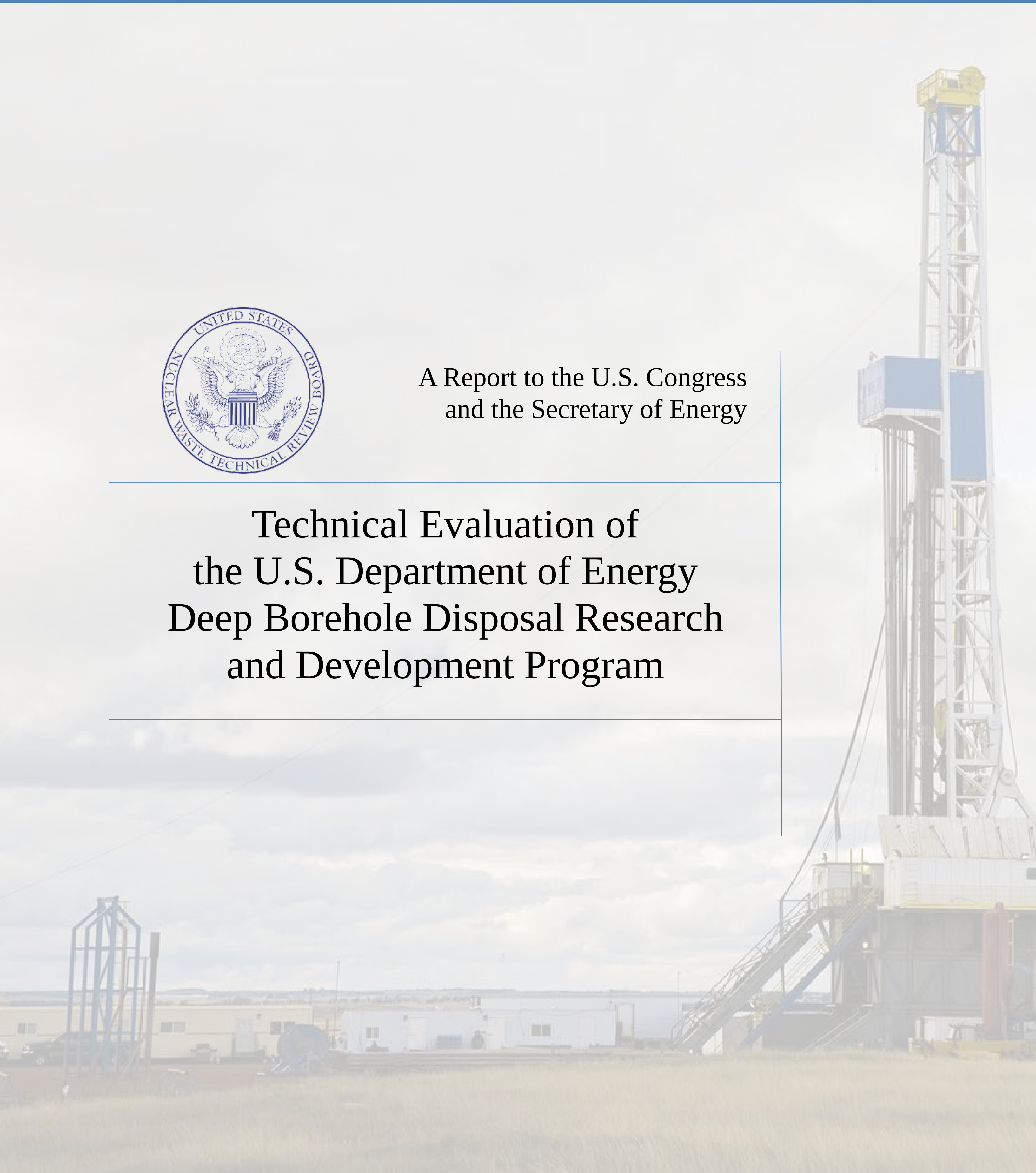
U.S. Nuclear Waste Technical Review Board



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

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

January 2016

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

January 27, 2016

The Honorable Paul Ryan
Speaker of the House
United States House of Representatives
Washington, DC 20515

The Honorable Orrin G. Hatch
President Pro Tempore
United States Senate
Washington, DC 20510

The Honorable Ernest J. Moniz
Secretary
U.S. Department of Energy
Washington, DC 20585

Dear Speaker Ryan, Senator Hatch, and Secretary Moniz:

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, the Board submits this report, *Technical Evaluation of the U.S. Department of Energy Deep Borehole Disposal Research and Development Program*, to the U.S. Congress and the Secretary of Energy. The report presents the Board's findings, conclusions, and recommendations related to activities being undertaken by the U.S. Department of Energy (DOE) to assess the feasibility of deep borehole disposal of some high-level radioactive waste, including a planned Deep Borehole Field Test to obtain technical information and understanding of critical processes related to deep borehole disposal.

The Board held an international technical workshop on deep borehole disposal of radioactive waste on October 20–21, 2015, in Washington, D.C., at which DOE presented its concept of deep borehole disposal of some radioactive wastes and discussed specific details of its Deep Borehole Field Test. The Board also invited experts from this and other countries to participate in the workshop and to provide their technical and scientific perspectives on issues related to the DOE plans. Following the workshop, the Board prepared the enclosed report, which addresses 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 select waste forms in deep boreholes. The following is an abbreviated summary of the Board's 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.*

- *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 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 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.*

Based on these findings, the Board makes the following 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.

- **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.

- **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 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.

- **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.

- **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.

- **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.

- **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.

- **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.

- **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.

The Board looks forward to receiving a copy for review of the DOE draft drilling and test plan for the Deep Borehole Field Test as early as possible. The Board will continue its independent technical and scientific evaluation of this and other important DOE activities, and report on its findings to Congress and the Secretary.

Sincerely,

Rodney C. Ewing
Chairman

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EXECUTIVE SUMMARY

In 2009, the U.S. Department of Energy (DOE) began investigating the technical and scientific issues associated with disposal of radioactive waste in deep boreholes and developing its deep borehole disposal concept. The concept of deep borehole disposal of radioactive waste is decades old, and both Sweden and the United Kingdom reviewed the concept. In both countries, after review of the concept, the recommendation was to not go forward with disposal of radioactive waste in deep boreholes, but rather focus efforts on a mined, geologic repository. In 2012, the Blue Ribbon Commission on America's Nuclear Future recommended that further research, development, and demonstration of this concept be conducted "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."

The DOE Deep Borehole Disposal Research and Development Program roadmap includes providing the technical basis for fielding a demonstration program, defining the scientific research activities associated with site characterization and post-closure safety, and defining the engineering demonstration activities associated with deep borehole drilling and surrogate waste package emplacement. DOE recently initiated a demonstration program—the Deep Borehole Field Test—and announced on January 5, 2016, that a Battelle Memorial Institute-led team had been selected to conduct this test at a site near Rugby, North Dakota.

The DOE deep borehole disposal concept envisions disposal of radioactive waste in one or more boreholes drilled to a depth of 5 km (3.1 mi) in crystalline basement rock. The lower 2 km (1.2 mi) of the borehole would be used as the disposal zone, wherein a series of waste packages would be emplaced. The upper 3 km (1.9 mi) of the borehole would then be sealed with bentonite and concrete. The disposal zone in the borehole disposal concept is significantly deeper than in a mined, geologic repository, which is typically 0.5- to 1-km (0.31- to 0.62-mi) deep. The volume and capacity of the disposal zone in a single borehole are, of course, much smaller than in a mined, geologic repository. Waste isolation in the DOE deep borehole disposal concept is based on the assumptions of long radionuclide travel time through the rock 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 concept takes very limited credit for engineered barriers, such as seals, waste packages, and waste forms following closure of the borehole.

DOE has identified the following waste forms as potential candidates for deep borehole disposal:

- Cesium and strontium capsules stored at the Hanford site in Washington State.

- Untreated calcine high-level radioactive waste currently stored at the Idaho National Laboratory.
- Salt wastes from electrometallurgical treatment of sodium-bonded fuels that could be packaged in small canisters as they are produced.
- Some DOE-managed spent nuclear fuel currently stored in water-filled pools at the Idaho National Laboratory and at the Savannah River Site in South Carolina.

DOE has acknowledged that all of the above waste forms also could be accommodated in a mined, geologic repository. However, DOE believes the deep borehole disposal concept "could offer a pathway for earlier disposal of some wastes than might be possible in a mined repository." DOE also has indicated that commercial spent nuclear fuel is not being considered for deep borehole disposal, mainly because of its size.

The U.S. Nuclear Waste Technical Review Board (Board)[1] held the *International Technical Workshop on Deep Borehole Disposal of Radioactive Waste* in Washington, D.C., on October 20 and 21, 2015, to review the technical and scientific validity of DOE activities related to assessing the feasibility of using deep boreholes to dispose of some radioactive waste. During the workshop, DOE made presentations on its Deep Borehole Disposal Research and Development Program and its plan for the Deep Borehole Field Test. These were followed by presentations by and discussions among U.S. and international experts on relevant aspects of deep borehole disposal of radioactive waste. The discussions were organized into seven panels that addressed the following technical and scientific topics: (1) experience in deep drilling in crystalline rocks, (2) emplacement mode, (3) borehole seals, (4) hydrogeology at depth, (5) geochemistry of fluids at depth, (6) multiple barriers (waste forms and package materials), and (7) efficacy of deep borehole disposal and risk analysis. During the workshop, the Board reviewed specific details of the DOE Deep Borehole Field Test, as well as broader issues related to the DOE deep borehole disposal concept.

