UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
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December 30, 2021

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

Dear Dr. Huff:

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

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

- Providing a sound technical basis for multiple viable disposal options in the United States.
- Increasing confidence in the robustness of generic disposal concepts.
- Developing the science and engineering tools needed to support disposal concept implementation.[1]

[1] This letter uses the term "disposal concept" as defined by DOE to refer to geologic disposal in a repository in either crystalline, salt, or argillite host rock. These are three types of host rocks that other nations are investigating for geologic disposal of SNF and HLW. Likewise, DOE uses the term "disposal option" to refer to the collection of specific repository features including engineered barriers, such as backfill, the type of disposal waste package, such as a dual-purpose (storage and transportation) canister, which could be disposed of without repackaging stored SNF,

DOE's program examines disposal options in crystalline, salt, and argillite host rocks.

The Fall 2020 meeting on disposal research builds on information gathered during several previous Board reviews. In 2014, the Board reviewed DOE's salt disposal R&D activities[2] and made several recommendations to DOE.[3] In 2019, the Board reviewed recent advances in repository science and operations from international underground research laboratory (URL) collaborations.[4] That information formed the basis for the Board's 2020 report entitled *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*.[5] At its Summer 2020 meeting, the Board reviewed DOE's R&D on geologic disposal of commercial SNF in dual-purpose canisters.[6]

At its Fall 2020 meeting, the Board received an opening presentation from Mr. Tim Gunter (DOE-NE) that summarized DOE's non-site-specific disposal research program. The Board then heard several presentations from researchers at Sandia National Laboratories. These presentations described the program's technical direction and R&D activities related to crystalline, salt, and argillite host rock. Speakers from the IGD-TP (Implementing Geological Disposal of radioactive waste Technology Platform) group[7] and the United Kingdom's Radioactive Waste Management described their disposal research strategies. Sandia National Laboratories and Lawrence Berkeley National Laboratory staff described prioritization of cross-cutting R&D activities. One presentation described an unsaturated alluvium reference case, disposal of dual-purpose canisters (DPCs), and the Geologic Disposal Safety Assessment (GDSA) framework.[8] Another presentation addressed the engineered barrier system (EBS) and the HotBENT experiment in Switzerland. The final presentation addressed DOE's prioritization of its international activities and DOE's Disposal Research R&D 5-Year Plan. The Board's findings, conclusions, and recommendations are summarized immediately below. The enclosure to this letter provides more information on the presentations and the Board's findings, conclusions, and recommendations, as well a listing of several areas on which the Board plans to follow-up.

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and waste emplacement geometry (vertical or horizontal with respect to the orientation of emplacement tunnels) that comprise a disposal option.

[2] https://www.nwtrb.gov/meetings/past-meetings/spring-2014-board-meeting

[3] https://www.nwtrb.gov/docs/default-source/correspondence/rce025.pdf?sfvrsn=11

[4] https://www.nwtrb.gov/meetings/past-meetings/spring-2019-workshop-april-24-25-2019

[5] https://www.nwtrb.gov/docs/default-source/reports/nwtrb-url-report.pdf?sfvrsn=9

[6] https://www.nwtrb.gov/meetings/past-meetings/summer-2020-board-meeting

[7] The IGD-TP group is dedicated to initiating and carrying out European strategic initiatives to facilitate the stepwise implementation of safe, deep geological disposal of spent fuel, high-level waste and other long-lived radioactive waste. It aims to address the remaining scientific, technological and social challenges, and support European waste management programs.

[8] DOE uses the term "reference case" to refer to a specific modeling case that DOE analyzes using the GDSA framework to assess a disposal option.

Board Findings, Conclusions, and Recommendations

After discussing and examining the information presented at the fact-finding meeting and the public meeting, the Board has derived several findings, conclusions, and recommendations as noted below. Summary findings and conclusions follow. The enclosure documents the many specific findings that are the basis of the summary findings.

Summary Findings and Conclusions

Board Findings

- Other countries in an early radioactive waste management and disposal program stage have identified challenges to ensuring and carrying out an acceptable early-stage R&D program. Successful repository implementation needs a legal framework that clearly describes the roles of the implementer, regulator, and society. Procedures for conducting the site selection and implementing the repository program must be accepted by all these parties. Success requires a long-term political commitment.

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

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

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

- Overall, DOE has made good progress toward developing the technical bases and the tools to support the evaluation of multiple disposal options. Regular program planning, prioritization of R&D activities, and integration among its program elements and other countries are occurring. DOE has taken the initiative to develop a knowledge management program.[9] Through the HotBENT experiment, DOE has advanced its understanding of coupled thermal-hydrologic-mechanical-chemical processes in the EBS at high temperatures in crystalline and argillite host rocks. DOE has adopted advanced mathematical methods used in their performance assessment calculations that have reduced the computational time by a factor of 35 thus allowing for more robust and detailed analysis of performance and uncertainties therein.

[9] Knowledge management is the process of creating, sharing, using, and managing the knowledge and information of an organization. It refers to a multidisciplinary approach to achieve organizational objectives by making the best use of knowledge.

- DOE can advance its program by:
    - Fostering stakeholder engagement, consistently and clearly explaining to stakeholders the various disposal options, and better defining the safety functions of the engineered barriers and geologic setting for each disposal option.
    - Improving how it sets priorities and by further developing the GDSA framework.
    - Addressing processes that will occur upon instantaneous dissolution of DOE SNF.
    - Addressing the effects of clay layers that are expected in bedded salt formations.
    - Using natural analogue information that can inform understanding of the performance of bentonite and argillite at high temperatures over long periods.

Board Recommendations

The enclosure includes nine specific recommendations that are reproduced here.

Recommendation 1. The Board recommends that DOE use a well-developed technology maturity scoring method as one of the factors in setting R&D priorities.

Recommendation 2. The Board recommends that DOE assess the need for and scope of new technical siting guidelines for a repository for each of its potential disposal concepts (e.g., disposal in an argillite host rock).

Recommendation 3. The Board recommends that, when DOE is developing models for disposal options, there should be more focus on how the experimental data that are needed to set values of modeling parameters will be acquired.

