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

December 14, 2022

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

Dear Dr. Huff:

On behalf of the U.S. Nuclear Waste Technical Review Board (Board), I want to thank you and your staff, as well as the staff from the national laboratories, for supporting the Board's 2022 Summer Meeting, which was held on September 13–14, 2022, in Arlington, VA. The purpose of the meeting was to review information on the U.S. Department of Energy, Office of Nuclear Energy (DOE-NE) research and development (R&D) activities related to the geologic disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) in argillaceous host rocks[1] and R&D on clay-based engineered barriers. This letter presents the Board's findings, recommendations, and observations resulting from the meeting. The agenda, presentation materials, meeting transcript, and an archived recording of the webcast for the meeting are posted on the Board's website at https://www.nwtrb.gov/meetings/past-meetings/summer-2022-board-meeting---september-13-14-2022.

The Board also thanks the staff from DOE and the national laboratories for supporting a technical fact-finding meeting, which was held at Sandia National Laboratories on July 19, 2022. This fact-finding meeting enabled the Board to prepare for the Summer 2022 public meeting.

Background

Over the past several years, DOE has been conducting R&D activities related to the potential geologic disposal of SNF and HLW in several alternative host rock types, including argillaceous host rock formations. These argillaceous formations are considered to have properties beneficial to waste isolation, including low porosity and permeability, geochemically reducing conditions, capability to self-seal fractures, and the presence of minerals that strongly sorb some radionuclides. DOE also has been conducting R&D on clay-based engineered barriers, e.g., bentonite buffer and backfill, that are being considered for use in both argillaceous and

[1] Argillaceous rocks are rocks composed of clay or having a notable portion of clay in their composition. Argillaceous rocks include shale, argillite, and claystone. Argillite refers to a compact rock derived from mudstone (claystone or siltstone) or shale that has hardened via heat or pressure or introduction of a cementing material (American Geological Institute. 2011. *Glossary of Geology*, Fifth Edition, Revised, Alexandria, VA). DOE uses the terms clay, shale, and argillite for clay-bearing rock formations.

crystalline host rock repository concepts.[2] These clay-based engineered barriers are intended to protect and isolate the waste canisters and to retain and retard radionuclides released from breached canisters. The objective of DOE's R&D activities is to develop models and generate experimental data for understanding and predicting the long-term performance of geologic repositories in argillaceous host rocks and that of clay-based engineered barriers. Although DOE presentations in previous Board meetings have touched upon some aspects of these R&D activities and the Board has commented on those in Board reports[3] or letters to DOE,[4,5] the September 2022 meeting was an opportunity for the Board to conduct a review focused on these efforts.[6]

At the meeting, the Board heard several presentations from the national laboratory researchers who are conducting the work for DOE. These presentations included an overview of R&D activities related to argillaceous host rocks and clay-based engineered barriers; details of the numerical models developed to assess the long-term integrity of argillaceous host rocks; information on numerical modeling and laboratory- and field-scale experiments that focus on understanding coupled processes in bentonite buffers at high temperatures; and details of how process-level models of argillaceous host rock and engineered barrier system behavior are integrated into the Geologic Disposal Safety Assessment Framework, which is used for performance assessment calculations.

The Board also heard presentations by Dr. Maria Victoria Villar, a research scientist at the Center for Energy, Environmental and Technological Research (CIEMAT) in Madrid, Spain, and by Dr. Chris Neuzil (U.S. Geological Survey, retired), a hydrogeologist with four decades of research experience on argillaceous rocks. Dr. Villar described laboratory studies focused on understanding coupled processes in clay-based engineered barriers and the technical challenges related to laboratory experiments at high temperatures. Dr. Neuzil discussed the technical issues related to characterizing argillaceous formations and the key technical gaps that need to be addressed to better understand behavior of argillaceous formations at dimensions comparable to those of a repository. Dr. Neuzil's presentation included issues such as validity of traditional Darcy's Law for a low-permeability medium like clay or bentonite and the need to better understand fluid pressure anomalies (e.g., due to glacial loading and unloading) that can occur over repository time scales (e.g., up to a million years).