This report addresses two topics: (1) technical and scientific issues that may affect the feasibility of the concept of using deep boreholes to dispose of select radioactive waste forms, and (2) whether the results that will be obtained from the Deep Borehole Field Test will provide the necessary technical and scientific data to support the DOE evaluation of the feasibility of disposing of select waste forms in deep boreholes. Based on the information presented at the workshop by DOE, its contractors, and the members of the expert panels, the Board makes the following overarching findings:

- Available performance assessments do 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 being considered for deep borehole disposal could be disposed of in a mined, geologic

[1]The U.S. Nuclear Waste Technical Review Board was created by Congress in the 1987 Nuclear Waste Policy Amendments Act (Public Law 100-203) and charged with evaluating the technical and scientific validity of activities undertaken by the Secretary of Energy to manage and dispose of high-level radioactive waste and spent nuclear fuel. The Board reports its findings and recommendations to Congress and the Secretary of Energy.

repository. Many large waste forms, such as the packages of vitrified high-level waste of the type being produced at the Savannah River Site, are not suitable for disposal in deep boreholes given current technical limits on borehole diameter. Thus, disposal of radioactive waste in deep boreholes does not eliminate the need for a mined, geologic repository.

- 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. However, deep boreholes lack 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 is extremely limited as compared with a mined, geologic repository. Also, the Board has not been presented with any compelling evidence that deep borehole disposal can 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.

- The Deep Borehole Field Test and the DOE approach to assessing the feasibility of the deep borehole disposal concept are 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 does 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 does it fully consider how data from the potentially complex system at one site can be applied to another site. Thus, even if the DOE assumptions are confirmed during the Deep Borehole Field Test, DOE runs 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 will not have been obtained during the test.

- The operational safety strategy required for drilling and emplacement operations involving radioactive material is very different from that for operations involving non-radioactive material. Hence, it is important to consider the operational implications and limitations of handling and emplacing actual, highly radioactive waste and how these may be simulated during the Deep Borehole Field Test. 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.

It is clear that substantial time and effort will be required to fully evaluate the concept of deep borehole disposal. In the Board's view, the Deep Borehole Field Test, which DOE presented to the Board at the workshop, should carefully consider the key parameters and information that would be needed to fully evaluate the feasibility of deep borehole disposal of radioactive waste.

This would provide a basis for additional planning, including definition of 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 greatly improve the technical basis and rationale for the DOE Deep Borehole Disposal Program. Specific Board recommendations are as follows:

- ***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.*

- ***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.*

- ***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 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.*

- ***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.*

- ***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.*

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- ***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.*

- ***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.*

- ***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.*

ACKNOWLEDGMENT

The Board thanks the participants from the U.S. Department of Energy (DOE) and its contractors from the Sandia National Laboratories for presenting the DOE Deep Borehole Disposal Research and Development Program and for sharing their expert knowledge of the program. The Board also thanks the invited speakers from the U.S. and other countries for sharing their extensive expertise and providing thoughtful insights and ideas during the workshop discussions.

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BOXES

FIGURES

Introduction

The U.S. Nuclear Waste Technical Review Board (Board)[1] held the *International Technical Workshop on Deep Borehole Disposal of Radioactive Waste* in Washington, D.C., on October 20 and 21, 2015. The Board's purpose in organizing this workshop was to review the technical and scientific validity of U.S. Department of Energy (DOE) activities related to assessing the feasibility of using deep boreholes to dispose of some radioactive waste. During the workshop, the Board reviewed specific details of the proposed DOE Deep Borehole Field Test (SNL, 2015; Kuhlman *et al*., 2015), as well as broader issues related to the DOE deep borehole disposal concept.

The workshop began with DOE presentations on the Deep Borehole Disposal Research and Development Program and the plan for the Deep Borehole Field Test. These presentations were followed over the next day and a half by discussions among U.S. and international experts on relevant aspects of deep borehole disposal of radioactive waste. The discussions were organized into seven panels, each of which addressed specific technical and scientific topics. A plenary presentation by Professor Fergus Gibb of the University of Sheffield (United Kingdom) provided an overview of the broader concept of deep borehole disposal. The workshop agenda and list of speakers are included in Appendix A. The presentations, the transcript of the proceedings, and the archived webcast of the workshop in its entirety are available on the Board's website (http://www.nwtrb.gov/meetings/meetings.html).

This report addresses two topics: (1) the technical and scientific issues that may affect the feasibility of the concept of using deep boreholes to dispose of select radioactive waste forms, and (2) whether the results that will be obtained from the Deep Borehole Field Test, as described by DOE presentations and reports, will provide the necessary technical and scientific data to support the DOE evaluation of the feasibility of disposing of select waste forms in deep boreholes. The Board's findings, conclusions, and recommendations are based on the workshop presentations and discussions, as well as publications by DOE and others (see reports in the Cited References Section and the bibliography in Appendix B).

The concept of deep borehole disposal of radioactive waste is decades old. Both Sweden (SKB, 1992, 2010) and the United Kingdom (NIREX, 2004) reviewed the concept and compared the option of disposal of spent nuclear fuel in deep boreholes with that in a mined, geologic repository. SKB (2010) concluded that "disposal in deep boreholes is not a realistic alternative" to the Swedish KBS-3[2] geologic repository concept and that "a crucial difficulty in judging the deep borehole concept is that very little is known about the actual geological, hydrogeological and geochemical conditions at the great depths in question." SKB (2010) also concluded that a

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[2]The KBS-3 concept (SKB, 2011) developed for the planned spent nuclear fuel repository in Sweden envisions emplacement of copper canisters with a ductile iron insert containing spent nuclear fuel at a depth of approximately 500 m (1,640 ft) in groundwater-saturated crystalline (*e.g*., granitic) rock. The copper canisters will be surrounded by a compacted bentonite buffer to restrict water flow around the canisters and delay the release of radioisotopes to the groundwater.

canister could get stuck in the hole and break before it has reached disposal depth, and, without the protection of a bentonite buffer, release radionuclides to the groundwater. NIREX (2004) identified "two aspects of the deep borehole disposal concept that require thorough evaluation: (1) the performance of the disposal system, especially the thermal and hydraulic environment around the disposal zone and its seals; and (2) the engineering aspects of borehole construction and package handling, including safety during the operational phase." In both Sweden and the United Kingdom, after review of the deep borehole disposal concept, the recommendation was to not go forward with disposal of radioactive waste in deep boreholes, but rather focus efforts on a mined, geologic repository.

In addition, Professor Gibb and his colleagues, in a series of peer-reviewed papers (Gibb, 2000; Chapman and Gibb, 2003; Gibb *et al.*, 2007, 2012), examined various aspects of deep borehole disposal of spent nuclear fuel and reinvigorated international interest in this disposal option. Furthermore, the Blue Ribbon Commission on America's Nuclear Future (BRC, 2012) recommended further 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."

The DOE research and development program on deep borehole disposal is briefly described in Box 1.

DOE Perspective: Deep Borehole Disposal Concept

The DOE deep borehole disposal concept, as presented at the workshop, envisions disposal of radioactive waste in one or more boreholes with a down-hole diameter of 43.2 cm (17 in), drilled to a depth of 5 km (3.1 mi) in crystalline basement rock at a suitable site (Arnold *et al.*, 2012). The borehole site would be determined using technical criteria (see Box 2) that seek to minimize undesirable features (*e.g.*, high permeability connections to the surface). In the DOE conceptual model, the lower 2 km (1.2 mi) of the borehole would be used as the disposal zone, wherein a series of waste packages would be emplaced (Figure 1). The upper 3 km (1.9 mi) of the borehole would then be sealed with bentonite and concrete. In the uncased seal zone, which would be between 2 and 3 km (1.2 and 1.9 mi) in depth in crystalline basement rock, the well casing would be removed and the seals would be in direct contact with the borehole wall.

The proposed 3- to 5-km (1.9- to 3.1-mi) depth of the disposal zone in the borehole disposal concept is significantly deeper than that of a mined, geologic repository [typically 0.5 to 1 km (0.31 to 0.62 mi), Figure 1]. However, deep boreholes lack

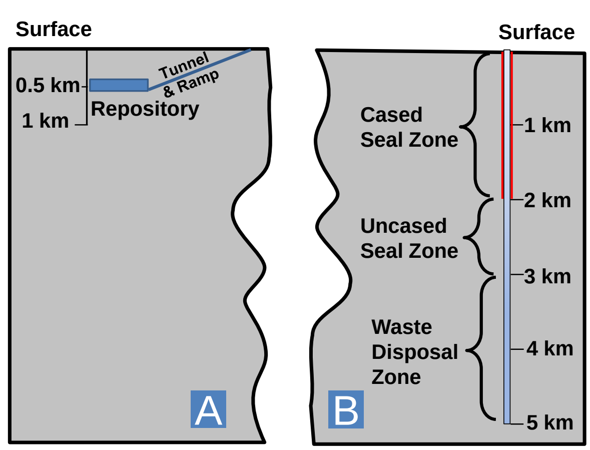


Figure 1. Comparison of the concepts of radioactive waste disposal in (A) a mined, geologic repository and (B) a deep borehole

Box 1. Brief Summary of the DOE Deep Borehole Disposal R&D Program

In 2009, the Department of Energy (DOE) began investigating the technical and scientific issues associated with disposal of radioactive waste in deep boreholes and developing its deep borehole disposal concept. A research and development (R&D) program roadmap was developed that includes providing the technical basis for fielding a demonstration program, defining the scientific research activities associated with site characterization and post-closure safety, and defining the engineering demonstration activities associated with deep borehole drilling and completion, and surrogate waste canister emplacement (Arnold *et al.*, 2012). DOE developed a reference design that provides the technical requirements for engineered barriers, describes the handling and emplacement operations, and discusses the required surface facilities (Arnold *et al*., 2011a).

DOE Deep Borehole Disposal Safety Case

The DOE safety case for deep borehole disposal[1] includes consideration of the design, planned engineered and natural barriers and their required performance, and characteristics of the site, which will be selected using technical site selection criteria (see Box 2) (DOE, 2015a; Arnold *et al.*, 2012). Although the reference design specifies that the "[w]aste canisters should retain their integrity as long as practical" (Arnold *et al.*, 2011a), the DOE deep borehole disposal concept places no reliance on the waste canisters as a barrier to radionuclide release after the borehole is sealed. Importantly, it has no requirement for waste form performance. Borehole seals "shall function at temperatures up to 200 °C for the duration of the thermal period" and are relied on to provide a low permeability barrier (less than 10^{-16} m^2) to fluid flow within the borehole (Hardin, 2015, p. 22).