Recommendation 4. Because DOE-NE models all DOE SNF as instantaneously dissolving once a waste package is breached in a repository, the Board recommends that DOE-NE include all processes within the repository that would occur upon instantaneous dissolution of DOE SNF, such as gas generation from the dissolution of uranium metal, in the GDSA framework or provide a technical basis that demonstrates those processes would not adversely impact engineered barriers and overall system performance.

Recommendation 5. DOE should assess whether it needs to develop reference cases and identify supporting R&D for disposal options in domal salts and brittle argillites and, if DOE decides these are not needed, provide a rationale for the decision.

Recommendation 6. The Board recommends that DOE's testing and models address the effects of clay layers in bedded salt formations and their impact on salt repository performance.

Recommendation 7. The Board recommends that DOE consider natural analogues in its strategic planning and determine whether a natural analogue exists that could be used to evaluate the consequences of aging of bentonite and argillite at high temperatures over longer periods than those possible in laboratory or underground research experiments.

Recommendation 8. The Board recommends that DOE become a member of the IGD-TP organization and focus on lessons learned, mainly societal information sharing, communication, and ways of building public confidence and trust, from countries that have advanced their repository programs beyond concept evaluation.

Recommendation 9. The Board recommends that DOE make clear and effective communication of its disposal options, and their associated barriers, barrier functions, and supporting technical bases, an integral part of its disposal R&D program. DOE should use a communication approach that is informed by stakeholder input and can consistently describe in verbal and graphic forms the claims, argument and evidence supporting the disposal option. These should include pre-disposal management activities such as any repackaging or storage that are required prior to disposal.

The Board would like to thank you again for the support of DOE-NE staff members during the Board's planning and preparation for the Fall 2020 Board Meeting. The presentations and interactions during these meetings provide valuable information for the Board as it carries out its mission to review and evaluate DOE activities related to the management and disposal of SNF and HLW. We look forward to future productive interactions with you and your staff.

Sincerely,

{Signed by}

Jean M. Bahr
Chair

Enclosure

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

Enclosure

Fall 2020 Board Meeting Summary, Findings, and Recommendations

As a complement to the letter, this enclosure summarizes the contents of the presentations made at the Fall 2020 Board Meeting. Interlaced with the presentation summaries are the Board's findings and recommendations that arose from the Fall 2020 meeting presentations and discussions, and from previously reviewed written materials. The topics that were addressed are underlined, **the findings are noted in bolded text** *and the recommendations in italics*.

U.S. Department of Energy (DOE) Disposal Research Program: Program Overview, Purpose, Scope, and Goals. Mr. Timothy Gunter, Program Manager for Disposal Research in the Office of Spent Fuel and Waste Science and Technology of DOE's Office of Nuclear Energy (DOE-NE), summarized DOE's non-site-specific disposal research program. Mr. Gunter described the program's mission and purpose and a disposal research program conceptual timeline (Figure E-1). During his talk, Mr. Gunter described how DOE sets priorities for research and development (R&D) activities. The program's goals include developing a sound technical basis for multiple U.S. disposal options and developing the science and engineering tools needed to evaluate disposal concepts. The program uses international experience and develops the U.S. program capabilities by collaborating with other international programs. The R&D program focuses on disposal in salt, crystalline, and argillite host rocks and addresses disposal of dual-purpose canisters (DPCs).

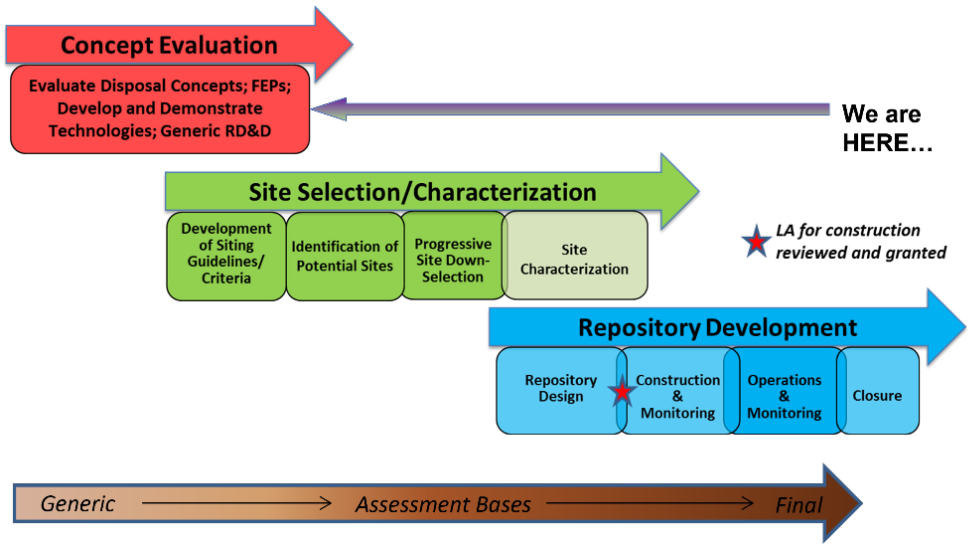

Figure E-1. Disposal research program conceptual timeline (Gunter 2020).[1]

The Board is encouraged by DOE's continued focus and R&D progress on developing generic options for managing spent nuclear fuel (SNF) and high-level radioactive waste (HLW) disposal. DOE deserves credit for enabling national laboratory staff to engage with

[1] Gunter, T.C., 2020, *Disposal Research Program: Program Overview, Purpose, Scope and Goals*, https://www.nwtrb.gov/docs/default-source/meetings/2020/december/2_gunter.pdf?sfvrsn=4.

international programs, and for supporting multi-year experiments in underground research laboratories (URLs) that help propel the program.

Mr. Gunter described factors that affect setting priorities for program activities. **Applying a form of technology maturity scoring, such as Technology Readiness Levels, which DOE uses to assess the maturity of technologies needed in design projects,[2] or Scientific Readiness Levels™, which the United Kingdom (UK) disposal program uses, can be beneficial.** These techniques could inform DOE about the maturity of its disposal options and further focus the R&D program.

Recommendation 1. The Board recommends that DOE use a well-developed technology maturity scoring method as one of the factors in setting R&D priorities.

