to be considered a" sister" are the cladding type (e.g., Zircaloy-4, Zirlo, M5), the initial enrichment, the relative reactor core location, and the reactor operating history when the fuel was being irradiated.
[3] Sylvia Saltzstein e-mail August 2, 2017 – "EPRI/DOE Sister Pin Simplified Test Plan"

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

The Board also offers some suggestions to further strengthen and clarify the test plan:

1. On page 12, the plan says it will "narrow the focus of the sister-pin test plans to two goals: 1. Identify types and number of tests to provide a core set of material property and physical data that can be compared to the ten-year stored rods", and "2. Provide core baseline data of the pre-stored rods for comparison to post stored-rods". The planned heat treatment (cask drying simulation) tests to be conducted at 400°C are not related to either of these goals because the temperature of the ten-year-old, pre-stored, and post-stored rods will be much less than 400°C. The plan would be improved by including the technical goals to be met by the tests at 400°C.

2. Based on previous discussions and report reviews, the Board notes that one of the purposes of the heat treatment tests is to provide data to support modeling efforts that will allow the test results to be extended to other types of HBF. However, the plan does not address how test results will be used in the modeling efforts. It would be useful to identify the models and the test data that the models will use.

3. In several bullets in Sec 4.2, the plan says, "test using 6-inch defueled segments and at least one grid spacer". Indication of whether this means that portions of grid spacers will be tested, or that rod segments at the axial location of the grid spacer will be tested, would provide more clarity.

4. The HDRP sister rods constitute a valuable resource for research and development to meet presently unforeseen needs related to spent nuclear fuel management and disposal. The Board is pleased that the plan recognizes this and says that "After the high priority testing, if there is time and budget, more data can be obtained from the 25 high burnup sister rods." How the rods will be stored so that their characteristics do not change during storage and how documentation on these rods will be preserved for future use need to be considered in the near term.

5. The time sequence of executing the planned tests may be important. The plan should define and provide the logic for the time sequence of executing the planned tests.

Once again, the Board thanks you for the opportunity to review this sister rod characterization and testing plan. We look forward to reviewing the evolving technical details of how testing will be accomplished in a practical, relevant manner and how the results will be linked to modeling efforts.

Sincerely,

Jean M. Bahr

Jean M. Bahr
Chair

cc: Jack Wheeler (DOE, Office of Nuclear Energy)
Bill Boyle (DOE, Office of Nuclear Energy)
Ned Larson (DOE, Office of Nuclear Energy)
Sylvia Saltzstein (SNL)

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

Department of Energy
Washington, DC 20585

RECEIVED SEP 19 2017

September 12, 2017

Dr. Jean M. Bahr
Nuclear Waste Technical
Review Board
2300 Clarendon Boulevard
Suite 1300
Arlington, VA 2201-3367

Dear Dr. Bahr:

Thank you for your August 25, 2017 letter providing the Nuclear Waste Technical Review Board (Board) comments on the "EPRI/DOE High Burnup Fuel Sister Pin Test Plan Simplification and Visualization" (SAND2017-7597, July 2017).

This project continues to be very important to the DOE, and the Board and staff have consistently worked with us on this project. Your comments on our test plan provide useful insights and we look forward to future interactions with the Board. If you require further clarification regarding any of these issues, please contact me or William Boyle, at (702) 295-2436.

Sincerely,

Edward G. McGinnis
Acting Assistant Secretary
for Nuclear Energy

Printed with soy ink on recycled paper

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

November 7, 2017

Mr. Edward McGinnis
Acting Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Mr. McGinnis:

Thank you for the opportunity to review the latest draft of the sister rod test plan, "EPRI/DOE High-Burnup Fuel Sister Rod Test Plan Simplification and Visualization" (SAND2017-10310 R, September 15, 2017). Due to the limited time between receipt of the draft report (October 10, 2017) and your preferred comment deadline (November 2, 2017)[1], the Board reviewed only the main body of the draft.

We believe the report would be improved if the following points were clarified:

1. The draft plan lays out the destructive examination tests to be completed, but it also refers to the attached Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNNL) test plans. If there are differences in the tests to be performed between the new test plan and the attached individual laboratory test plans, is it correct that the tests defined in the new plan take precedence?
2. Step 1, page 4 indicated that all 25 rods will be punctured at ORNL. Will the rods being sent to PNNL be resealed? If not, how will the internal atmosphere in the rods be controlled?
3. Step 3, page 4 states, "pressurized to End-of-Life Rod-Internal-Pressures representative of pressures at 400°C." Should this be interpreted as the maximum pressure in the current fleet of spent nuclear fuel expected to be stored, as this would likely imply pressurizing to the end of life pressure associated with Integral Fuel Burnable Absorber [2] rods that have not been included in the testing program?