DOE identified features, events, and processes (FEPs) it considers important to the deep borehole disposal concept based on the performance objectives of containment, limiting releases, and defense-in-depth. DOE identified how the information necessary to evaluate the important FEPs would be obtained in the demonstration program or how other information would be used (Arnold *et al.*, 2012). DOE indicated that laboratory testing will establish the behavior of engineered barrier materials under conditions simulating the temperature, pressure, and chemical conditions in the borehole (Arnold *et al*., 2012, p. 29). DOE acknowledged that "waste canister corrosion, bentonite alteration, cement degradation, and seal degradation are the critical unknowns that will need to be analyzed through a combination of laboratory testing, chemical equilibrium modeling, and kinetic analysis" (Arnold *et al*., 2012, p. 29). DOE prioritized its R&D activities based on its safety case and list of important FEPs (Arnold *et al*., 2012, Table 6-1).

DOE Performance Assessments

DOE conducted performance assessments to evaluate the long-term safety of disposal of spent nuclear fuel in deep boreholes and compared the results to disposal in a mined, geologic repository (Arnold *et al*., 2013; Freeze, 2015). The results for the two disposal options are similar in the sense that the calculated doses for both options are below regulatory limits. However, for deep borehole disposal performance assessments, DOE noted that key uncertainties remain, such as whether a specific site has properties favorable for disposal in deep boreholes (*e.g*., old saline groundwater, low-permeability rock, absence of fast transport pathways) (Swift, 2015). Seal performance and the effect of the disturbed rock zone surrounding the borehole also have been noted as needing evaluation along with an enhanced understanding of coupled thermal–hydrological–mechanical–chemical processes near the borehole (Freeze, 2015).

[1]DOE has developed a draft generic safety case for deep borehole disposal of high-level radioactive waste (Arnold *et al*., 2013, Appendix A)

Box 2. DOE Technical Siting Criteria

The DOE *Request for Proposal for the Deep Borehole Field Test: Site and Characterization Borehole Investigations* (DOE, 2015a) identified several technical criteria for selecting a site for drilling the field test boreholes that also would apply to selecting a suitable site for deep borehole disposal of radioactive waste (Arnold *et al.*, 2012). The site criteria are as follows:

- Depth to crystalline basement rock less than 2 km (1.2 mi).
- Simple basement structure, indicated by a lack of known major regional structures, major shear zones, or major tectonic features within 50 km (31 mi) of the proposed site.
- Low seismic and tectonic activity, with the distance to Quaternary age volcanism or faulting greater than 10 km (6.2 mi).
- Lack of conditions associated with fresh groundwater flow at depth, demonstrated by a lack of significant topographic relief that would drive deep recharge, by evidence of ancient groundwater at depth, and/or by data suggesting the presence of high-salinity groundwater at depth.
- Preferably, a geothermal heat flux less than 75 milliwatts per square meter.
- Sufficient area to accommodate two drilling operations with boreholes nominally separated by at least 200 m (656 ft).
- Lack of surface or subsurface anthropogenic radioactive or chemical contamination.
- Low potential for interference with testing from other surface and subsurface usage, such as wastewater disposal by deep well injection, oil and gas production, mining, or underground drinking water extraction. Preferably, potential natural resources in the crystalline basement rock and sedimentary overburden are absent.

the easy working access for characterizing the disposal zone and emplacement of wastes that shafts, ramps, and tunnels would provide in the case of a mined, geologic repository. The volume and capacity of the disposal zone in a single borehole are much smaller than in a mined, geologic repository. Moreover, waste retrieval from a sealed borehole would be more difficult than from a mined repository because the waste is deeper and, thus, less accessible.

In deep borehole disposal, the primary means of impeding the release of radionuclides to the environment is a combination of hydrogeologic and geochemical factors that act as natural barriers, namely:

- Long travel time through the rock to sources of drinking water due to the long distance and the presumed 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.

- Chemically reducing conditions at depth that would decrease the solubility and mobility of some redox-sensitive radionuclides, particularly actinide elements.

As articulated by DOE at the workshop, deep borehole disposal is a simple concept that provides reliable isolation for select, small-diameter waste forms through a system of geologic barriers. The waste packages are not relied on to provide long-term isolation as they are intended to maintain their integrity only until the borehole is sealed (Hardin, 2015) and "are assumed to rapidly degrade after emplacement and sealing" (Sassani, 2015, p. 131). Furthermore, the overlying seals in the borehole only need to prevent the upward transport of released radionuclides for some 300 years, *i.e.*, the time required to get beyond the currently calculated thermal pulse of heat-producing waste (Brady, 2015a, p. 313). After the thermal pulse, reducing conditions and the density stratification of the fluids return and "the seals somewhat become superfluous because there is no driving force" (Brady, 2015a, p. 313) for moving the radionuclides upward.

DOE views the deep borehole disposal concept as a modular strategy in the sense that additional boreholes can be located at different sites as needed. By locating the boreholes near where the waste is generated or currently stored, the need for transportation, such as to a distant geologic repository, would be significantly decreased.

In DOE presentations at the workshop and in DOE reports (*e.g.*, SNL, 2014), the following DOE-managed waste forms were identified as potential candidates for deep borehole disposal:

- Cesium and strontium capsules stored at the Hanford site in Washington State.
- Untreated calcine high-level radioactive waste currently stored at the Idaho National Laboratory.
- Salt wastes from electrometallurgical treatment of sodium-bonded fuels that could be packaged in small canisters as they are produced.
- Some DOE-managed spent nuclear fuel currently stored in water-filled pools at the Idaho National Laboratory and at the Savannah River Site in South Carolina.

DOE has acknowledged that all of the above waste forms also could be accommodated in a mined, geologic repository (SNL, 2014). However, DOE believes the deep borehole disposal concept "could offer a pathway for earlier disposal of some wastes than might be possible in a mined repository" (DOE, 2014). DOE also has indicated that commercial spent nuclear fuel is not being considered for deep borehole disposal, mainly because of its size (Griffith, 2015, p. 268).

DOE Plan: Deep Borehole Field Test

DOE is pursuing a Deep Borehole Field Test to assess the feasibility of the deep borehole disposal option. The DOE Deep Borehole Field Test,[3] as presented at the workshop and in

[3] In 2015, the DOE issued the *Request for Proposal for the Deep Borehole Field Test: Site and Characterization Borehole Investigations* (DOE, 2015a). According to the terms of the Request for Proposal, the subcontractor is responsible for providing a suitable site for hosting the Deep Borehole Field Test, developing a detailed drilling and test plan, and supporting procurement for drilling and construction services. The contractor also is responsible for developing the process and procedures for establishing and operating a Technical Advisory Committee, which will monitor site activities, especially during drilling and testing, and ensure that the necessary data and information are collected. The contractor also is encouraged to propose additional research, including more tests and measurements that would improve knowledge of the subsurface; however, funding to undertake such research is not included in the statement of work for the Deep Borehole Field Test Request for Proposal. On January 5, 2016, DOE announced that it had selected a Battelle Memorial Institute-led team to drill a test borehole into a crystalline basement rock formation near Rugby, North Dakota (DOE, 2016).

various DOE documents (DOE, 2015a; SNL, 2015), envisions drilling two 5-km (3.1-mi) deep boreholes into crystalline basement rock in a geologically stable continental region. First, a "characterization" borehole with a diameter at the bottom of approximately 21.6 cm (8.5 in) will be drilled and completed. This will facilitate a suite of tests to log physical properties down-hole, as well as scientific test activities. According to DOE, the scientific testing and analysis activities in the characterization borehole will be used to identify the critical down-hole measurements that must be made at a future deep borehole disposal site to determine if conditions at depth are favorable to long-term isolation of radioactive waste.

Second, assuming favorable results from the characterization borehole, a "field test" borehole, approximately 43.2 cm (17 in) in diameter at the bottom, is planned to be drilled within a few hundred meters of the characterization borehole to facilitate the proof-of-concept of design and operational activities. As part of the Deep Borehole Field Test, DOE will test a prototype waste package, a waste package surface handling system, and a subsurface system for emplacing and retrieving packages in a deep borehole (Hardin, 2015). However, no radioactive waste will be emplaced as part of the field test. The Deep Borehole Field Test will simulate waste disposal operations, which means the test operations will be designed and implemented to demonstrate methods for radiological protection, even though radiological protection is not required for demonstration activities as no radioactive waste will be involved in the field test. For example, the shielding that would be required for actual waste package handling operations may be simulated during the Deep Borehole Field Test (Hardin, 2015, p.4).

No *in situ* seals tests are currently planned as part of the Deep Borehole Field Test. However, laboratory studies of engineered materials, including seals, under representative down-hole conditions are planned as part of the DOE Deep Borehole Disposal Research and Development Program to provide a technical basis for predicting the performance of these materials (Arnold *et al.*, 2013).

Observations by Independent Expert Panelists

The independent expert panelists at the workshop summarized information gained previously from boreholes drilled deep into crystalline basement rock. The expert panelists noted that the deep subsurface is often complex and heterogeneous in its structural, petrophysical, geochemical, and hydrogeologic properties and, consequently, surprises should be expected. Typical complexities that have been observed in deep boreholes drilled to date include:

- Salinity inversions (*i.e.*, zones where salinity decreases rather than continues to increase with depth). This is indicative of active fluid flow (both vertical and horizontal) within the subsurface brine environment rather than a density-stabilized stratification.
- High levels of differential tectonic stress (*i.e.*, the forces acting within Earth's crust due to gravity and other sources). High differential stresses at depth will deform the rock surrounding the borehole during and following drilling.
- Considerably higher bulk permeabilities in the subsurface rock than those determined from measurements on intact cores and permeabilities that may vary over time as well as space in response to changes in effective stress.