Mr. Gunter indicated that development of siting guidelines and criteria for selecting potential repository sites follows concept evaluation (Figure E-1). He did not address the decades-old siting guidelines[3] and whether these guidelines are appropriate for use with DOE's disposal options, including potential higher temperature designs associated with the disposal of DPCs, or would need to be updated before being used to guide the current R&D program. **Site selection criteria are important to understanding what questions have to be answered, and in turn, that could help define what DOE R&D priorities should be.**

Recommendation 2. The Board recommends that DOE assess the need for and scope of new technical siting guidelines for a repository for each of its potential disposal concepts (e.g., disposal in an argillite host rock).

Technical Approach and Prioritization of Activities. Dr. David Sassani, Sandia National Laboratories (SNL), addressed the planning and prioritization efforts for the disposal R&D program. He described the 2012 Roadmap, and the priorities and results in the roadmap. Dr. Sassani also presented the evaluation bases, major findings, gaps, and defined focus areas for the 2019 Roadmap Update.

The purpose for the 2012 Roadmap was to set priorities systematically for the disposal R&D program. The 2012 Roadmap effort used repository safety functions, such as containment and limiting release of radionuclides, and features, events, and processes to identify R&D issues. To set priorities for each issue, DOE determined the issue's importance to safety and state-of-art-knowledge level. DOE assessed these metrics at four points in time along the conceptual timeline (Figure E-1). To plan work, disposal R&D program staff then combined results for individual issues into higher-level topic areas. Example topic areas are design concept development, generic disposal system modeling, knowledge management, and URLs. Dr. Sassani said that by around 2017, the disposal R&D program had addressed many of the 2012 Roadmap priorities but had identified some additional R&D gaps. These gaps included waste package degradation and the engineered barrier system (EBS) chemical environment resulting

[2] https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-09-admchg1/@@images/file.

[3] "10 CFR 960—General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories," 49 *Federal Register* 47,752, December 6, 1984.

from coupled thermal-hydrologic-chemical processes. Both the disposal program progress and the gaps suggested that it was appropriate to re-evaluate the disposal R&D program priorities which led to the 2019 roadmap effort.

The 2019 Roadmap Update efforts set priorities for the R&D of a mature program. The 2019 effort did not use barrier functions and separate decision points as part of setting priorities. DOE and national laboratory staff assessed existing activities, identified research gaps (gap activities), and then assigned priorities for all R&D activities. For the update, for each R&D activity, the large staff team developed the importance to safety and state-of-art-knowledge level ratings and justifications. The team assessed these factors for each host rock and cross-cutting activity groups such as DPC, EBS, performance assessment, and international activities. The team used consensus evaluations of the importance to the safety case values and the state-of-art-levels for each activity to decide an overall low-medium-high R&D priority score. Based on the score, the team assigned a priority ranking to each activity. For example, a high priority R&D activity had to have both high importance to the safety case and fundamental gaps in method or fundamental data needs, or both.

The Board's findings and recommendation on DOE's technical approach and prioritization of activities, presented here, are based on Dr. Sassani's presentation and on subsequent presentations provided by national laboratory staff. **A prioritization process that focuses on safety functions, such as used in the 2012 Roadmap, is helpful to identify significant gaps and to communicate how disposal options will work.** Such an approach defines the functions of each barrier[4] and the degree to which each barrier must perform its functions. If DOE decides to dispose of SNF in DPCs, temperatures in the near field of a repository could reach up to 200 °C, which is 100 °C higher than the temperature limits used by other countries. Higher temperatures will affect the performance of engineered barriers including the SNF, waste package, and bentonite buffer. DOE has not identified consistently the information it needs to support barrier performance in higher temperature alternatives.[5] The Board is interested in learning more from DOE on how barrier functions and expected performance would differ at these higher temperatures. **DOE needs to specify modeling requirements and how it will get the data to set modeling parameter values.**

Recommendation 3. The Board recommends that, when DOE is developing models for disposal options, there should be more focus on how the experimental data that are needed to set values of modeling parameters will be acquired.

The Board would like to better understand the effort and time DOE needs to address each of the high priority activities, how DOE tracks the completion status of high priority activities, and when all high priority activities will be completed.

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[4] A barrier may be a geologic feature, an engineered structure, a canister, a waste form with physical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around the waste, provided that the material substantially delays movement of water or radionuclides.

[5] DOE's activity descriptions related to the high temperature alternatives use different temperatures (150, 200, and 250 °C) to describe the high temperature alternatives and for which information is needed to close individual R&D activities (See the 2019 Roadmap Update, *DOE SFWST Campaign R&D Roadmap Update Rev.1*., https://www.osti.gov/servlets/purl/1559571).

DOE has used relevant international data sets and approaches for modeling the flow and transport processes in the far-field of the different host rocks, and for modeling parts of the EBS and the near-field.[6] During the Board questioning, Dr. Sassani said that modeling efforts to incorporate the biosphere into its overall performance assessment framework, known as the Geologic Disposal Safety Assessment (GDSA) framework, are at an early stage. Like its far-field modeling efforts, DOE could use international biosphere data sets and modeling approaches to its advantage.

Host Rock Presentations. Presentations on crystalline, salt, and argillite host rocks addressed disposal options and R&D activities. Based on those presentations, the Board provides findings and recommendations on the overall generic host rock R&D effort. The Board's evaluation of each host rock R&D activities follows the Board's overall comments.

DOE uses one or more reference cases for each host rock type. Multiple reference cases for each host rock reflect alternatives with different waste package capacity and orientation. For example, one crystalline rock reference case uses a vertical waste package that contains 4 pressurized water reactor (PWR) commercial SNF assemblies whereas another crystalline rock reference case uses a horizontal waste package containing 12 PWR assemblies.

DPCs can contain up to 37 PWR assemblies and most commercial SNF in dry storage is in DPCs. A reference case that uses waste packages that contain fewer SNF assemblies than the smallest DPCs, which contain 24 PWR assemblies, implies repackaging of stored SNF into the smaller waste package.[7] Repackaging would need to occur before emplacing the waste in a repository. DOE would need to store existing DPCs many decades to hundreds of years before the DPCs could be as cool as 4 or 12 PWR assembly-containing waste packages.