In the Board's recent review of the test plan, "EPRI/DOE High Burnup Fuel Sister Pin Test Plan Simplification and Visualization" (SAND2017-7597, July 2017), the Board raised the following issues that do not appear to be addressed in this version of the plan. We believe the usefulness of the plan would be enhanced if these issues, quoted below from our August 25, 2017 letter regarding this subject, could be addressed before it is released.

---

[1] In a recent meeting, Mr. Ned Larson indicated that the Board could have extra time to comment on the report.
[2] Fuel rods containing a burnable poison used to control the reactivity level in the reactor.

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

1. Based on previous discussions and report reviews, the Board notes that one of the purposes of the heat treatment tests is to provide data to support modeling efforts that will allow the test results to be extended to other types of HBF (high burnup fuel). However, the plan does not address how test results will be used in the modeling efforts. It would be useful to identify the models and the test data that the models will use.
2. The HDRP (High Burnup Dry Storage Cask Research Project) sister rods constitute a valuable resource for research and development to meet presently unforeseen needs related to spent nuclear fuel management and disposal. The Board is pleased that the plan recognizes this and says that "After the high priority testing, if there is time and budget, more data can be obtained from the 25 high burnup sister rods." How the rods will be stored so that their characteristics do not appreciably change during storage and how documentation on these rods will be preserved for future use need to be considered in the near term.

Since any follow-up work will be based on the outcome of the testing outlined in this test plan, members of the Board would like to observe future meetings held to evaluate the test results and discuss how to proceed with further testing.

Once again, the Board thanks you for the opportunity to review this and previous sister rod characterization and testing plans. We look forward to reviewing the evolving technical results and details of how testing will be accomplished, and how the results will be linked to modeling efforts.

Sincerely,

Jean M. Bahr

Jean M. Bahr
Chair

cc: Mr. Ned Larsen (DOE, Office of Nuclear Energy)
Ms. Nancy Buschman (DOE, Office of Nuclear Energy)
Ms. Sylvia Saltzstein (SNL)

Telephone: 703–235–4473 Fax: 703–235–4495 www.nwtrb.gov

Department of Energy
Washington, DC 20585

February 2, 2018

Dr. Jean M. Bahr
Chair
Nuclear Waste Technical Review Board
2300 Clarendon Boulevard
Suite 1300
Arlington, VA 22201-3367

Dear Dr. Bahr,

We appreciate your review of the latest draft of the "EPRI/DOE High-Burnup Fuel Sister Rod Test Plan Simplification and Visualization." The Board raised five points that are addressed below.

NWTRB suggestions to improve clarity of the report:

1. The Board's first question asks if the *High-Burnup Fuel Sister Rod Test Plan Simplification and Visualization* tests take precedence over the attached PNNL and ORNL plans. For Phase 1 testing, the NWTRB is correct. Tests defined in the *Simplified and Visual Plan* take precedence over those discussed in the ORNL and PNNL plans located in the Appendices. During Phase 2 testing, the community will draw from the tests described in the PNNL and ORNL plan for potential future testing to target the quantification of more specific mechanical attributes.

2. The Board's second question asks how the 25 sister rods will be resealed to maintain the internal atmosphere. Care will be taken to ensure the seals are not made in a way that could affect the cladding or fuel. The rods will be punctured at ORNL and then placed in tubes and sealed with Swagelok® (or similar) fittings. The tubes will be filled with an inert gas to remove moisture and oxygen from the environment. Each lab will document their method for storage.

3. The Board's third question asks if the rods heat treated to 400°C could be interpreted to mean that we would pressurize to the highest pressures in the current fleet. The answer to this question is no. The 400°C rods will be pressurized to a pressure close to the pressure that is realistically representative of the internal pressure the rod in the High-Burnup Spent Fuel Data Project would experience at 400°C. We are aware there are different types of rods in the fleet that have higher pressures and those conditions may be addressed in Phase 2, we may try to obtain some Integral Fuel Burnable Absorber (IFBA) rods, or we may take a more analytical path to address these rods.