- Potentially active faults and fractures that can serve as highly permeable, preferential flow zones.
- Significant microbial activity, which is known to cause corrosion of steel well-casing. Such microbial activity also could potentially corrode the waste packages and degrade the seals.
- Significant concentrations of gases, such as methane or hydrogen.

The expert panelists described the deep borehole environment as a complex system of interactions and feedbacks among the engineering activities (*e.g.*, drilling, emplacement, and sealing) that perturb the physical and chemical conditions in the subsurface (*e.g.*, stress fields, groundwater composition, hydrogeologic conditions, and hydraulic connections between water at disposal depths and groundwater in shallower zones).

The expert panelists and DOE also noted that the existing deep boreholes have been drilled at sites that were selected for purposes other than radioactive waste disposal research (Sassani and Hardin, 2015, p. 8). For example, existing deep boreholes were drilled for geothermal exploration, geologic exploration and technology development, and exploring the San Andreas Fault. As a consequence, the extent to which the complexities listed above would be observed at a site that meets the DOE siting criteria is unknown. *In the Board's view, it is nonetheless unlikely that subsurface conditions needed to support the DOE safety case for deep borehole disposal of radioactive waste will be found at all sites.*

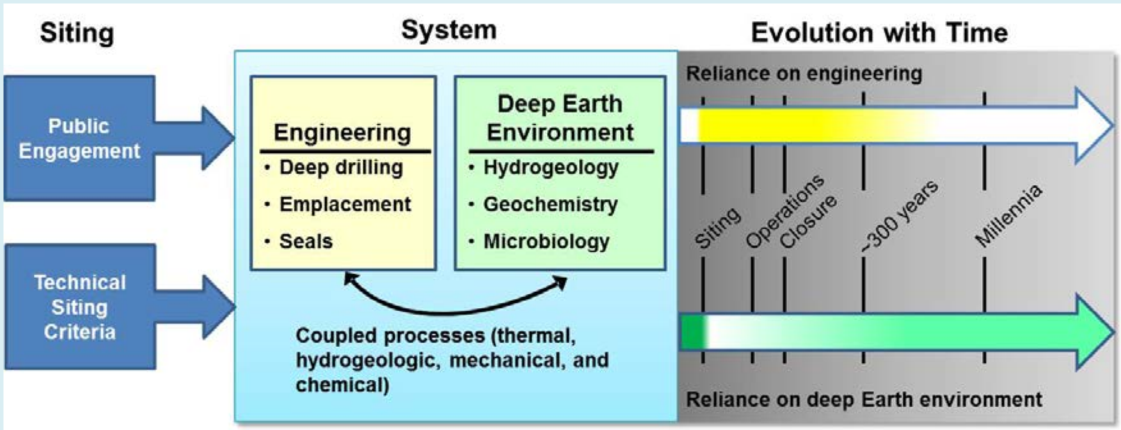
Board Perspective: Deep Borehole Disposal System

Given the complexity and heterogeneity of the deep subsurface noted by the expert panelists at the workshop and discussed in the preceding section, the Board views deep borehole disposal as a complex system, described in Box 3, in which a large number of coupled processes operate over a range of temporal and spatial scales. As examples of the complexity of some of these coupled processes, the Board notes:

- Coupled thermal–hydrogeologic–mechanical processes: Time-dependent, drilling-induced borehole wall failure (so-called breakouts) due to unequal horizontal stresses at depth will increase the extent of the damage zone around the borehole after drilling operations end (Bell and Gough, 1979; Zoback *et al*., 1985). Such deformation will be affected by heat from radioactive decay of the emplaced waste (Arnold *et al*., 2011b). The damage zone is a possible pathway for radioactive material released in the disposal zone to reach shallower hydrogeologic systems. The results of DOE modeling indicate that maintaining the permeability below 10^{-13} m^2 in a damage zone with a 1-m^2 cross-sectional area, which includes the borehole and its seals[4], is important for reducing upward migration of radionuclides (Hadgu *et al*., 2012).

[4]In the DOE modeling of thermal–hydrogeologic processes (Arnold *et al*., 2011b; Hadgu *et al.*, 2012), the damage zone is assumed to extend radially about 13 cm (5 in) from the 44-cm (17.3-in) diameter borehole.

Box 3. Board Perspective: Deep Borehole Disposal System



The Deep Borehole Disposal System is composed of two subsystems: the "Engineering" subsystem and the "Deep Earth Environment" subsystem. These two subsystems interact continuously over a range of temporal and spatial scales, and involve a range of coupled processes. For example, borehole-caused disturbances will change the deep environment and alter its hydrogeologic, geochemical, microbiological, and geomechanical properties. In turn, to the extent they exist at the deep borehole site, potentially active faults, salinity inversions, high levels of differential tectonic stress, microbial activity, and high permeability fractures at depth could impact the integrity of the engineering system at times ranging from operations to closure to thousands of years after closure.

The interplay of the Engineering and Deep Earth Environment subsystems determines the integrity of the Deep Borehole Disposal System as a whole, with the latter becoming more important than the former with increasing time. For example, at the operations and closure stages, the success of this system depends mostly on the integrity of its Engineering subsystem (drilling and emplacement operations and the performance of the seals). After that stage, the degree of migration, laterally and vertically, of radionuclides that will be released from the waste form and waste container and, thus, the risk associated with the Deep Borehole Disposal System as a whole, depends mostly on the properties of the natural and borehole-disturbed environment in the disposal zone.

- Coupled chemical–hydrogeologic processes: Corrosion of the steel well-casing and packages will generate hydrogen that could remain dissolved in the brine or form a free gas phase. DOE currently assumes rapid degradation of the well-casing (Hardin, 2015) and waste package (Sassani, 2015, p. 131); however, it has not adequately assessed corrosion of steel engineered components, whether a free gas phase could form (Brady, 2015b, p.117), or the implications of a free gas phase on radionuclide transport. DOE also has not fully considered the implications of the presence of other dissolved (or as a free phase) gases, such as carbon dioxide and methane, and the production of gaseous species as a result of radiolysis.

In contrast to a mined, geologic repository where the extent of the underground workings would allow extensive characterization at disposal depths, deep borehole disposal would require an array of boreholes for a comparable level of characterization. It is likely that each borehole site will require independent characterization because of the potential for variations in geologic environment at depth.

In the Board's view, a deep borehole disposal system could be as complex as a mined, geologic repository and assessing the performance of both disposal options may require an equivalent level of data collection and testing. The DOE approach to assessing the feasibility of the deep borehole disposal concept does not yet take account of many of the complex interactions and feedbacks noted in Box 3.

Furthermore, although deep boreholes might provide a disposal option for certain types of DOE-managed waste, all of the waste forms being considered for deep borehole disposal could be disposed of in a mined, geologic repository, as DOE has acknowledged. Disposal of radioactive waste in deep boreholes does not eliminate the need for a mined, geologic repository, which will still be required for large waste forms, such as commercial spent nuclear fuel and canisters of vitrified high-level waste, given current technical limits on the maximum diameter of deep boreholes.

Board Evaluation: Deep Borehole Field Test

Based on the presentations and discussions at the workshop, the Board identified a number of key scientific, engineering, and operational issues that it considers should be addressed for the Deep Borehole Field Test to effectively support assessment of the deep borehole disposal concept. These issues include the following:

- Drilling and emplacement technologies
- Heterogeneous and complex *in situ* conditions at depth
- Scope and objectives of Deep Borehole Field Test site characterization activities
- The role of multiple barriers
- Simulation of deep borehole operations involving radioactive materials
- Development of environmental safety standards and implementing regulations
- Opportunity to explore public engagement issues affecting successful siting
- Requirement for strong technical leadership

These key issues are described and discussed below, together with the Board's findings, conclusions, and recommendations, and the information on which the recommendations are based.

Drilling and emplacement technologies

The experts on drilling who participated in the workshop agreed that, although no 43.2-cm (17-in) borehole has been drilled to 5-km (3.1-mi) depth in crystalline basement rock, there appear to be no insurmountable technological barriers to completing such a borehole. They agreed, however, that surprises should be anticipated during the field test and that the Deep Borehole Field Test drilling team must prepare for the unexpected. Expert management of the drilling process and appropriate state-of-the-art technologies, such as directional control, minimizing drill pipe vibrations, down-hole motors, automated drilling systems, and polycrystalline diamond compact drill bits, also will be required to drill and maintain a stable borehole to the necessary specifications. In addition, a custom-designed drilling fluid program will be needed to maximize borehole stability and borehole cleaning in the crystalline basement rock.

Deep drilling in crystalline basement rocks to date—essentially all of which has been undertaken at sites selected using criteria other than the DOE siting criteria for radioactive waste disposal (Box 2) (DOE, 2015a; Arnold *et al.*, 2013)—suggests that the following down-hole conditions may be encountered:

- High levels of differential tectonic stress, a ubiquitous property found in all rock types in Earth's crust that could lead to borehole deformation during and after drilling.

- Intersecting fracture zones with possible significant fluid influx or loss.

The drilling and test plan should anticipate these conditions and also integrate the scientific data needs and the performance expectations for the rest of the program. For example, down-hole sampling and testing need to be an integral part of the drilling and test plan because some of these activities may need to be undertaken periodically during drilling, which would require a pause in drilling operations. Also, to support the DOE technical basis for the performance of the seals, DOE should conduct *in situ* seals tests. Furthermore, given the potential that a waste package may become stuck during emplacement operations, either in the equipment at the surface or down-hole, and that a package stuck down-hole may be left in place for safety reasons, DOE will need to give more consideration to the operational and post-closure radiological implications of a stuck waste package when assessing the feasibility of deep borehole disposal of radioactive waste.