In describing disposal options for a repository in a crystalline host rock or argillite host, DOE should have explained that repackaging of DPCs or storage of DPCs many decades to hundreds of years prior to emplacement may be required depending on disposal option details, which DOE has done previously.[8] **The Board positively notes Dr. Kris Kuhlman's, SNL, presentation on salt R&D.** Dr. Kuhlman presented the best account of how a host rock contributes to safety functions. Dr. Kuhlman also described the repository attributes for safe disposal and addressed the duration of pre-disposal storage. **The Board finds that consistently describing the disposal options, including pre-disposal waste management activities such as repackaging or storage, is important, especially as DOE moves forward with its consent-based siting process that would be used to identify sites to store the nation's spent nuclear fuel.**

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[6] See *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*, January 2020, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

[7] See *Letter from Chair Jean M. Bahr to the Honorable Rita Baranwal, Assistant Secretary for DOE-NE; January 11, 2021*, related to disposal of commercial SNF contained in DPCs in a geologic repository. https://www.nwtrb.gov/docs/default-source/correspondence/jmb026.pdf?sfvrsn=8.

[8] Hardin, E., 2020, *Technical Basis for Engineering Feasibility and Thermal Management*, https://www.nwtrb.gov/docs/default-source/meetings/2020/july/3_hardin_technical-basis-for-engineering-feasibility-and-thermal-management.pdf?sfvrsn=4.

The disposal R&D program is not adequately addressing DOE SNF. DOE is currently required to dispose of this waste in a repository. DOE SNF dissolution can be different than that expected for commercial SNF[9] or metallic waste packages. For example, uranium-metal SNF rapidly reacts in water lacking dissolved oxygen and produces hydrogen that could adversely affect the engineered barriers. Understanding gas generation and migration is a key issue in the assessment of repository performance.[10] Water lacking dissolved oxygen persists in crystalline rocks at repository depths. DOE models all DOE SNF assuming instantaneous dissolution of the waste once a waste package is breached and water enters. DOE does not address gas generation that would occur with dissolution of uranium-metal DOE SNF, which is the dominant type of DOE SNF on a mass basis.

Recommendation 4. Because DOE-NE models all DOE SNF as instantaneously dissolving once a waste package is breached in a repository, the Board recommends that DOE-NE include all processes within a repository that would occur upon instantaneous dissolution of DOE SNF, such as gas generation from the dissolution of uranium metal, in the GDSA framework or provide a technical basis that demonstrates those processes would not adversely impact engineered barriers and overall system performance.

DOE has not evaluated the full range of expected conditions for salt and argillite. DOE is focusing its salt R&D on horizontally bedded salt formations. The stress orientation in these formations leads to rapid mechanical deformation and closure of the bedded salt drifts. In contrast, in domal salt formations rapid closure of emplacement drifts does not occur in the dome flanks. For example, the Morsleben, Germany, deep repository for low and intermediate level radioactive waste is in the flanks of a domal salt deposit. Large underground galleries (on the order of 100's of feet long and 10's of feet wide and high) remain open and do not have significant mechanical closure issues. This could be an advantage during repository operations but a disadvantage during post-closure when deformation imparts self-sealing attributes. The domal salt disposal concept (open galleries) is different from the bedded salt idea considered by DOE. The United States contains both bedded salt and domal salt formations. DOE is not assessing disposal in domal salt.

DOE is focusing on self-sealing argillites and is not examining brittle argillites. These types of rock have different mechanical and hydrologic properties. DOE's argillite R&D does not address the range of mechanical and hydrologic properties of U.S. argillites.

Recommendation 5. DOE should assess if it needs reference cases and supporting R&D for domal salts and brittle argillites and, if DOE decides these are not needed, provide a rationale for the decision.

Crystalline Host Rock: Disposal Concepts and Research & Development Activities. Dr. Yifeng Wang, SNL, described characteristics of crystalline rocks and disposal concepts. For the crystalline host rock, DOE has only studied waste packages for SNF containing 4 and 12 PWR

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

[10] Rutqvist, J., 2019, *Gas Migration in Clay-Based Materials – International Collaboration Activities as Part of the DECOVALEX Project*, https://www.nwtrb.gov/docs/default-source/meetings/2019/april/rutqvist-gas.pdf?sfvrsn=6.

assemblies. Dr. Wang described technical gaps and priorities and process model development and integration. He outlined future activities for the crystalline host rock R&D. One DOE focus is better characterization and understanding of fractured rock, fluid flow, and radionuclide transport. The second DOE focus is designing an effective EBS for waste isolation. Dr. Wang described recent efforts to assess using lead/lead-alloy as a corrosion-resistant outer layer packaging material. The Board notes that DOE also looked at these materials as part of the design options review in the Yucca Mountain, Nevada, repository program.

Dr. Wang described the fuel matrix degradation model that is used for commercial SNF. DOE will use this SNF degradation model for all reference cases in all host rock types. Dr. Wang described ambient temperature three-electrode electrochemical cell experiments. DOE uses the experimental results to assess and parameterize the model. Dr. Wang described the status of process models and total system integration. Dr. Wang explained that DOE is addressing how higher temperatures affect the backfill and seals portion of the EBS and host rocks but not how it will affect the degradation of commercial SNF. **DOE will need to validate the commercial fuel matrix degradation model at temperatures greater than ambient unless it can be demonstrated that waste packages are unlikely to fail before the temperature of the repository returns to ambient conditions.**

Disposal in crystalline host rocks relies heavily on the EBS for containment and isolation. The material used for sealing the EBS has different attributes than the host rock. There are differences in the thermal, hydrologic, chemical (composition), and mechanical properties between bentonite and other clay-based materials and host rocks. Seal materials are mechanically weaker than crystalline rocks by design to allow plastic deformation and have lower hydraulic conductivity compared to fractured crystalline rock, in which the degree of fracturing controls the hydraulic conductivity. Moreover, transport of radionuclides away from the EBS is mainly by water flow in rock fractures as opposed to transport through intact rock. **Understanding processes at the interfaces between these materials is important.** Processes in the near field disturbed zone[11] are also important. DOE has made good progress in understanding and modeling the interface between metallic waste packages and the sealing material.