NWTRB suggestions to improve the usefulness of the report:

1. The Board's first suggestion for improvement requests an identification of the specific models that will be used in the future. Identification of specific models is out of the scope of this test plan, but we intend for all the data in the Phase 1 testing to be used in models and we will share the data with interested modelers.
2. The Board's second suggestion for improvement asks how PNNL and ORNL will store the rods for future testing. The rods will be punctured at ORNL and then placed in tubes sealed with Swagelok fittings. The tubes will be filled with an inert gas to remove moisture and oxygen from the environment and stored in a hot cell.

DOE appreciates the Board's review of this and previous versions of this document and looks forward to continued input and insight from the Board on this topic as the testing progresses.

Sincerely,

Raymond V. Furstenau
Associate Principal Deputy Assistant Secretary
for Nuclear Energy

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

June 27, 2018

The Honorable Anne White
Assistant Secretary for Environmental Management
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Mr. Ed McGinnis
Principal Deputy Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Ms. White and Mr. McGinnis:

On behalf of the U.S. Nuclear Waste Technical Review Board (Board), I want to thank you and your staff for supporting the Board's 2018 Summer Meeting, which was held on June 13, 2018, in Idaho Falls, Idaho. The purpose of the meeting was to identify and discuss technical and integration issues that will need to be addressed before the Department of Energy (DOE) can implement a nationwide program to transport commercial and DOE-managed spent nuclear fuel (SNF) and high-level radioactive wastes (HLW). To remove SNF and HLW from their current storage locations at commercial power plant sites and federal facilities around the country, transportation of the wastes will be necessary. The agenda and presentation materials for the 2018 Summer Meeting are posted on the Board's website at http://www.nwtrb.gov/meetings/past-meetings/summer-2018-board-meeting---june-13-2018. Materials submitted by members of the public as part of the meeting record will also be posted on the same web page.

Nuclear waste transportation has been a topic of Board review since the Board first began operation almost thirty years ago. Congress created the 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 and to advise Congress and the Secretary on technical issues related to nuclear waste management. Among the topics specifically identified in the law for Board evaluation is the transportation of SNF and HLW.

Consistent with the ongoing national discussions regarding nuclear waste management, the Board has continued its efforts to evaluate issues related to the need to prepare for transporting nuclear wastes from where they are now stored to a permanent repository or a temporary interim storage facility. These efforts have included staff-to-staff discussions with DOE, fact-finding meetings at national laboratories, and the 2018 Summer Meeting. This letter provides some preliminary Board observations, based on the meeting presentations and information gathered to date. As part of its ongoing evaluation of this topic, the Board is also planning future review activities and is developing a report on the technical and integration issues that will need to be addressed before DOE can implement a nationwide effort to transport nuclear wastes. The report, which we expect to issue later this year, will reflect the information obtained during future review activities as well as the information presented and discussed at the 2018 Summer Meeting.

The scope of the technical issues to be addressed before a large transportation effort can begin is broad. These issues include uncertainties about the condition of the SNF to be transported, particularly the many DOE-managed SNF types and commercial SNF that was used in reactors for relatively long periods ("high burnup" SNF). These uncertainties lead to questions about the ability of these SNFs to meet the requirements for transportation.

Other uncertainties apply to the casks and canisters storing SNF and HLW. As an example, for commercial SNF, there are questions about the transportability of some of the welded stainless-steel canisters that are prevalent in dry storage at commercial nuclear power plant sites. For commercial SNF canisters and for the welded stainless-steel canisters storing DOE-managed SNF and HLW, inspections may have to be conducted prior to transportation to ensure the canisters have not experienced corrosion or other degradation that may prevent the canisters from meeting the transportation requirements. Addressing these and other issues, as well as integrating the waste transportation program within DOE and with the activities of other organizations such as the Nuclear Regulatory Commission (NRC), the Department of Transportation, the States, and the private sector will require significant advanced planning and coordination.

At its 2018 Summer Meeting, the Board heard presentations from past and present transportation system managers at DOE and staff involved in current activities related to transportation planning. The Board also heard from representatives of the nuclear industry, including domestic companies and one utility in Switzerland, and from representatives of stakeholder groups and the NRC. Based on these presentations and previous interactions with DOE, the Board makes the following preliminary observations.