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[2] Sassani, D. et al. 2021. SFWST Disposal Research R&D 5 Year Plan – FY2021 Update. SAND2021-12491 R. Albuquerque, New Mexico: Sandia National Laboratories. August.

[3] NWTRB. 2020. *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*. Arlington, Virginia: U.S. Nuclear Waste Technical Review Board. January. https://www.nwtrb.gov/docs/default-source/reports/nwtrb-url-report.pdf?sfvrsn=9. (Accessed on December 8, 2022)

[4] Bahr, J.M. 2021. Board letter to Dr. Kathryn Huff with comments from December 2020 Board meeting (December 30, 2021). https://www.nwtrb.gov/docs/default-source/correspondence/jmb028.pdf?sfvrsn=4. (Accessed December 8, 2022)

[5] Bahr, J.M. 2022. Board letter to Dr. Kathryn Huff with comments from November 2021 Board meeting (January 7, 2022). https://www.nwtrb.gov/docs/default-source/correspondence/jmb039.pdf?sfvrsn=4. (Accessed December 8, 2022)

[6] Processes that may impact the performance of clay-based engineered barriers in crystalline host rocks, such as buffer erosion and colloid generation and transport, were outside the scope of the meeting.

Board Findings, Recommendations, and Observations

After discussing and examining the information presented at the meeting and supporting DOE reports, the Board has several observations, findings, and recommendations that are provided below. The Board notes that the meeting presentations were informative and addressed many of the questions the Board posed in the meeting agenda.

Technically valid R&D approach

As mentioned above, DOE's R&D activities seek to develop models and generate experimental data that can be used to predict the long-term performance of geologic repositories in argillaceous host rocks and that of clay-based engineered barriers. DOE's R&D activities have particular focus on understanding the host rock and engineered barrier behavior at high temperatures, which are conditions unique to the U.S. geologic disposal program.[7] The Board notes that DOE is using state-of-the-art modeling approaches and methods of analysis for evaluating and predicting long-term repository performance. The Board recognizes the technical challenges DOE faces related to field and laboratory studies needed to support and validate numerical models, but is encouraged by ongoing DOE efforts to collaborate with and leverage experience from disposal programs in other countries.

> *The Board finds that DOE has a technically valid approach to developing its modeling capability that will enable it to evaluate the post-closure performance of a potential SNF and HLW repository in an argillaceous host rock.*
>
> *The Board encourages DOE to continue its R&D efforts related to argillaceous host rocks and clay-based engineered barriers, including leveraging the experience of disposal programs in other countries.*

Need for self-assessment of DOE R&D progress

DOE has been conducting R&D activities related to argillaceous host rocks and clay-based engineered barriers since 2010. These activities include developing conceptual and numerical models, conducting laboratory- and field-scale experiments, and participating in international collaborative R&D programs. The technical accomplishments of these R&D activities were presented to the Board during its fact-finding and public meetings. However, the Board notes that some speakers, particularly those providing overview presentations, did not clearly articulate the knowledge gaps and how the results of R&D activities contributed to improving DOE's understanding of barrier capability and long-term repository performance. DOE reports relevant to argillaceous host rocks and clay-based engineered barriers provide detailed descriptions of the technical progress made in each R&D task, any updates to DOE's R&D priorities, and the

[7] The inventory of U.S. commercial SNF may be disposed of in large waste packages holding more than twice as much SNF, hence higher heat load, as any other country (Hardin, E. et al. 2012. *Repository Reference Disposal Concepts and Thermal Load Management Analysis*. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition. FCRDUFD-2012-00219 Rev. 2; Hardin E. et al. 2015. "Investigations of Dual-Purpose Canister Direct Disposal Feasibility – 15106." WM2015 Conference, March 15–19, 2015, Phoenix, Arizona).

technical gaps that were being addressed. [8,9,10] However, these reports, as well as the presentations at the Board meeting, do not provide information on the progress of each R&D task toward meeting the R&D program objectives or addressing the technical gaps, how the R&D has improved the understanding of processes, and how the R&D has contributed to the development of DOE's modeling capability and to the evolution of DOE's argillite reference case. Documenting progress to achieving objectives or addressing gaps, especially for those R&D tasks that did not achieve the objectives or provided unexpected results, will preserve the institutional knowledge, and serve as a useful resource for future researchers, as well as provide a basis for communicating DOE's progress on its disposal R&D portfolio.[11] Moreover, by not clearly identifying whether the work conducted addressed a technical gap, DOE may be less able to focus its resources on remaining technical gaps.