Salt Host Rock: Disposal Concepts and Research & Development Activities. Dr. Kris Kuhlman, SNL, updated the Board's understanding of DOE's salt-related disposal R&D. He described well the characteristics of horizontal bedded salt and DOE's safety strategy and disposal options. Dr. Kuhlman addressed the susceptibility of a salt repository to climate change. He described how the characteristics of salt, such as brine corrosion of instrumentation, challenges its characterization and monitoring. Dr. Kuhlman stressed why using underground experiments, such as the Brine Availability Test in Salt (BATS), can address those limits. He described how DOE applied high priority R&D to advance coupled processes knowledge and modeling. Dr. Kuhlman explained that understanding coupled thermal-hydrologic-mechanical-chemical processes was necessary to assess a salt repository's performance.

[11] The excavation of shafts and tunnels in a waste repository and decay heat from the emplaced waste will cause a disturbance to the surrounding rock mass with possible alterations to rock mass stability and hydraulic properties. The properties and extent of the disturbed zone must be considered in the design of a repository and in the assessment of its long-term safety.

In 2014, the Board held a public meeting on DOE's salt-related disposal R&D. The Board provided recommendations to DOE in a letter.[12] The Board recommended that DOE better address the effects of clay layers that occur in bedded salt formations. The clay layers can affect the amount of fluid, heat transport, and significantly impact mechanical performance of "intact" salt. The Board noted that quickened plastic flow because of heat-producing waste was possible. The Board noted these factors are potential disadvantages for a salt repository during the operational phase. The Board recommended that "attention be given to these factors in order to ensure a balanced evaluation of the performance of salt as a medium for a geologic repository." In 2014, the Board also recommended that DOE include possible entry of water from sources external to the salt body in a performance assessment of a salt repository.

DOE's current salt R&D tasks do not adequately address clay layers. The BATS experiment does not test the effects of clay layers because of its location away from clay layers. The detailed models DOE is developing to address coupled thermal-hydrologic-mechanical-chemical processes do not address the effects of clay layers.

Recommendation 6. The Board recommends that DOE's testing and models address the effects of clay layers in bedded salt formations and their impact on salt repository performance.

Argillite Host Rock: Disposal Concepts and Research & Development Activities. Dr. Carlos Jové Colón, SNL, described argillaceous rock characteristics and DOE's repository concept and post-closure safety strategy. Dr. Jové Colón described the waste forms and EBS, which includes cement and backfill, and seals such as bentonite. DOE's analyses have addressed different waste package arrangements, such as in-drift axial emplacement and horizontal emplacement boreholes that extend perpendicular to the drift axis. DOE has completed analyses for packages that contain 4, 12, and 21 to 37 PWR SNF assemblies. DOE used a 4-kW waste package thermal power limit for packages containing between 21 to 37 PWR assemblies to limit degradation of a protective buffer or backfill. Dr. Jové Colón described high priority R&D and briefly addressed a higher temperature reference case.

Dr. Jové Colón presented ordinary Portland cement and cement plug/liner degradation as high priority R&D topics. DOE's assignment of high priority means fundamental gaps in a method or a need for fundamental data exists, and the topic has a high importance to the safety case.[13] This seems inconsistent with the broad knowledge base for understanding and modeling ordinary Portland cement and cement plug/liner degradation. For example, the Nuclear Energy Agency has completed specific radioactive waste-related studies on these topics.[14]

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[12] See *Letter from Chairman Rodney C. Ewing to Dr. Peter B. Lyons, Assistant Secretary for DOE-NE, and Mr. David Huizenga, Senior Advisor for Environmental Management; June 4, 2014*, on R&D activities related to salt as a geologic medium for disposing of SNF and HLW. https://www.nwtrb.gov/docs/default-source/correspondence/rce025.pdf?sfvrsn=11.

[13] See the 2019 Roadmap Update, *DOE SFWST Campaign R&D Roadmap Update Rev.1.*, https://www.osti.gov/servlets/purl/1559571.

[14] NEA. 2012. *Cementitious Materials in Safety Cases for Radioactive Waste: Role, Evolution and Interactions*. NEA/RWM/R(2012)3/REV. https://www.oecd-nea.org/upload/docs/application/pdf/2020-01/rwm-r2012-3.pdf.

While the Board commends DOE for developing a higher temperature argillite disposal case, it remains concerned that DOE has not obtained a technical basis for assessing the performance of bentonite over longer periods than can be assessed in laboratory or underground experiments, such as HotBENT. A robust disposal R&D program uses an iterative process with laboratory experiments, modeling, and field observations.[15] The Board noted a robust program includes URL and natural analogue studies to address field observations and that natural analogues may help address longer timescales than can be addressed in URL experiments.[16] For example, the thermal effect induced by the Morrón de Mateo volcanic dome, Spain, on the adjacent bentonitised tuffaceous beds has been studied as a natural analogue of the thermal behavior of the bentonite-engineered barrier of a geologic repository.[17] It may be possible to find another analogue that reflects more closely the conditions expected for a higher temperature argillite disposal case.

Later in the meeting, Dr. Birkholzer's presentation on international disposal research activities did not address any efforts with the international natural analogue community, such as through participation in the Natural Analogue Working Group. Neither the 5-year R&D plan[18] or 2019 Roadmap update includes any current or future tasks related to natural analogues.

Recommendation 7. The Board recommends that DOE consider natural analogues in its strategic planning and determine whether a natural analogue exists that could be used to evaluate the consequences of aging of bentonite and argillite at high temperatures over longer periods than those possible in laboratory or underground research experiments.

Geologic Disposal Research Strategies from Abroad: Examples from IGD-TP (Implementing Geological Disposal of radioactive waste Technology Platform) and the United Kingdom (UK). Dr. Irina Gaus, IGD-TP chair, and Dr. Lucy Bailey, Radioactive Waste Management (RWM), UK, presented their organization's disposal research strategies. Dr. Gaus also presented IGD-TP member views, based on their experience in national programs, of the relationship between early program development stages, site selection, and R&D programs.

IGD-TP sets up and carries out European efforts to facilitate the stepwise implementation of safe deep geological disposal of SNF, HLW, and other long-lived radioactive waste. IGD-TP does not limit membership to European organizations and DOE is not a member. IGD-TP serves as a forum to discuss research, development, and demonstration (RD&D) issues and priorities. IGD-TP members share RD&D information and results. Members also share information and

[15] See *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*, January 2020, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

[16] See *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*, January 2020, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

[17] Pérez del Villar, L., et al, 2005, "Thermochemically induced transformations in Al-smectites: A Spanish natural analogue of the bentonite barrier behaviour in a radwaste disposal," *Applied Geochemistry*, volume 20, issue 12, pages 2252-2282.