- DOE's preliminary evaluations of removing commercial SNF from shutdown sites, which involved working with site personnel, utilities, and local stakeholders, have generated valuable information and are important to continue. As these studies have shown, considerable planning and coordination will be required to refurbish or re-establish the capabilities to handle and load SNF containers, re-constitute needed site infrastructure (e.g., electrical power, radiological controls), and rebuild the roadways and/or rail lines necessary to support SNF transportation.
- The current effort by the DOE Office of Nuclear Energy (NE) to plan and coordinate a nationwide transportation program does not appear to be well integrated with activities of the DOE Office of Environmental Management (DOE-EM). Furthermore, the current transportation program plan does not include sufficient consideration of the SNF and HLW materials and packages that are managed by DOE-EM.
- The Waste Isolation Pilot Plant (WIPP) transportation approach represents a useful model and provides relevant lessons for the development of a nationwide transportation program for SNF and HLW. However, transuranic waste is transported to WIPP by road, while

transportation of commercial SNF is expected to be mostly by rail, so the differences between highway and rail transport will need to be considered in applying WIPP experience in developing the SNF and HLW transportation program.

- Several presenters emphasized the need for early and continuous engagement and collaboration between DOE and stakeholders at the state and local level as well as other organizations such as nuclear utilities and rail carriers that are essential to ensuring an effective nationwide transportation program.

- Several presenters mentioned that a lack of adequate and predictable funding adversely affects the development of a transportation program, including, for example, advanced procurement of casks and other essential equipment, full stakeholder engagement, and emergency preparedness planning.

- DOE will need to develop designs for new casks and canisters for transporting DOE-managed SNF and HLW. Additional types of new casks and canisters may be required for the transport of some commercial SNF. Furthermore, several presenters noted advantages to developing a waste management program based on new standardized cask and canisters designs. Given the need for new cask and canister designs, several presenters noted that the lead times for licensing and procurement of any new types of casks and canisters may be greater than ten years, and therefore, considerable advanced coordination with NRC will be required.

- The advances made by DOE-NE in developing the system analysis and planning tools are to be commended. These tools will be a major asset in designing the transportation program, particularly as development of the tools is continued and as DOE gains access to the detailed technical information necessary to conduct realistic system analyses.

Further details about these and other Board observations, findings, and associated recommendations are expected to be included in the Board report on this topic.

The Board also would like to thank you for your support of tours and technical briefings for the Board on June 11, 2018, at the Idaho National Laboratory. Staff members in the DOE Offices of Nuclear Energy and Environmental Management, the DOE Idaho Field Office, and the Idaho National Laboratory ensured the tours and briefings proceeded effectively and efficiently. These interactions provided valuable information for the Board as it continues its evaluation of DOE activities related to the management of SNF and HLW. We look forward to future productive interactions with you and your staff.

Sincerely,

Jean M. Bahr

Jean M. Bahr
Chair

cc:
Dr. William Boyle, DOE Office of Nuclear Energy
Mr. Kenneth Picha, DOE Office of Environmental Management

3

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

November 27, 2018

Mr. Edward McGinnis
Principal Deputy Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Mr. McGinnis:

The U.S. Nuclear Waste Technical Review Board (Board) held its 2018 Fall Meeting on October 24, 2018, in Albuquerque, New Mexico, to review information on recent U.S. Department of Energy (DOE) research and development (R&D) activities related to managing and disposing of commercial spent nuclear fuel (SNF). The public meeting included presentations by representatives of DOE and four national laboratories. The meeting agenda, presentation materials, archived recording of the webcast, and materials submitted by members of the public as part of the meeting record are available on the Board's website at https://www.nwtrb.gov/meetings/past-meetings/fall-2018-board-meeting---october-24-2018. The meeting transcript will be posted on the same web page in the near future.

The Board extends its appreciation to your staff and the technical experts from the national laboratories for their work preparing for the meeting and providing informative presentations. The Board also thanks them for supporting a technical fact-finding meeting that was held on August 22, 2018, in Las Vegas, Nevada. This fact-finding meeting involved more detailed presentations of technical issues related to managing and disposing of commercial SNF and enabled the Board to better prepare for the October 24 public meeting. We also thank the Sandia National Laboratories (SNL) staff for providing an informative tour of SNL experimental facilities in Albuquerque, New Mexico, on October 25, 2018.