> *The Board finds that DOE has not clearly articulated the progress of its R&D activities related to argillaceous host rocks and clay-based engineered barriers toward achieving its program objectives and addressing the technical gaps.*
>
> *The Board recommends that DOE assess the overall progress of its R&D activities relative to achieving the stated objectives and addressing the identified technical gaps and how each R&D task contributed to understanding processes in the natural and engineered barrier systems and to developing DOE's argillite reference case. This self-assessment could also serve as a tool for knowledge management and for clear and effective communication on its disposal options, including disposal in argillaceous rocks. Ongoing and future assessments could help refine the focus of DOE's R&D activities documented in the disposal R&D 5-year plan.*

Public and stakeholder engagement

The Board previously had recommended that DOE "take account of lessons learned in other countries about listening to and informing the public, in order to improve communications, better understand community perspectives, and avoid unnecessary delays" in moving the national waste program forward.[12] The Board expanded on that recommendation in its review of DOE's

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[8] Jové Colón, C.F et al. 2021. *Evaluation of Nuclear Spent Fuel Disposal in Clay-Bearing Rock – Process Model Development and Experimental Studies*. M2SF-21SN010301072. Albuquerque, NM: Sandia National Laboratories. August.

[9] Matteo, E.N. et al. 2021. *Evaluation of Engineered Barrier Systems FY21 Report*. M2SF-20SN010308043. Albuquerque, NM: Sandia National Laboratories. November.

[10] Sassani, D. et al. 2021. *SFWST Disposal Research R&D 5 Year Plan – FY2021 Update*. SAND2021-12491 R. Albuquerque, New Mexico: Sandia National Laboratories. August.

[11] Bahr, J.M. 2021. Board letter to Dr. Kathryn Huff with comments from December 2020 Board meeting (December 30, 2021). https://www.nwtrb.gov/docs/default-source/correspondence/jmb028.pdf?sfvrsn=6. (Accessed December 8, 2022)

[12] NWTRB. 2021. *Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward*. Arlington, Virginia: U.S. Nuclear Waste Technical Review Board. April. https://www.nwtrb.gov/docs/default-source/reports/nwtrb-six-recommendations-report.pdf?sfvrsn=20. (Accessed on December 8, 2022)

disposal R&D program[13] and in its recent feedback on DOE's current efforts to employ a consent-based approach to siting federal consolidated interim storage facilities.[14] Given that DOE's vision for an integrated waste management system[15] includes facilities for interim storage and disposal, it would be beneficial for the insights and lessons learned from the consent-based siting process related to interim storage facilities to be fully integrated into DOE's current and future disposal program. Key topics could include fostering public and stakeholder engagement, risk communication and better understanding of community perspectives. The Board notes that several technical and programmatic issues related to both sets of activities are closely linked[16] and that better integration would be beneficial to both programs, especially as DOE considers its existing waste management strategy[17] and develops a draft integrated waste management program plan.

> *The Board finds insufficient integration between DOE activities related to consent-based siting of federal consolidated interim storage facilities and those related to geologic disposal.*
>
> *The Board recommends integration of DOE activities related to consent-based siting of federal consolidated interim storage facilities and those related to geologic disposal to enable effective public and stakeholder engagement.*

The Board had also previously recommended that DOE consider "compiling best practices, innovative approaches, and notable successes and failures in public outreach, engagement, and risk communication from the experiences of URL programs in other countries."[18] The Board commends DOE for already exploring how underground research laboratories (URLs) can play an important role in attracting and training the next generation of waste disposal scientists and engineers. Having a well-developed professional workforce will be vital to any future waste disposal program. The Board is encouraged by innovative programs such as the Next-Gen