[18] See *SFWST Disposal Research R&D 5-Year Plan*, July 31, 2020, SAND2020-9053 R, Sandia National Laboratories, Albuquerque, New Mexico.

experience on RD&D planning and management. IGD-TP coordinates RD&D on topics of shared interest between programs and groups of organizations. Dr. Gaus described the benefits from IGD-TP participation. These benefits include competence building, joint work and use of resources, joint work on strategies, and knowledge transfer. Dr. Gaus encouraged DOE's participation in the IGD-TP.

Dr. Gaus described the results of her elicitation of some repository implementors that focused on obtaining their lessons learned on generic disposal RD&D programs and the transition to siting a repository.[19] IGD-TP implementors from Belgium, Germany, the Netherlands, Spain, Hungary, UK, and Switzerland took part in the elicitation. These countries are at the same early repository development phase as DOE. Dr. Gaus presented their lessons learned on disposal RD&D programs and the transition to siting a repository as a series of key observations.

To ensure and carry out an adequate RD&D program at an early stage, Dr. Gaus stated:

> "Successful repository implementation needs the legal framework with the roles of each party clearly described (implementer, regulator, society), how to implement the repository program and conduct the site selection needs to be set out and accepted by all parties, and a long-term political commitment is required."

These factors are integral to a satisfactory early-stage RD&D program like DOE's. The European implementors noted:

> "While RD&D is an important part of the repository program, it is widely felt that the challenges for repository implementation do not lie in the technical aspects (although optimization will always remain a driver), but rather in the success of mastering the societal challenges."

The Board concurs with the European implementors that mastering societal challenges is crucial.[20]

Dr. Gaus discussed lessons learned related to social and economic RD&D developments and identifying who deals with these. Not considering these issues, Dr. Gaus said, can adversely impact program success. To stress the importance of societal aspects, Dr. Gaus presented the recently completed results of the Netherlands' safety case. That safety case found that the host rock, including geotechnical properties and long-term evolution, was the most important consideration and "integrating societal aspects into technical research" was the next most important consideration.

[19] Dr. Gaus collected this information to support the Board's meeting and her effort, documented in her presentation, demonstrates how valuable the IGD-TP could be to DOE and the U.S. efforts to dispose of SNF and HLW in a geologic repository.

[20] See *Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward*, April 2021, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

Dr. Gaus ended the presentation by listing the challenges of early-stage programs, many of which DOE is facing. As the Board noted in its Six Recommendations Report,[21] DOE is facing a loss of knowledge because of the suspension of the Yucca Mountain program and attrition due to workforce aging. DOE must find the balance between a narrowly focused R&D program and a broad enough program to cover all disposal options. Dr. Gaus noted that a good safety case focuses the RD&D program and helps to address the challenge of maintaining program agility and long-term collaborations with academia.[22] **Clearly explaining the disposal options and better defining the safety functions of the barriers and their technical bases for each option will help focus DOE's R&D program.**

Based on the information Dr. Gaus provided, the Board notes the importance of having a strong implementor defining the R&D needs. The lack of an active, near autonomous implementor, which is the case for DOE,[23] challenges the R&D program and the process for setting priorities.

The Board believes that DOE would benefit from working with organizations, such as IGD-TP, whose members are currently demonstrating proposed repository operations in URLs and surface facilities or constructing a geological repository, and with countries who have advanced to or beyond the progress of DOE's non-site-specific disposal R&D program.

Recommendation 8. The Board recommends that DOE become a member of the IGD-TP organization and focus on lessons learned, mainly societal information sharing, communication, and ways of building public confidence and trust, from countries that have advanced their repository programs beyond concept evaluation.

Dr. Bailey stressed that during the early stage of the UK siting process, the UK's RWM focuses on building and communicating its understanding of the safety of the repository. RWM builds confidence in the safety of the geologic repository by developing an understanding of how the barriers perform and change through time. RWM focuses on the barrier's safety roles and the features, events, and processes that affect the safety roles. RWM also focuses on developing an understanding of radionuclide release and transport to the accessible environment and the effects of engineering design. RWM's strategy includes expected operations, including construction, and hazard identification and mitigation. The final part of the RWM strategy is understanding the transport of the waste to the disposal site. RWM uses Scientific Readiness Levels™, which are like Technology Readiness Levels, to assess its level of understanding of the safety of the repository. RWM also uses Scientific Readiness Levels™ as a measure of progress and to

[21] See *Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward*, April 2021, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

[22] Unlike in the United States, where national laboratories conduct most of the disposal R&D, European nuclear waste disposal implementers rely on academic collaborations for much of their RD&D support.

[23] The Board observes that DOE is in this position because two of the three factors [legal framework with the roles of each party clearly described (implementer, regulator, society), how to implement the repository program and conduct the site selection needs to be set out and accepted by all parties, and a long-term political commitment] needed to ensure and execute an adequate RD&D program are uncertain or missing in the US. How to implement the repository program and conduct the site selection has not been set out and accepted by all parties and a long-term political commitment is still required.

decide what understanding can reasonably be obtained at the generic stage of a repository program.

Dr. Bailey described the regulatory basis for communicating the UK safety case. That regulatory approach uses a claims, arguments, and evidence approach. Dr. Bailey described the importance of this communication to the success of a disposal program. Dr. Bailey also introduced RWM's tool for seeing "claims to be made against the regulatory requirements, arguments that explain how those claims will be met, and evidence to support the arguments." **The claims, arguments, and evidence approach may make it easier for a non-technical audience to understand the disposal options, and their associated barriers, barrier functions, and supporting technical bases.**

RWM uses the ViSI (Visualization of System Information) tool as a digital safety case.[24] The tool identifies claims, arguments, and evidence in a tree-like diagram. RWM uses that diagram not only to communicate with stakeholders but also to identify research gaps. The Board suggests that a visualization tool, such as ViSI, could be an important means for DOE to communicate its disposal options, and their associated barriers, barrier functions, and supporting technical bases and manage its R&D portfolio. This could help address a limitation of the disposal R&D presentations at this meeting from DOE that, in general, did not provide consistent links between the field, laboratory, and modeling work. Presenting those links through a visualization tool such as ViSI would have helped communicate the work's relationship to disposal options, and their associated barriers, barrier functions, and supporting technical bases.