Background

During the past few years, DOE has conducted several R&D activities related to the management and disposal of commercial SNF. First, DOE has been doing research, including the High-Burnup Spent Nuclear Fuel Data Project (HDRP), to determine the performance and potential degradation of high-burnup SNF during extended storage and subsequent transportation. In 2016, the Board held two fact-finding meetings and a public meeting to hear from DOE and its contractors from the national laboratories on the initial results of the HDRP and to discuss with them the issues pertaining to resolving several technical information needs related to understanding the performance of high-burnup SNF during extended storage and transportation. After the public meeting, the Board sent to DOE a letter with recommendations.[1] Since that

[1] May 23, 2016, Board letter to Acting Assistant Secretary John Kotek following up the Board Meeting held February 17, 2016. In the letter, the Board recommended "that DOE make transparent how it integrates the results from Nuclear Energy University Programs, and other relevant U.S. and foreign research activities into its overall research program on high-burnup fuel degradation." At the October 24, 2018, public meeting, DOE discussed how it addressed this recommendation.

Telephone: 703-235-4473 Fax: 703-235-4495 www.nwtrb.gov

time, DOE and its contractors have made significant progress on obtaining the required data, including those related to cask drying, thermal measurements and modeling, hydride reorientation, and SNF rod non-destructive and destructive evaluations.

Second, DOE recently completed a test that transported an Equipos Nucleares Sociedad Anónima (ENSA) SNF cask containing simulated SNF assemblies from Spain to the United States, via truck, barge, cargo ship, and train, supplemented by additional testing at the Transportation Technology Center in Pueblo, Colorado. The purpose of the tests was to determine the actual stresses SNF may experience during normal conditions of transport.

Third, DOE has been evaluating the technical feasibility of direct disposal of SNF in dual-purpose canisters (DPCs) in a geologic repository. In the United States, the majority of SNF already in dry storage, as well as nearly all SNF currently being placed into dry storage, are in DPCs. DPCs containing SNF can be stored in licensed storage overpacks or vaults, and also can be transported to an interim storage facility or a geologic repository in licensed transportation overpacks. Direct disposal of SNF in DPCs, sealed in disposal overpacks, is a possible alternative to repackaging the SNF into other containers prior to disposal in a repository.

Board Meeting Presentations

At the Board's 2018 Fall Meeting in Albuquerque, staff from DOE and the national laboratories provided to the Board an update on the results of and conclusions from the work that has been completed and on the progress of on-going research. The first presentation was by William Boyle [DOE Office of Nuclear Energy (DOE-NE)], who provided an update on DOE's spent fuel and waste disposition program. In a following presentation, Brady Hanson [Pacific Northwest National Laboratory (PNNL)] described the recent results of and future plans for the HDRP. These included the measurements and computer modeling of the temperatures inside the TN-Americas (Orano) TN-32 SNF cask that was loaded with actual high-burnup SNF. He also discussed sampling of gas inside the cask. Samuel Durbin (SNL) followed with a presentation on the thermal-hydraulic measurements conducted using a scaled test assembly at SNL that simulates a dry-storage cask for boiling water reactor fuel. The simulator uses electrical heaters shaped like fuel rods as a heat source instead of actual spent fuel. The measurements were done to verify the accuracy of computational modeling that, for example, can be used to calculate the temperatures of materials in dry-storage casks.

Next, Rose Montgomery [Oak Ridge National Laboratory (ORNL)] presented the initial results of post-irradiation characterization of "sister rods," which are fuel rods that have been removed from assemblies that went into the HDRP dry-storage cask or from assemblies with similar irradiation histories. The characterization included visual examinations, gamma radiation scans, eddy current scans, and measurements of rod diameter, free volume, internal pressure, and gas transmission. Michael Billone [Argonne National Laboratory (ANL)] ended the morning session with a presentation on recent results of and future plans for tests related to hydride reorientation in SNF cladding. This testing is part of efforts to better understand changes in cladding properties and degradation mechanisms due to hydride reorientation, and the potential implications for cladding integrity during transport following extended storage.

Sylvia Saltzstein (SNL) started the afternoon session with an overview presentation of the ENSA cask multimodal transport test. Nicholas Klymyshyn (PNNL) then discussed the results of the test, concluding that the data show the shock and vibration loads on the SNF rods during normal conditions of transport are below the level at which damage to the SNF would be expected to occur. He also discussed the use of the test data to validate structural response models, which will be used to evaluate the impact of similar shock and vibration loads on other fuel types and during transportation operations using other conveyance systems. In the following presentation, Ned Larson (DOE-NE) summarized the work DOE has completed and the path forward for DOE R&D on storage and transportation activities, including how the work completed and planned will serve as a basis to understand high-burnup SNF performance during extended storage and subsequent transportation for conditions differing from those experimentally observed.