The emplacement modes considered in detail in a recent Sandia National Laboratories report (Cochran and Hardin, 2015) are wireline emplacement (lowering single waste packages on an electric cable) and drill-string emplacement (lowering a string of packages connected by threaded joints at the end of a standard drill pipe). Emplacement using coiled steel tubing[5] and freefall or gravity emplacement also were briefly discussed in the Sandia National Laboratories report. During the workshop, one additional potential emplacement mode, conveyance liner,[6] was mentioned. Figure 2 illustrates three of the five emplacement modes. DOE should provide a justification for considering only wireline or drill-string emplacement in its detailed assessment.

Furthermore, the experts on the emplacement mode panel at the workshop questioned the completeness of the risk assessment used to compare between wireline and drill-string

[5]Coiled tubing refers to a very long metal pipe that is supplied spooled on a large reel. The small diameter pipe, normally 25 to 83 mm (1 to 3.25 in) in diameter, is hydraulically driven into the hole, in contrast to the wireline emplacement method, which relies on gravity to lower the package.

[6]A conveyance liner is a large-diameter casing that is sealed at the bottom and held in place at the well head. Waste packages are stacked inside the conveyance liner using a wireline. Then the entire casing is lowered into place using a drill string. To maintain a casing path for the conveyance casing, using the same size waste packages, a larger diameter borehole is needed in the disposal zone than for the other emplacement modes (SNL, 2015).

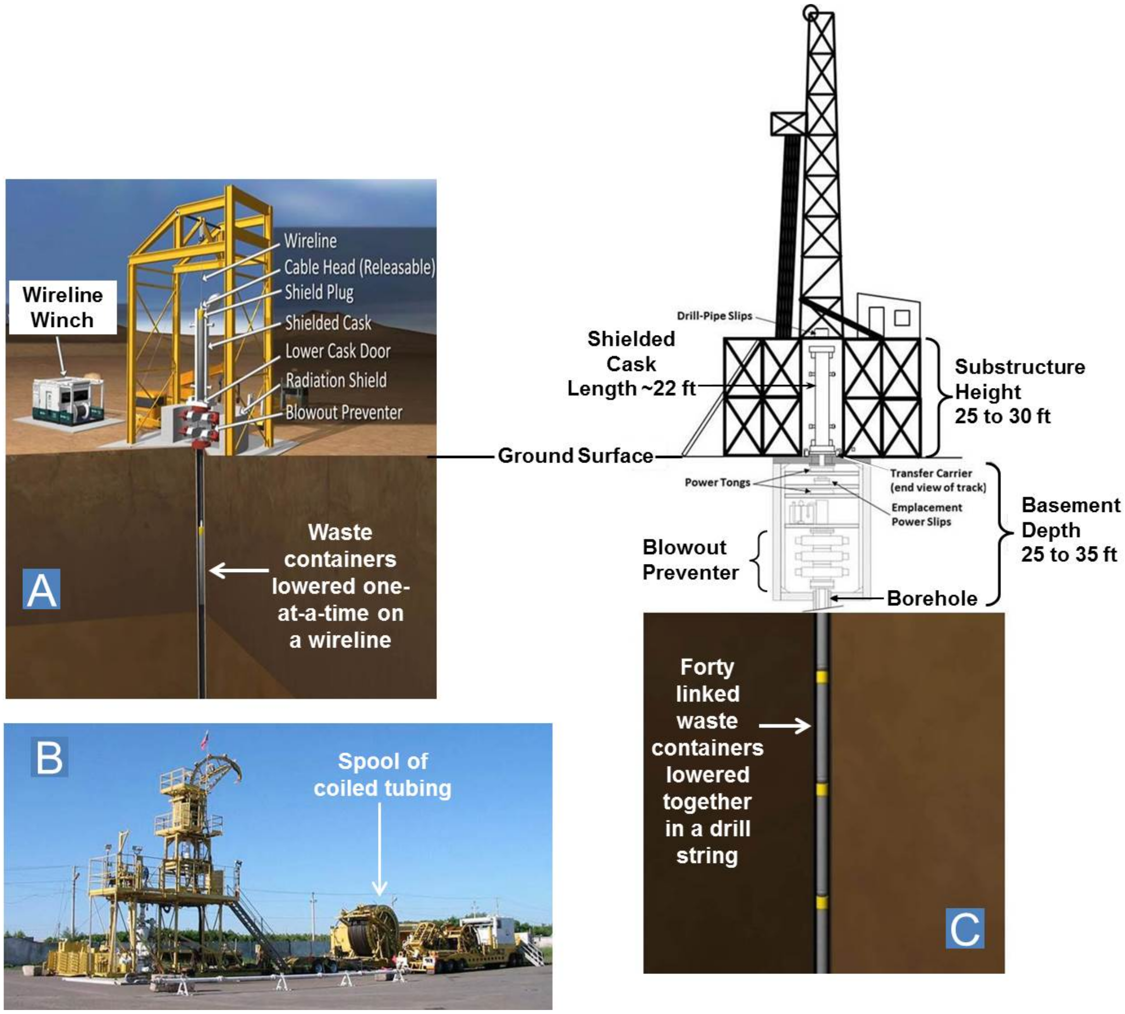


Figure 2. Comparison of deep borehole emplacement modes: (A) wireline, (B) coiled tubing, and (C) drill-string

emplacement. For instance, the analysis of wireline emplacement did not consider maintenance, equipment condition/status monitoring, and status of emplacement fluid, which were included in the assessment of drill-string emplacement. The detailed assessment also did not consider the potential for nuclear criticality in comparing the two emplacement options. Criticality could be a discriminating factor under waste package drop scenarios for packages containing spent nuclear fuel, which DOE has identified as a possible waste type for borehole disposal.

The Deep Borehole Field Test Request for Proposal (DOE, 2015a) calls for creation of a Technical Advisory Committee chaired by the Deep Borehole Field Test project lead with the ability to report to DOE on short-term issues. Membership representation on that advisory committee was not specified.

*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.

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.

Heterogeneous and complex in situ *conditions at depth*

Data from existing boreholes in deep crystalline rock at sites around the world, as well as other evidence, point to numerous complexities involving coupled thermal, hydrogeologic, mechanical, and chemical processes in the upper 5 km (3.1 mi) of Earth's crust. Furthermore, the act of drilling and casing a well, together with emplacement of thermally hot waste packages, will perturb the ambient subsurface conditions. In the Board's view, the Deep Borehole Field Test's primary goal should be to gain an understanding of the deep borehole disposal system and its key characteristics that is adequate to support an evaluation of the deep borehole disposal concept and, if the concept is pursued, the subsequent design of deep boreholes. Examples of key characteristics that need to be better understood are described below.

Geomechanical and Hydrogeologic Properties. Near-hydrostatic pore pressure, *i.e.*, pressure equal to that exerted by a column of fluid (water or brine) at the depth of the measurement, is observed in all deep boreholes. This observation is indicative of large-scale rock permeability at depth. Permeability measurements in the laboratory, in which rock core samples taken from deep wells are subjected to pressure conditions similar to those at depth, yield values in the range of 10^{-18} to 10^{-21} m^2 (Figure 3). These permeability values are too low to allow effective transmission of fluid pressure and are inconsistent with the near-hydrostatic pore pressure observed at depth. Extensive *in situ* testing and sampling in a number of scientific boreholes to depths of 2 to 8 km (1.2 to 5.0 mi), as well as other evidence, have consistently demonstrated that large-scale permeability in crystalline basement rock is controlled by the existence of critically-stressed faults, *i.e.*, faults and fractures that are well-oriented for slip in the ambient tectonic stress field (Townend and Zoback, 2000).

Because permeability and the *in situ* stress state are inextricably linked at depth in the crust, processes that impact the *in situ* stress state and that occur far from the location of a field test or disposal site could impact that site. For example, induced seismic activity in crystalline basement rock in Oklahoma, a geologically stable continental region, is caused by the injection of massive quantities of saline wastewater into a rock formation overlying the crystalline basement rock (Walsh and Zoback, 2015). The injection of wastewater, which is produced during oil and gas operations, slightly increases the subsurface fluid pressure (on the order of 2 percent). Because of the hydraulic connectivity between the overlying rock formation and the crystalline basement rock, the small increase in pressure triggers earthquakes in the basement rock, usually within weeks to months of the injection. The modeled fluid pressure perturbation propagates to distances of 35 km (22 mi) and tracks earthquake locations to that distance (Keranen *et al*., 2014).

Even if high permeability zones or favorably-oriented fractures are not encountered in the field test or disposal borehole, they might exist in the surrounding crystalline basement rock. Based on the Oklahoma example, pressure changes on the order of 2 percent in an overlying rock formation can generate earthquakes in the crystalline basement rock. Fault slip due to these earthquakes could create potential pathways for fluid migration (Ingebritsen and Manning, 2010). The possibility that induced earthquakes could occur underscores the need for a comprehensive understanding of the subsurface system at distances beyond the immediate location of the borehole.