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[13] Bahr, J.M. 2021. Board letter to Dr. Kathryn Huff with comments from December 2020 Board meeting (December 30, 2021). https://www.nwtrb.gov/docs/default-source/correspondence/jmb028.pdf?sfvrsn=6. (Accessed December 8, 2022)

[14] Bahr, J.M. 2022. Board letter to Dr. Kathryn Huff with comments from March 2022 Board meeting (June 7, 2022). https://www.nwtrb.gov/docs/default-source/correspondence/jmb041.pdf?sfvrsn=4. (Accessed December 8, 2022)

[15] DOE. "Integrated Waste Management" https://www.energy.gov/ne/consent-based-siting/integrated-waste-management. (Accessed on December 8, 2022).

[16] Bahr, J.M. 2021. Board letter to Dr. Kathryn Huff with comments from July 2020 Board meeting (January 11, 2021). https://www.nwtrb.gov/docs/default-source/correspondence/jmb026.pdf?sfvrsn=8. (Accessed on December 8, 2022)

[17] DOE. 2013. *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Waste*. January. https://www.energy.gov/sites/prod/files/Strategy%20for%20the%20Management%20and%20Disposal%20of%20Used%20Nuclear%20Fuel%20and%20High%20Level%20Radioactive%20Waste.pdf. (Accessed on December 8, 2022)

[18] NWTRB. 2020. *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*. Arlington, Virginia: U.S. Nuclear Waste Technical Review Board. January. https://www.nwtrb.gov/docs/default-source/reports/nwtrb-url-report.pdf?sfvrsn=9. (Accessed on December 8, 2022)

Nuclear Waste Disposal Internship program,[19] but notes that, so far, projects in this program are limited to laboratory or modeling studies and do not yet include URL experiences.

Based also on international experience, it is apparent that URLs and other facilities (e.g., Waste Isolation Pilot Plant) can play an important role in public information, outreach, and engagement efforts. Providing the public opportunities to observe aspects of a waste program first-hand can facilitate communication with the public and enhance its understanding of nuclear waste issues in a way that websites, lectures, printed materials, and other means often cannot. With DOE's current efforts on a consent-based siting process for federal consolidated interim storage facilities, it is worth again emphasizing the potential role of URLs and other facilities in public outreach, communication, and information. DOE can, for example, evaluate whether the use of existing facilities, such as the Waste Isolation Pilot Plant, can be broadened without impacting their primary missions.[20]

> *The Board commends DOE for recognizing the importance of URLs in training the next generation of scientists and engineers.*
>
> *The Board recommends that DOE further consider how URLs and other DOE facilities could play a role in public information and community engagement efforts and in training programs. As DOE proceeds with its consent-based siting process for federal consolidated interim storage facilities, systematic consideration should be given to how URLs and other facilities might contribute. This should include systematically reviewing and learning from the experiences by other countries.*

Impact of bentonite buffer on repository performance

DOE's near-term R&D activities include understanding coupled thermal, hydrologic, mechanical, and chemical processes that may affect engineered barrier system performance. A focus of these R&D efforts is on understanding bentonite behavior when subjected to high temperatures.[21] In DOE's reference disposal concept for a repository in an argillite host rock, a bentonite buffer surrounds the waste package. DOE has used the Geologic Disposal Safety Assessment Framework to assess repository performance for this argillite reference case. The Board notes that DOE has not evaluated repository performance for alternative scenarios, for example, scenarios wherein the bentonite buffer is either absent or is replaced with a buffer made of crushed host rock. Analysis of these alternative scenarios can help clarify the relative importance of the bentonite buffer on repository performance in argillaceous rocks (e.g., if and by how much it reduces the dose to the receptor). The Board acknowledges that DOE's disposal

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[19] Lawrence Berkeley National Laboratory. "Next-Gen Nuclear Waste Disposal Internship." https://sites.google.com/lbl.gov/eesa-student-opportunities/nextgen-nuclear-waste-disposal-internship. (Accessed on December 8, 2022)

[20] NWTRB. 2020. Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program. Arlington, Virginia: U.S. Nuclear Waste Technical Review Board. January. https://www.nwtrb.gov/docs/default-source/reports/nwtrb-url-report.pdf?sfvrsn=9. (Accessed on December 8, 2022)

[21] Sassani, D. et al. 2021. *SFWST Disposal Research R&D 5 Year Plan – FY2021 Update*. SAND2021-12491 R. Albuquerque, New Mexico: Sandia National Laboratories. August.