The presentations then shifted to the subject of direct disposal of commercial SNF in DPCs. Timothy Gunter (DOE-NE) and Ernest Hardin (SNL) gave an overview of past DOE R&D activities on direct disposal of commercial SNF in DPCs. They summarized the recommendations that came out of those activities, as well as the planned activities for fiscal year 2019. The last presentations were by John Scaglione (ORNL) and Laura Price (SNL), who described ongoing DOE studies to address one of the main technical challenges related to direct disposal of SNF in DPCs—the risks from nuclear criticality during the repository post-closure period. The studies include evaluating the use of fillers to prevent moderator (i.e., water) intrusion into DPCs and, thus, prevent post-closure criticality, and performing DPC criticality consequence analyses to understand the potential impacts of criticality on repository performance.

Board Observations

The Board commends the speakers for their well-organized presentations that explained clearly the background and rationale for the projects, provided succinct summaries of the results and the implications of those results, and discussed future work to address the remaining technical uncertainties. Mr. Larson's presentation was particularly helpful in highlighting the connections among the presentations on high-burnup fuel and the ENSA cask multimodal transport test and their implications for the overall DOE R&D program on storage and transportation.[2] It is evident DOE's integrated approach to its storage and transportation R&D efforts, using both experiments and modeling and involving multiple national laboratories and universities, is effective in addressing a variety of technical issues related to the performance of high-burnup SNF during extended storage and during transport.

Based on the presentations and discussions at the meeting, the Board offers several sets of observations noted below and organized around common themes.

[2] Mr. Larson's presentation addressed the Board's 2016 recommendation by making transparent how DOE integrates the results of its various partnerships (e.g., universities, national labs, and international collaborators) into its overall research program on high-burnup fuel degradation.

Obtaining Data to Advance Understanding of SNF Behavior during Storage, Transportation, and Disposal

The Board is impressed with DOE's level of international engagement in its R&D program and with DOE's collaborations and partnerships with other organizations, particularly in the Extended Storage Collaboration Program (ESCP).[3] DOE's participation in the ENSA cask transport test and the planned SNF cask drop tests by the German Federal Institute for Materials Research and Testing [Bundesanstalt für Materialforschung und –prüfung (BAM)] in Germany are also noteworthy. DOE showed constructive flexibility in accelerating its plan to undertake the ENSA cask transport test in order to take advantage of Spanish and Korean interest in and available funding for the test. These collaborations help leverage DOE resources by enabling DOE to have access to potentially useful data from other organizations or programs and by avoiding duplication of research undertaken elsewhere. The Board encourages DOE to maintain awareness of other opportunities for international collaborative research.

The results presented at the meeting on the HDRP, the ENSA cask transport test, and the dry-cask simulator experiment demonstrate the great value of carrying out full-scale experiments to generate high-quality data that are useful for validating models. Much can be learned from these types of experiments, in addition to laboratory based single-effect experiments to obtain a more fundamental understanding. The Board encourages DOE to continue to focus on high-value opportunities to obtain experimental data that will better support its understanding of SNF behavior during storage, transportation, and disposal.

The Board commends DOE for its efforts to obtain more data on the detailed characteristics of SNF discharged from commercial U.S. nuclear power plants through a new call for nuclear utilities to submit Form GC-859, "Nuclear Fuel Data Survey," particularly since a similar effort to acquire SNF data from the utilities was last conducted in 2013. The Board also believes it important for DOE to make it a priority to gain access to new fuel design information and post-irradiation examination results needed to support the efforts of national laboratories to understand SNF characteristics, such as the potential for hydride reorientation and criticality analysis of loaded DPCs. The Board recognizes this effort will require access to proprietary information, which would require the agreement and participation of fuel fabricators and other organizations.

Performance and Potential Degradation of High-Burnup SNF during Storage and Transportation

For the fuel and cladding types included in the HDRP testing, DOE is making significant progress toward developing the technical bases to support the extended storage and subsequent transportation of commercial SNF. There is generally good integration of DOE

[3] ESCP, which is sponsored by the Electric Power Research Institute, is a group of organizations in the United States and other countries representing the nuclear industry, national governments, research laboratories, and suppliers of dry-storage systems for SNF. ESCP is investigating aging effects and mitigation options for the extended storage and transportation of SNF and high-level radioactive waste (HLW).