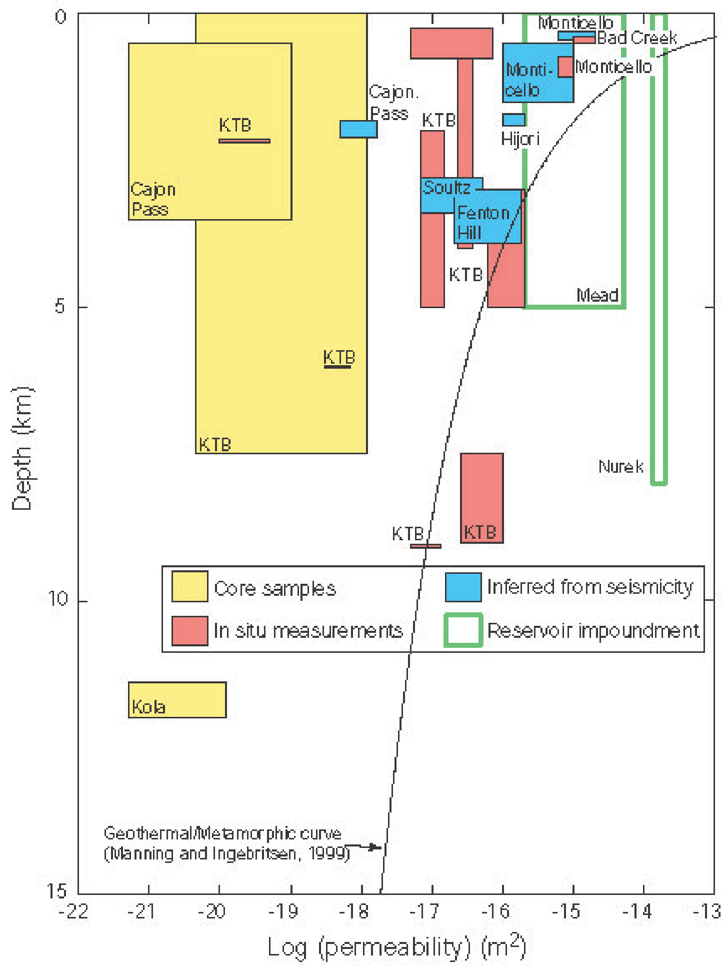


Figure 3. Deep crustal permeability data acquired from core samples, *in situ* hydraulic tests, and induced seismicity. From Townend and Zoback (2000)

Field observations and modeling results discussed by the experts on the hydrogeology panel during the workshop provide evidence of crustal permeabilities that can be even higher, at least transiently, than those measured by *in-situ* tests or induced seismicity (Ingebritsen and Manning, 2010). The panelists also discussed the potential, at least in some settings, for significant regional-scale flow through crystalline basement rock in the depth range of 2 to 5 km (1.2 to 3.1 mi), as well as other examples of the presence of permeable fractures extending to depths corresponding to the proposed borehole disposal zone.

Geochemistry. A key observation by experts on the panel convened to discuss the geochemistry of deep borehole disposal was that drilling the borehole and emplacing the waste packages would change both the hydrogeologic and geochemical conditions at depth, and that extensive modeling would be required to predict those changes. Modeling, in and of itself, will be difficult, given the lack of thermodynamic and kinetic data for many chemical species in concentrated brines. The experts on the geochemistry panel also pointed out that, while on one hand the brine might be perceived as a positive attribute of deep borehole disposal because dense brine is not expected to move upward, on the other hand, the solubilities of many materials are higher in fluids with high salt concentration than in fresh water (*e.g.*, Pirajno, 1992; Seward *et al*., 2014). If heat or pressure buildup in the borehole or fractures caused the brine to move, this could allow radioactive material to be transported along with the brine. However, the concentrations of radionuclides in the brine are difficult to estimate because of a lack of knowledge of the solubility controlling phases, a lack of thermodynamic data for these phases, and a limited understanding of the interaction parameters between radionuclides and salts in solution.

Another aspect of the deep borehole disposal concept that the experts on the geochemistry panel questioned was the conditions under which seals at intermediate depths above the disposal zone would have to perform. The panel noted that microbial life likely would flourish at these depths (*e.g.*, Teske *et al*., 2013), which could alter the geochemical conditions (*e.g.*, pH, redox) and hydrogeologic conditions (*e.g.*, clogging of pores due to biofilm formation). Finally, the panel emphasized that gases produced by package and well-casing corrosion, as well as possibly by microbial action, could move up the borehole if a free gas phase formed, even if aqueous fluids were stratified by density. Once the packages are penetrated by corrosion, the down-hole brine also will dissolve the waste form and become contaminated with radionuclides. If gas bubbles form, they could cause convection that could promote distant transport of contaminated brine.

Waste isolation in the DOE deep borehole disposal conceptual model is based on assumptions of stable and relatively immobile brine under pre-disposal conditions, followed by transient, but relatively short-lived and limited, convective flow due to thermal pulse heating after waste emplacement (Arnold *et al*., 2014). In the Arnold *et al.* (2014) finite element models of subsurface evolution, the damage zone surrounding the borehole does not change with time and the crystalline rock outside is considered to be homogeneous and uniform. This view does not consider potential complexities at depth in crystalline rock described by the independent experts at the workshop and detailed above. Nor does the DOE conceptual model include the role of microbial activity or of corrosion-generated hydrogen on the geochemical and geomechanical evolution of the subsurface system. Relatively small pressure perturbations from both heating and corrosion-generated hydrogen gas could trigger fault slips, creating permeable pathways and, possibly, earthquakes. Additional modeling will need to take account of these possible effects.

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 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.*

Scope and objectives of Deep Borehole Field Test site characterization activities

The Deep Borehole Field Test is designed to test the validity of assumptions underpinning the safety case of the deep borehole disposal concept. The field test also should provide a data set with which to refine and test the sensitivity of the safety case to more realistic deviations from those assumptions. However, the field test data set will only be useful in that regard if it includes adequate characterization of the disposal zone, as well as shallower zones that may be hydraulically connected to the disposal zone under both pre-disposal conditions and perturbed post-disposal conditions.

In the Board's view, characterization of the subsurface should include both surface-based geophysical measurements at the site prior to drilling and down-hole characterization of the subsurface. Drilling a deep borehole in crystalline basement rock is a complex and expensive endeavor. In all past scientific deep drilling and in standard industry practice, extensive surface geophysical surveys were carried out to characterize the subsurface geophysical, geomechanical, hydrogeologic, and geochemical conditions likely to be encountered. Although Kuhlman *et al*. (2015) state that surface-based characterization would be used to guide the exploratory drilling program once a Deep Borehole Field Test site had been selected, subsequent documents (Kuhlman, 2015; DOE, 2015a) do not indicate whether that step will be performed prior to drilling. The Deep Borehole Field Test Request for Proposal indicates that surface-based characterization will rely primarily on collating existing data (DOE, 2015a; Kuhlman *et al*., 2015). If surface-based geophysical data are not available or insufficient, then surface-based geophysical measurements should be conducted. The data derived from these measurements could then inform the design of the drilling program.

Data from deep boreholes that have been drilled to date have shown that the characteristics of the deep subsurface vary substantially among the sites. Correlating the interpretations of surface-based geophysical surveys with subsurface characteristics measured during the Deep Borehole Field Test would provide the beginning of the basis for preliminary screening of other sites based on surface-based measurements and prior to costly drilling of characterization boreholes, *i.e*., for building the basis for the transferability of characterization results from one deep borehole site to another.

As part of the Deep Borehole Field Test Request for Proposal (DOE, 2015a), DOE provided the *Deep Borehole Field Test: Characterization Borehole Science Objectives* report (Kuhlman *et al*., 2015) to assist bidders in developing the drilling and test plan. DOE also indicated it will furnish borehole design information and scientific testing guidance that the contractor can use to develop the drilling and test plan. The Board recognizes that many parameters will be measured as part of the Deep Borehole Field Test (Kuhlman *et al.*, 2015). However, detailed, reliable hydrogeologic testing may require considerably more time than is currently scheduled for drilling and characterizing the characterization borehole. DOE assumes that drilling, and the testing required during drilling, will take seven months and that research and testing involving the drill rig will continue for an additional seven months after drilling is completed (DOE, 2015a). DOE plans to make only a limited number of hydraulic tests, which means that the tests may miss sparsely distributed high permeability zones. Furthermore, an individual permeability measurement could take two weeks, whereas equilibrating very low permeability intervals in the borehole to formation pressure could require time scales of up to two years. Moreover, successful permeability testing and measurement of ambient pressures may be precluded by challenges associated with isolating test intervals at great depths and in a borehole affected by drilling-induced borehole damage. Finally, any hydraulic testing must be carefully scheduled to accommodate sampling fluids and rock for geochemical analyses. These factors must be considered in developing the test and drilling plan.

Kuhlman *et al*. (2015) indicate that hydraulic testing will be done only for the characterization borehole, which means that any permeability measurements will represent averages over fairly small volumes of rock surrounding the hole. Hydraulic testing that makes use of multiple wells typically provides a more representative average of properties and may also allow identification of high permeability zones that extend over larger distances. Cross-hole tracer testing between the characterization borehole and the field test borehole might be extremely challenging given the borehole depths, diameters, lateral separation, and limited ability to generate suitable induced hydraulic gradients. However, it might be feasible to monitor pressure changes in packed-off intervals of the characterization borehole during drilling and completion of the field test borehole to identify zones of hydraulic connection and, possibly, to make estimates of permeability representative of larger volume averages.

A key observation from the experts on the geochemistry panel was the need for a very careful plan for the types and the scheduling of sampling and analysis of waters at the intended disposal depth in crystalline basement rock. The high salinity and immobility of waters at these depths would need to be demonstrated through chemical, isotopic, and permeability measurements. Water sampling in deep crystalline basement rock is technically difficult and the volumes obtained for analysis often are limited, making assessment of the water chemistry and residence time in the system difficult.

*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 Board recommends that DOE address the potential heterogeneity of the subsurface geology and the complex in situ *conditions at depth 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 role of multiple barriers

As noted earlier, waste isolation in the DOE deep borehole disposal concept is based on the assumptions of long radionuclide travel time through the rock 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 redox-sensitive radionuclides. However, the effects of coupled processes described above introduce uncertainties in the evolution of the borehole environment at depth and in the effectiveness of the barrier system in the DOE deep borehole disposal concept.

In contrast to the DOE reliance on the natural system for isolating the radioactive waste, a major tenet of nuclear waste disposal is the use of multiple barriers—a combination of both natural and engineered barriers—to isolate radioactive waste in, and prevent radionuclide migration from, a repository or other disposal system. A multiple barrier approach ensures that the overall disposal system is robust and not wholly dependent on any single barrier. It provides the foundation for a stronger safety case, not only for post-closure performance, but also during the operational period. The deep borehole concept, as presented by DOE (Arnold *et al*., 2012), takes very limited credit for engineered barriers following closure of the borehole. Seals need only be effective during the thermal pulse generated by the waste. Waste packages are assumed to maintain their integrity for a few decades. The waste forms can be moderately to very soluble, as in the case of cesium chloride.