R&D program is in the early stages and that detailed analysis and evaluation of engineered barriers will be performed in the future.

> *The Board finds that additional analysis is required to clarify the relative importance of the bentonite buffer on the performance of a repository in an argillaceous host rock.*
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> *The Board recommends that DOE assess the performance of argillite repositories with no buffer or with a crushed host rock buffer.*

Observations related to numerical models

Several DOE numerical models of groundwater flow in argillite host rock and bentonite buffer use equations based on the traditional Darcy's law. In his presentation, Dr. Neuzil discussed the potential inadequacy of Darcy's law, when applied to a low-permeability medium like clay or bentonite. The Board notes that DOE previously developed additional models to represent non-Darcian flow in both argillites and bentonite buffers.[22,23] The Board suggests that DOE clearly articulate the technical basis for the assumptions made in its numerical models for flow in the bentonite buffer and argillite host rock. DOE is planning to update features, events, and processes for generic repositories and the Board suggests that the applicability of Darcy's Law to low permeability media like argillites and bentonite buffers be evaluated as a part of this update.

Observations related to laboratory and field experiments

The presentations at the meeting indicated that several DOE R&D tasks involve developing numerical models and using data from laboratory- and field-scale experiments to quantify input and/or validate the models. The Board notes that direct interactions between numerical modelers and experimentalists can help (1) identify any changes that may be needed in the design or data collection method (e.g., frequency of collection or type of data collected) during the conduct of the experiment; (2) better explain measured data and/or model predictions that may seem counterintuitive; and (3) advance fundamental understanding of the processes that significantly impact barrier capabilities. The Board encourages DOE to consider incorporating frequent and ongoing interactions between modelers and experimentalists in its current and future tasks. The Board commends DOE's participation in the HotBENT Modeling platform[24] that provides this type of interaction.

Several presenters at the meeting (e.g., Neuzil, Rutqvist, Zheng) noted the challenges associated with monitoring and characterizing low permeability media like argillites. One of the challenges is accounting for uncertainties that can be quantified, such as errors associated with sensor measurements. The Board observes that DOE has not provided information on these quantifiable uncertainties (i.e., epistemic uncertainties) in DOE reports or presentations, especially when

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[22] Liu, H.-H. and J. Birkholzer (2012). *On the relationship between water flux and hydraulic gradient for unsaturated and saturated clay*. Journal of Hydrology Vol. 475, pp. 242-247.

[23] Zheng, L. et al. 2015. *Investigation of Coupled Processes and Impact of High Temperature Limits in Argillite Rock*. United States. FCRD-UFD-2015-000362. LBNL-187644. Lawrence Berkeley National Laboratory. Berkeley. CA. July.

[24] Matteo, E.N. et al. 2021. *Evaluation of Engineered Barrier Systems FY21 Report*. M2SF-20SN010308043. Albuquerque, NM: Sandia National Laboratories. August.

comparing model predictions with laboratory and field data. The Board suggests that DOE include comparable information in its reports and presentations, if available, to better illustrate the capabilities and limitations of the numerical models. The Board acknowledges that, in some cases, the uncertainty and variability of the natural system may be significantly greater than such quantifiable uncertainties.

Thank you again, on behalf of the Board, for the participation of DOE-NE staff and technical experts from the national laboratories at our November meeting. We look forward to continuing our ongoing review of DOE's technical activities related to managing and disposing of SNF and HLW.

Sincerely,

{signed by}

Jean M. Bahr
Chair

cc: Dr. Kimberly Petry, DOE-NE
Dr. William Boyle, DOE-NE
Mr. Timothy Gunter, DOE-NE