While highlighting the importance of communication, Dr. Bailey stated that

> "Our safety cases [are] really only as powerful as our ability to communicate it. … Building understanding is the most important focus for research during early siting. Communicating that understanding to all stakeholders is vital if we're going to build trust. … Information remains just information until it is integrated, until it's linked, until we put pieces of the jigsaw together, until we identify how or what that actually means."

The Board finds her statements compelling. Public engagement, which requires transparency, openness, and two-way communication with the public, in geologic disposal programs is one of the core principles of nuclear waste management programs.[25] It is important to have a clear explanation of each disposal option, including the safety functions of the barriers and their technical bases, to integrate the team of researchers and engage the public towards gaining an understanding where individual research projects fit into supporting a disposal option.

Recommendation 9. The Board recommends that DOE make clear and effective communication of its disposal options, and their associated barriers, barrier functions, and supporting technical

[24] Hall, O., and L. Gray, 2021, *ViSI: RWM's Digital Safety Case Management Tool*, https://www.research-support-office-gdf.ac.uk/wp-content/uploads/sites/244/2021/09/12.-ViSI_RWM-Safety-Case-Management-Tool-Introduction.pdf.

[25] See *Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward*, April 2021, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

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

Both Drs. Gaus and Bailey stressed the importance of repository programs developing and preserving links to academic institutions. Dr. Bailey described RWM's research support office. That office seeks to develop a long-term strategic relationship with UK universities. The office is better aligning academic research that addresses RWM's needs with a stronger university delivery-focus. The office seeks increased sharing with world-class cutting-edge science and "increased contextual understanding and enhanced advocacy within a respected and influential stakeholder group." RWM is aiming for a better coordinated community of RWM funded researchers and is developing the next generation of researchers. RWM seeks a "sustained and enhanced multi-disciplinary capability through collaborative long-term relationships." By reviewing European academic engagement models, DOE might identify possible improvements to its university support programs.

Prioritization of Cross-Cutting Research and Development Activities: Unsaturated Alluvium Reference Case, Disposal of Dual-Purpose Canisters, and Geologic Disposal Safety Assessment. Dr. Emily Stein, SNL, defined the GDSA framework and its role in DOE's safety assessment process. She also presented an unsaturated alluvium case. DOE developed that reference case to provide understanding on a few key subjects, such as coupled thermal-hydrologic-chemical processes in hydrologically unsaturated environments, for inclusion in the GDSA framework.

On the previous day, Dr. Sassani mentioned that a key objective for assessing safety is to provide the basis for planning and setting technical work priorities. Dr. Stein identified the GDSA framework as DOE's safety assessment computational platform. She stressed the GDSA framework's role in assessing what RD&D DOE should do in the next stage of program development. DOE's Disposal Research R&D 5-Year Plan states that this software framework will provide DOE with "robust, sophisticated simulation and analysis tools that will support site selection, site characterization, and licensing for the nation's next deep geologic disposal facility."[26] Dr. Sassani indicated that DOE has not developed the GDSA framework enough to apply it to repository post-closure safety analyses that can inform decision making or prioritize the R&D activities. Dr. Sassani stated that developing that capability is on DOE's near-term agenda.

Dr. Stein addressed the advanced non-linear solvers considered in the GDSA framework. She described the Newton Trust Region Dogleg Cauchy approach[27] the program had developed that has reduced computational time by a factor of 35. **The Board commends the staff who developed this approach.** It was an important contribution to reducing the computational

[26] See *SFWST Disposal Research R&D 5-Year Plan*, July 31, 2020, SAND2020-9053 R, Sandia National Laboratories, Albuquerque, New Mexico.

[27] The Newton Trust Region Dogleg Cauchy approach combines two separate algorithms (Newton Trust Region and Dogleg Cauchy) for time stepping (iteration methods) that minimize the residual of a multidimensional function.

burden in computationally intensive analyses such as repository performance assessments thus enabling more detailed modeling of repository performance.

The Board notes other opportunities for reducing computational time. Adding a very complex model to capture some more detail of the physics of a process would add computational burden. Understanding the ability of models having varying levels of detail to predict system performance can tell DOE whether it actually needs to routinely use a more complex model, or a simpler model will suffice for the intended application.

Dr. Stein noted the need to further develop both the source term, EBS evolution, and biosphere models. She stated that much development work remains on temperature-dependent and material-specific corrosion models. Dr. Stein also outlined DOE's plans to develop models for temperature-dependent reactions and coupled thermal-hydrological-mechanical evolution of the near field. She noted that DOE plans to incorporate mechanistic approaches into the GDSA framework. These approaches will be computationally intensive. The Board recognizes that in the future DOE will need to develop the capability to address other scenarios[28] such as a human intrusion scenario. So far DOE has focused on a nominal scenario.

Prioritization of Cross-Cutting Research and Development Activities: Engineered Barrier System Overview and the HotBENT Experiment at the Grimsel Test Site. Dr. Ed Matteo, SNL, presented a review of EBS-related R&D. Dr. LianGe Zheng, Lawrence Berkeley National Laboratory (LBNL), presented an update on the HotBENT experiment. Dr. Matteo explained that understanding the behavior of cement and bentonite are EBS R&D priorities and identified how international efforts such as the Cement Task in the EBS Task Force, which is a group led by Sweden's implementer, support their efforts. To address knowledge gaps, DOE has focused on repository seals integrity and processes at material interfaces. Dr. Matteo described that coupled processes remain a knowledge gap. Dr. Matteo explained they focused on increasing understanding of mineralogic changes and permeability evolution in seals and liners and better understanding of mineralogic changes at the buffer and waste package interface.

Focusing on filling the knowledge gaps associated with processes at the buffer and waste package interface is important and DOE's progress is encouraging. The Board recognizes DOE's strong international involvement with many of the R&D priority tasks. DOE's participation in the EBS Task Force program and its leadership on the high temperature bentonite experiment are important.