R&D activities on high-burnup SNF, high-quality data are being acquired, and the ongoing HDRP cask monitoring and sister rod testing will provide additional useful information.

During his presentation, Mr. Larson indicated DOE is coming to the conclusion, based on currently available data, that high-burnup SNF cladding will remain intact and its integrity will not be challenged during extended storage and subsequent transport under normal conditions. The data presented at the meeting show that the measured temperatures and hoop stresses on the HDRP SNF cladding are much lower than expected, such that the extent of cladding hydride reorientation in commercial SNF likely will be insufficient to make the cladding brittle enough to cause failure. Also, the ENSA cask multimodal transport test results suggest that the stresses on the SNF cladding during transportation will be too low to cause cladding failure. However, DOE has not completed its ongoing assessment to demonstrate that the surrogate materials used in the ENSA cask transport test produced the loads that would be experienced by actual SNF during transportation.

It is not clear to the Board that the HDRP cask results and sister rod testing can resolve all the issues that apply to the entire SNF inventory, which has cladding types and fuel burnups more diverse than those of the SNF loaded into the HDRP cask. Mr. Larson and other speakers at the meeting indicated that variability in cladding alloys, their associated manufacturing techniques, and other factors that could impact cladding integrity but which were not addressed by the HDRP study, will be evaluated using numerical models. However, the Board notes that fuel performance modeling is not included in the numerical modeling described at the meeting. While there appears to be tight integration of the DOE experimental program with model validation for the cask thermal-hydraulics and the fuel structural response, there is an apparent lack of such integration with respect to fuel performance modeling. Further, a lack of understanding of the fundamental mechanisms associated with high-burnup fuel performance during storage and subsequent transportation, such as the hydrogen and hydride behavior in SNF cladding, will limit applicability of DOE program results to other cladding types. To be noted is that experimental data are needed to develop the material models used by fuel performance models.

More work also is needed to quantify the amount and form of moisture that remains in a dry-storage cask following drying performed according to typical industry practices. The Board encourages DOE to conduct more research on that topic and determine its implications for the long-term storage, transportation, and disposal of commercial SNF.

DOE indicated that, given that the temperatures in the HDRP cask are lower than originally planned, it may not be worthwhile to open the cask and assess the condition of its contents after 10 years of storage. The Board believes that opening the cask and examining the fuel after a decade of storage would still be very useful if for no other reason than to confirm predictions of minimal changes in fuel performance and to build public confidence in fuel integrity after extended storage. Also, DOE indicated no additional sampling of the gas inside the HDRP cask is planned until the end of the storage period prior to transportation. The Board encourages DOE to continue to consider the possibility of obtaining gas samples from the HDRP cask or SNF casks at other nuclear power plant sites.

Further details about these and other Board observations, findings, and associated recommendations on high-burnup fuel will be included in a Board report on this topic that is planned to be published in 2019.

Integration of DOE Storage and Transportation R&D Results into DOE Disposal R&D Activities

As noted above, there appears to be generally good integration of DOE R&D activities on storage and transportation of high-burnup SNF. However, the results from these R&D activities have not yet been integrated into the DOE R&D program on SNF disposal. For example, the HDRP thermal measurements indicate the temperatures inside dry-storage canisters are lower than previously have been assumed in at least some cases. Because thermal management is a key consideration in the design and operation of any geologic repository, the lower than expected canister temperatures may have implications for repository design and operation that need to be evaluated by DOE.

Direct Disposal of Commercial Spent Nuclear Fuel in Dual-Purpose Canisters

The DOE R&D on direct disposal of SNF in DPCs will be useful in considering the potential for directly disposing of the DPCs, rather than repackaging the SNF. Direct disposal could decrease the cost of SNF disposal, reduce the complexity of the SNF management system, reduce risks resulting from the additional handling operations required for repackaging, lower the cumulative worker dose, and decrease the amount of secondary waste. However, the Board notes that a decision to accommodate large packages in a repository would place some significant constraints on repository design and may limit the range of geologic environments that can be considered for repository development.