As an example of the potential benefits of multiple barriers, after the metal packages have been breached due to corrosion, the waste form in the packages will be exposed to heated brine along the 2-km (1.2-mi) length of the disposal zone. The most prominently mentioned initial candidate for deep borehole disposal is the approximately 1,900 cesium and strontium capsules stored at the Hanford site in Washington State. The two cesium isotopes of concern are cesium-137, with a half-life of ~30 years, and cesium-135, with a half-life of ~2.3 million years. The strontium isotope of concern is strontium-90, with a half-life of ~30 years. The short-lived cesium-137 and strontium-90 isotopes generate a considerable amount of heat. Cesium chloride will dissolve rapidly into the hot brine environment after the packages are breached. Strontium fluoride will likely dissolve more slowly because of its much lower solubility as compared with cesium chloride. Because cesium and strontium are not redox-sensitive elements, after the packages have been breached, the only barriers to the upward and lateral movement of the brines that contain dissolved cesium and strontium are the presumed density stratification of the fluids and low bulk permeability of the surrounding crystalline basement rock, as evidenced by the presumed presence of very old brines.

Experts on the panel on borehole seals noted that, in the current deep borehole disposal concept, the waste packages in the disposal zone at the bottom of the borehole will be surrounded by drilling fluid. DOE plans to seal the region above the disposal zone with bentonite and concrete. It will be difficult to assess whether the seals will perform as designed, even for the 300 years of the thermal pulse. DOE will need to verify whether seal performance will meet performance requirements. No *in situ* seal tests are currently planned in the Deep Borehole Field Test for either the characterization or field test boreholes.

To address these uncertainties, the experts on the panel on waste forms and package materials pointed to opportunities to complement the natural barriers with engineered barriers. For example, there are waste forms that could be used for the cesium and strontium that would be much more stable than their present waste forms, cesium chloride and strontium fluoride.

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.*

Simulation of deep borehole operations involving radioactive materials

The operational safety strategy required for operations involving radioactive materials is different from that for operations involving non-radioactive materials. The experts on emplacement mode at the workshop noted that several control systems (*e.g.*, safety control interlocks) important in actual deep borehole disposal of radioactive waste were listed in a DOE report (SNL, 2015) as not being necessary for the Deep Borehole Field Test. The Deep Borehole Field Test should simulate implementation of deep borehole disposal as if radioactive wastes were being emplaced. This includes normal operations, maintenance, and recovery from off-normal events, such as an accidental waste package drop. The simulation should include demonstration of all operations in conformance with existing or anticipated Environmental Protection Agency (EPA), Nuclear Regulatory Commission (NRC), and state regulations applying to a facility handling highly radioactive material.

In developing its plans for the Deep Borehole Field Test, it does not appear that DOE sufficiently considered how one might recover from an accident involving a waste emplacement package stuck in the borehole. Although techniques are available to recover a stuck waste package, there is a chance that the package could be damaged during recovery efforts. This would be problematic and hazardous if the damaged waste package is in the upper portion of the borehole and releases radioactivity along the entire length of the borehole as well as to facilities at the surface. Concern over issues related to stuck waste canisters was one of the main reasons SKB (2010) recommended against disposal of radioactive waste in deep boreholes. The experts on emplacement mode at the workshop noted that the current DOE plan to use wireline emplacement would make it more difficult to recover from such accidents as compared to drill-string emplacement because the wireline lacks the lifting capacity that exists with the drill-string. It is not clear whether a stuck, leaking waste package could be retrieved during operations, as DOE assumes, or whether such waste package would be left in place (McCartin, 2015, p. 43). For the latter case, no seals would have been emplaced below the stuck waste package and DOE has not yet assessed the long-term performance of the disposal system for this scenario. In this regard, the February 2014 release of radioactive materials from a waste package after emplacement at the Waste Isolation Pilot Plant is important in demonstrating the need to consider all potential accidents and non-standard operations that may result in the release of radioactive material from a waste package and how to mitigate them.

*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.*

Development of environmental safety standards and implementing regulations

Currently, no EPA environmental safety standards or NRC implementing regulations have been developed specifically for deep borehole disposal of radioactive waste. At the workshop, EPA staff described how existing laws and regulations may apply to deep borehole disposal of spent nuclear fuel, high-level waste, and transuranic waste. The EPA staff identified technical and regulatory issues and questions that EPA would need to address if it were to develop a new safety standard specifically for deep borehole disposal of radioactive waste. Examples of EPA issues and questions include: (1) what constitutes the accessible environment for purposes of determining compliance, (2) whether the disposal system can be adequately characterized, (3) whether and how human intrusion should be considered, and (4) how waste retrieval could be ensured (Schultheisz, 2015).

Although no NRC representative made a presentation at the workshop, an NRC-funded study (Winterle *et al.*, 2011), based on review of available literature, identified a number of technical issues important to performance, pre-closure operational safety, and post-closure waste isolation. The study found that significant technological uncertainties and potential safety challenges exist in the area of waste handling and in procedures for lowering waste into the disposal boreholes. Winterle *et al.* (2011) also noted that the ability to reliably evaluate post-closure performance of the deep borehole disposal concept is limited by key technical uncertainties, including the effect of waste heat on the host rock and fluids in the rock and the resulting potential for increased fluid movement, as well as the long-term reliability of borehole sealing materials.

The Blue Ribbon Commission on America's Nuclear Future (BRC, 2012) recommended that EPA and NRC develop a new safety standard and regulations in parallel with the DOE deep borehole research efforts. During the workshop, the EPA staff stated that EPA had not interacted with DOE nor followed the DOE deep borehole research efforts. The EPA staff also indicated that neither EPA nor NRC is developing new regulations due to lack of funding and, for NRC, explicit Commission direction, and that EPA would need about five years to develop a safety standard.

In a recent report, DOE staff identified a number of regulatory topics that may benefit from clarification for deep borehole disposal (Freeze, 2015). However, DOE staff have not formally engaged EPA or NRC, and DOE representatives commented at the workshop that DOE wants to gather more information before beginning a dialogue with those agencies.

Two existing legal requirements apply to recovery, retrieval, and removal of waste (the second applies specifically to spent nuclear fuel):

- Title 40 of the Code of Federal Regulations, Part 191.14(f) states

  "Disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal."

- Section 122 of the Nuclear Waste Policy Act of 1982 states

  "… any repository … shall be designed and constructed to permit the retrieval of any spent nuclear fuel placed in such repository, during an appropriate period of operation of the facility …."

From discussions at the workshop, retrievability requirements and the potential for radioactive release during emplacement (*e.g.*, as a result of attempts to dislodge a stuck waste package) emerged as key issues that require regulatory guidance and clarity. The drilling experts at the workshop were in agreement that, once the waste is emplaced in the borehole and the borehole is sealed, retrievability would be very difficult from a technical perspective, particularly in light of the DOE plan to remove the casing from the seal zone before sealing the borehole.

Given the technical challenges and the safety risk of attempting to retrieve packages of radioactive material from a borehole, DOE should place a high priority on engaging regulators to define retrievability requirements in the context of deep borehole disposal of radioactive waste.

The Board recommends that, as part of its assessment of the feasibility of deep borehole disposal of radioactive waste, DOE 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.

Opportunity to explore public engagement issues affecting successful siting

International experience has shown that both technical feasibility and social acceptability are needed for a successful radioactive waste disposal program (NWTRB, 2015). DOE is using technical siting criteria to select the Deep Borehole Field Test site (Box 2; Arnold *et al.*, 2013) and plans to use those criteria to select future disposal sites. Recently, DOE initiated a process for gathering public comment on the implementation of a consent-based process for siting different storage and disposal facilities, including deep boreholes for disposal of some small, high-level radioactive waste forms and, perhaps, some spent nuclear fuel (DOE, 2015b). The Board believes that, as DOE initiates and carries out the Deep Borehole Field Test, it has the opportunity to explore issues related to public engagement, such as:

- How to take account of public perceptions and concerns.
- How to keep communities informed.
- How to make the decision-making processes transparent.
- How to engage and communicate with stakeholders so they understand and have confidence in the technical and scientific process.

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.

Requirement for strong technical leadership

A common theme of the discussions during the workshop was the need to carefully coordinate the engineering and the science during the Deep Borehole Field Test. As an example, the selection of a drilling technology and its actual practice can compromise the ability to obtain valid samples of rock and fluids from the disposal zone. The project will require careful coordination between the demands of the drilling program and the needs of the scientific characterization 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.*

Findings

Based on the information presented at the workshop by DOE, its contractors, and the members of the expert panels, the Board makes the following overarching findings:

- Available performance assessments do 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 being 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, are not suitable for disposal in deep boreholes given current technical limits on borehole diameter. Thus, disposal of radioactive waste in deep boreholes does not eliminate the need for a mined, geologic repository.

- 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. However, deep boreholes lack 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 is extremely limited as compared with a mined, geologic repository. Also, the Board has not been presented with any compelling evidence that deep borehole disposal can 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.

- The Deep Borehole Field Test and the DOE approach to assessing the feasibility of the deep borehole disposal concept are 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 does 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 does it fully consider how data from the potentially complex system at one site can be applied to another site. Thus, even if the DOE assumptions are confirmed during the Deep Borehole Field Test, DOE runs 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 will not have been obtained during the test.

- The operational safety strategy required for drilling and emplacement operations involving radioactive material is very different from that for operations involving non-radioactive material. Hence, it is important to consider the operational implications and limitations of handling and emplacing actual, highly radioactive waste and how these may be simulated during the Deep Borehole Field Test. 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.