Dr. Zheng had previously described the HotBENT experiment to the Board at its April 2019 workshop on URLs.[29] The HotBENT experiment is being conducted at the Grimsel Test Site, a

[28] A scenario is a well-defined, connected sequence of features, events, and processes that can be thought of as an outline of a possible future condition of the proposed repository system. Scenarios can be undisturbed, in which case the performance would be the expected, or nominal, behavior for the system. Scenarios can also be disturbed, if altered by disruptive events such as human intrusion or natural phenomena such as volcanism or nuclear criticality.

[29] Zheng, L., 2019, *DOE's Engineered Barrier Integrity Activities: Understanding EBS Coupled Processes and Mineral Alterations at High Temperatures: From FEBEX-DP to HotBENT*, https://www.nwtrb.gov/docs/default-source/meetings/2019/april/zheng.pdf?sfvrsn=6.

URL in Switzerland. The experiment focuses on understanding the effects of high-temperatures (>150 ^{o}C) on bentonite-based buffers. The Board previously recommended[30] that DOE increase its focus on underground laboratory experiments to assess the extent to which coupled processes occur and whether DOE needs to develop new constitutive models to model accurately the longer-term underground HotBENT test.

Dr. Zheng updated the Board on the HotBENT experiment and supporting laboratory and modeling work. DOE is supporting high temperature bentonite column experiments, the Grimsel field scale test, and a modeling platform. Dr. Zheng explained the column experiment results showed hydration, clay swelling, heating dehydration, and mineral formation. Dr. Zheng described the field scale test's design, timeline, installation, and instrumentation. Dr. Zheng also described the objective of the HotBENT modeling platform. The modeling platform enables the experiment to inform the modeling and the modeling to inform the experiment. As Dr. Zheng explained, the modeling platform will speed up data analysis and model updates for system understanding and decision support. Dr. Zheng stated that pre-experiment scoping modeling helped to design the field experiment. Dr. Zheng explained that blind comparisons will be part of a model "validation" exercise. He explained that multiple modeling teams will use alternative conceptual models to analyze uncertainties.

The Board commends DOE for their initiative in co-developing the HotBENT experiment. DOE's commitment to a lengthy experiment is important and noteworthy. HotBENT is a good example of international collaboration and use of URLs. The Board notes that DOE sees an important role for the multiple modeling teams to analyze conceptual uncertainties. **However, it is still not clear whether there was enough pre-experiment modeling, employing distinct conceptual models, to identify what data DOE needs to collect to help it discriminate among the models.** DOE will need to develop a well-thought-out experimental matrix for "validation" of the models.

Prioritization of International Activities and Moving Forward: Disposal Research R&D 5-Year Plan. Dr. Jens Birkholzer, LBNL, presented an overview of the prioritization of international activities. Dr. David Sassani, SNL, described the Disposal Research R&D 5-Year Plan.[31] Dr. Birkholzer described how active collaboration with international programs is a central and fully integrated part of DOE's disposal research program. He stressed that DOE is now playing a more active role in defining international research efforts. DOE's leadership in developing the HotBENT experiment and chairing the current phase of the DECOVALEX project is noteworthy. The Board notes DOE's active leadership can play a major role in aligning future international efforts with the U.S. disposal R&D program strategic goals. In response to a Board question, Dr. Birkholzer noted that DOE's international collaborations have focused on conducting R&D. He pointed out that joining IGD-TP would be valuable for the lessons learned, especially if the U.S. disposal program moves forward into the site selection stage (Figure E-1).

[30] See *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*, January 2020, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

[31] See *SFWST Disposal Research R&D 5-Year Plan*, July 31, 2020, SAND2020-9053 R, Sandia National Laboratories, Albuquerque, New Mexico.

Dr. Sassani described challenges to program planning and DOE's efforts that led to its Disposal Research R&D 5-Year Plan. DOE's planning challenges included addressing a wide range of geologic disposal concepts with limited resources, defining the most important R&D activities, and defining how much generic R&D is enough. DOE also had to decide how best to use the vast international experience and integrate cross-cutting topics in its planning. Both the 2012 Roadmap and the 2019 Roadmap Update served as forerunners to the Disposal Research R&D 5-Year Plan.

Dr. Sassani addressed the purpose and structure and R&D priorities of the Disposal Research R&D 5-Year Plan. He described an integration example from fiscal year 2021 planning efforts. The plan serves as a strategic guide to the work within the disposal research R&D technical areas (for example, argillite R&D). The plan provides thrust topics in each disposal research technical area. The plan presents near-term (1-to 2-years' timeframe) and longer-term (3-to 5-years' timeframe) thrust topics. The longer-term topics provide a vision of where the R&D is heading assuming no major program changes. DOE will update the Disposal Research R&D 5-year Plan yearly to present short-term progress and the bases for changed priorities.

The Disposal Research R&D 5-Year Plan is a major advance in DOE's planning and setting priorities. The Board notes that DOE added "Technical Support for Underground Research Laboratory Activities" as a new disposal research technical area. DOE is also looking to use the Yucca Mountain, Nevada, Exploratory Studies Facility tunnel for R&D on passive monitoring techniques. **DOE's efforts are one step towards addressing the Board's recommendation for development of U.S.-based URLs.**[32] DOE's intent to develop best practices and technologies for site selection through international collaboration, such as described by Dr. Gaus for the IGD-TP, is important.

DOE identified back in 2017 knowledge management as a crucial issue to address. **DOE's knowledge management efforts are commendable.** Dr. Sassani said that DOE plans to put more effort into knowledge management. He stated they intend to expand their efforts to storage and transportation, and the Board encourages those efforts.

The Board looks forward to future productive interactions with DOE and supporting national laboratory staff on several topics including:

- How DOE is determining R&D priorities and assessing the maturity of disposal options. The Board would like to better understand the effort and time DOE needs to address each of the high priority activities, how DOE tracks the completion status of high priority activities, and when all high priority activities are planned for completion.
- How barrier functions and expected performance would differ in higher temperature disposal options.
- A further understanding of DOE's Portland cement and cement plug/liner degradation activities.

[32] See *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*, January 2020, U.S. Nuclear Waste Technical Review Board, Arlington, Virginia.

The Board looks forward to future updates of the Disposal Research R&D 5-Year Plan. The Board anticipates that future updates will indicate how DOE will address management of new fuels such as accident tolerant fuel, high-assay low-enriched uranium fuels, other advanced fuels, and existing DOE SNF.