The R&D work DOE has completed indicates there are engineering solutions to some of the technical challenges posed by direct disposal of SNF in DPCs. On this basis, DOE has eliminated a number of technical issues from consideration in future evaluations. One exception is post-closure criticality. For many years, approaches to meeting criticality requirements have focused on showing that the probability of a criticality event is acceptably small. At this meeting, the Board heard that DOE is now beginning an effort to evaluate the consequences of a post-closure criticality event if it were to occur. The Board concurs with DOE that it is important to evaluate the consequences of post-closure criticality to provide a basis for determining its impact on post-closure repository performance. More specifically, DOE indicated that it will conduct consequence analyses of DPC criticality, including developing a capability for multiphysics modeling of DPC criticality and a generic performance assessment model that can include simulation of the effects of potential DPC criticality in the post-closure period. The Board considers this work a step in the right direction, but notes that multiphysics modeling will face technical challenges, particularly with model validation and in the treatment of uncertainties. The work is at the beginning stages, and the Board will follow this and other DOE R&D efforts on direct disposal of SNF in DPCs with great interest.

Thank you again for the participation of DOE and national laboratory staff at our October meeting. We look forward to continuing our ongoing review of DOE's technical activities related to the management and disposal of SNF and HLW.

Sincerely,

{signed by}

Jean M. Bahr
Chair

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

November 27, 2018

Dr. William Boyle
Deputy Assistant Secretary for Spent Fuel and Waste Disposition
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Mr. Kenneth Picha
Acting Associate Principal Deputy Assistant Secretary for Field Operations
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Dr. Boyle and Mr. Picha:

On behalf of the U.S. Nuclear Waste Technical Review Board (Board), I want to thank you and your staff for supporting the Board's tour of the Waste Isolation Pilot Plant (WIPP) on October 22, 2018. A number of Board members and Board staff toured WIPP prior to the Board's public meeting on recent U.S. Department of Energy (DOE) research and development (R&D) activities related to managing and disposing of commercial spent nuclear fuel (SNF), which took place on October 24, 2018, in Albuquerque, New Mexico.

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. Among the topics specifically identified in the law for Board evaluation are DOE activities relating to packaging or transportation of SNF and high-level radioactive waste (HLW).

In addition to serving as the nation's only operating deep geologic repository for disposal of defense-related transuranic waste, the WIPP site hosts underground R&D experiments relevant to disposal of SNF and HLW in salt host rock. In that capacity, the site is part of an international network of underground research laboratories devoted to studies that can improve understanding of processes affecting isolation of radioactive wastes in geologic repositories. The Board will be holding a workshop on April 24-25, 2019, in the San Francisco Bay area in California to discuss recent advances in repository science and operations from international underground research laboratory collaborations.

The main purpose of the Board's WIPP tour was to learn about a program of heater tests at WIPP, which are funded by DOE's Office of Nuclear Energy. The Board appreciates the close coordination between the DOE Office of Nuclear Energy and Office of Environmental Management that led to a successful tour. Staff members from both offices and the DOE Carlsbad Field Office, and their contractors, worked to ensure that the tour and above-ground

Telephone: 703-235-4473 Fax: 703-235-4495 www.nwtrb.gov

briefings proceeded effectively and efficiently. The frank discussions about the heater tests, including the canister heater buried in run-of-mine salt, the borehole heater shake-down test, and the proposed borehole heater test, were enlightening. DOE's Office of Nuclear Energy has learned about experimental design from the early tests and the lessons learned are being used in designing the proposed borehole heater test. The Board anticipates hearing more about the WIPP borehole heater test at its Spring 2019 workshop.

At its June 2018 public meeting on DOE R&D activities in support of SNF and HLW transportation issues that was held in Idaho Falls, Idaho, the Board heard about the transportation lessons learned from the WIPP transportation program. The Board's visit to WIPP allowed it to gain further insights on waste transportation issues and WIPP repository operations. Transportation to and handling of multiple types of waste packages at the WIPP repository are like those expected for a geologic repository for SNF and HLW.

These constructive exchanges at WIPP provided valuable information for the Board as it continues its evaluation of 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

cc:
Dr. Jeff Griffin, DOE Office of Environmental Management
Mr. Ed McGinnis, DOE Office of Nuclear Energy
Ms. Anne White, DOE Office of Environmental Management

2

United States
Nuclear Waste Technical Review Board
2300 Clarendon Boulevard
Suite 1300
Arlington, VA 22201
(703) 235-4473
www.nwtrb.gov