Conclusions and Recommendations

Reflecting on all the Board heard at the workshop and learned from previously published reports and publications, it is clear that substantial time and effort will be required to fully evaluate the concept of deep borehole disposal. In the Board's view, the Deep Borehole Field Test should carefully consider the key parameters and information that would be needed to fully evaluate the feasibility of deep borehole disposal of radioactive waste. This would provide a basis for additional planning, including definition of 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 greatly improve the technical basis and rationale for the DOE Deep Borehole Research and Development Program. Specific Board recommendations are as follows:

- ***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.*

- ***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.*

- ***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 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.*

- ***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.*

- ***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.*

- ***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.*

- ***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.*

- ***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.*

- ***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.*

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Glossary

administrative controls	Management policies and procedures designed to eliminate or reduce exposure to a chemical, radiological, or physical hazard. Examples include warning signs and checklist procedures. These controls depend on human actions for implementation.
basement rock	The crust of Earth below sedimentary deposits, consisting of igneous and metamorphic rock.
bentonite	A soft, plastic, porous, light-colored rock composed of clay minerals formed by chemical alteration of volcanic ash. Compacted bentonite has been proposed for backfill and buffer material in many repositories.
breakout	Enlargement of the wellbore cross-section in a preferential direction caused by drilling-induced borehole wall failure arising from unequal horizontal stresses.
canister	The container into which the waste form is placed for handling, transport, storage, and eventual disposal. For example, molten high-level waste glass would be poured into a specially designed container where it would cool and solidify. The canister is normally a component of the waste package. However, DOE uses the term canister, instead of waste package, especially in older reports. Also, the Swedish radioactive waste disposal program uses the term canister instead of the term waste package.
crystalline rock	A term for igneous rocks and metamorphic rocks (*e.g*., granite and gneiss), as opposed to sedimentary rocks.
density stratification	Masses of water within rock with different densities, primarily from different amounts of salts dissolved within them. Normally, less dense water (*e.g.*, fresh water) will be on top of more dense water (*e.g.*, highly saline waters or brines). Inverse stratification refers to the case where more dense fluid is on top of less dense fluid.
engineered barrier system	The designed, or engineered, components of a disposal system that contribute to isolation of the waste from the human-accessible environment. Examples of engineered barriers include waste forms, waste packages, and seals with physical and chemical characteristics that significantly isolate the waste or decrease the mobility of radionuclides.
engineering controls	Manufactured safety features designed to eliminate or reduce exposure to a chemical, radiological, or physical hazard through the use or substitution of engineered machinery or equipment that do not require human actions.
geologic repository	A facility for disposing of radioactive waste located underground (usually several hundred meters or more below the surface) in a geologic formation. It is intended to provide long-term isolation of radionuclides from the human-accessible environment.

Note: Most of these definitions were taken from the International Atomic Energy Agency *Radioactive Waste Management Glossary*, 2003 Edition, Publication 1155, (IAEA: Vienna, 2003). The definitions of some terms were altered to make them more applicable to this report, and other terms have been added. The IAEA is not responsible for those changes. Definitions of geologic terms were derived from the American Geological Institute *Glossary of Geology*, Fifth Edition (AGI: Alexandria, VA, 2011).

geomechanical properties	The strength and deformation parameters of the rock, in addition to the initial *in situ* stresses that exist at a specific depth.
geophysical survey	Studying Earth by quantitative physical methods. Many methods and types of instrumentation are used in geophysical surveys. Technologies used for geophysical surveys include seismic, gravity, magnetic, electrical, and electromagnetic techniques.
high-level radioactive waste	Highly radioactive material resulting from reprocessing spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations, and other highly radioactive material that the U.S. Nuclear Regulatory Commission, consistent with existing law, determines by rule requires permanent isolation.
multiple barriers	The natural and engineered system of barriers used in a disposal system, such as a geologic repository, to isolate radioactive waste and prevent migration of radionuclides from the disposal system to the human-accessible environment.
natural barriers	Attributes of Earth that tend to isolate radionuclides from the human-accessible environment.
permeability	The property or capacity of a material such as a porous rock, sediment, or soil for transmitting a fluid.
petrophysical	Petrophysics is the study of the physical and chemical properties of rocks and their contained fluids. It emphasizes those properties relating to the pore system and its fluid distribution and flow characteristics. Petrophysical properties include porosity, permeability, relative permeability, capillarity, and fluid saturation.
Quaternary	The period of geologic time from about 2.6 million years ago to the present. If a site has Quaternary age faulting, this indicates faulting at the site occurred within the last 2.6 million years.
radionuclide	A radionuclide, or radioactive nuclide, is an atom that has excess nuclear energy, making it unstable. This excess energy can result in the emission from the nucleus of radiation (gamma radiation) or a particle (alpha particle or beta particle), or the excess energy can be transferred to one of the electrons, causing it to be ejected (conversion electron). During this process, the radionuclide is said to undergo radioactive decay.
redox	Contraction of the name for reduction–oxidation reaction, which is a type of chemical reaction that involves a transfer of electrons between two chemical species and, as a result, changes the oxidation state of the chemical species involved.
safety case	An integrated collection of arguments and evidence for demonstrating the safety of a facility. The safety case will typically include a safety assessment, but could also include independent lines of evidence and reasoning on the robustness and reliability of the safety assessment and the assumptions.
salinity inversion	Area underground where higher-density saline water is above lower-density saline water. (see density stratification)

thermal pulse	The period of time after waste disposal that the temperature of the water and rock near the waste is raised above the ambient temperature due to radioactive decay of the waste. For cesium and strontium capsule disposal in a borehole, using the DOE design assumptions, the thermal pulse will last about 300 years and raise the ambient temperature by about 50 °C.
waste canister	(see **canister)**
waste package	The vessel in which the canistered or uncanistered waste form is placed.

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Appendix A: Workshop Agenda and List of Speakers

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201
703-235-4473

AGENDA

International Technical Workshop on Deep Borehole Disposal of Radioactive Waste

Embassy Suites
1250 22nd Street NW
Washington, DC 20037

Tuesday, October 20, 2015 (Ballroom)

8:00 a.m. **Call to Order and Introductory Statements**
Rod Ewing, Board Chairman
Mary Lou Zoback, Board Member

8:15 a.m. **DOE's Strategy for Management and Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste, Including Deep Borehole Disposal of Smaller DOE-Managed Waste Forms**
Franklin Orr, Under Secretary for Science and Energy, U.S. Department of Energy

9:00 a.m. **DOE's Deep Borehole Disposal Research Program**
Timothy Gunter, U.S. Department of Energy, Office of Nuclear Energy

QUESTIONS TO BE ADDRESSED:
What is the rationale for deep borehole disposal? What wastes would be, or might be, disposed of via deep boreholes? What are the objectives of the program and which research activities address the objectives? What is being assumed concerning post-closure standards and regulations for deep borehole disposal? What is the safety case for deep borehole disposal? What features, events, or processes are crucial to the concept? What needs to be completed to achieve a proof-of-concept? What is the timeline for the research program, siting, licensing, and implementation of disposal of radioactive wastes?

10:00 a.m. **Break**

10:15 a.m. **DOE Deep Borehole Field Test: Site Characterization and Design Requirements**

David Sassani and Ernest Hardin, Sandia National Laboratories
QUESTIONS TO BE ADDRESSED:
What geological, hydrological, geomechanical, geochemical, and thermal data will be collected? How will the data test the assumptions of the concept and previous modeling? What is the design for testing the proof-of-concept for emplacement and retrieval of surrogate waste canisters? How will the activities of the deep borehole test allow DOE to assess the feasibility of the deep borehole disposal concept?

11:45 a.m. **Public Comments**

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

12:15 p.m. **Lunchtime Presentation: International Perspective on Deep Borehole Disposal**
Fergus Gibb, University of Sheffield, United Kingdom

1:00 p.m. **Break**

1:15 p.m. **Panel #1 Experience in Deep Drilling in Crystalline Rocks**
Moderator: Mary Lou Zoback, Board Member
Panelists: Stephen Hickman (U.S. Geological Survey), Claus Chur (CCConsulting, Germany), Eric van Oort (University of Texas at Austin)

QUESTIONS TO BE ADDRESSED:
In the context of DOE's plans to drill a 5 km deep hole in crystalline rock, with a bottom-hole diameter of up to 17" and with an emplacement zone for surrogate sealed waste canisters between 3-5 km depth:

- What are the technical/geomechanical challenges for drilling and completing such a borehole?
- What lessons have been learned during drilling deep boreholes in crystalline rock?
- What lessons have been learned in implementing down-hole characterization programs, including cross-hole testing?
- What is the ultimate bottom-hole diameter with foreseeable technological advances?

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

2:45 p.m. **Panel #2 Emplacement Mode**
Moderator: Allen Croff, Board Member
Panelists: Wesley Patrick (Southwest Research Institute), Mark MacGlashan (MacGlashan Engineering Consulting), Douglas Minnema (Defense Nuclear Facilities Safety Board), Ernest Hardin (Sandia National Laboratories)

QUESTIONS TO BE ADDRESSED:
In the context of DOE's plan to dispose of highly radioactive wastes in ~5 km deep boreholes in crystalline rock:

- Emplacement mode selection
  - What are the current and foreseeable options for the emplacement mode?
  - What is the recommended/preferred emplacement mode for deep borehole disposal implementation and what is the basis for the recommendation/preference?
  - How do (a) experience from non-waste-related package emplacement in deep boreholes and (b) the impacts of emplacing highly radioactive wastes in normal and off-normal situations affect the selection of the preferred emplacement mode?
- How does the safety of potential emplacement options compare in terms of operational impacts to the public and workers in normal and off-normal conditions?
- What data will be required to evaluate human health and technical risks, costs, and design implications of deep borehole disposal in the context of developing a safety case for borehole disposal?
- How will the Deep Borehole Field Test be designed to elucidate human health and technical risks associated with deep borehole disposal emplacement of highly radioactive wastes?

4:00 p.m. **Panel #3 Borehole Seals**
Moderator: Gerald Frankel, Board Member
Panelists: Paul Bommer (University of Texas at Austin), Nick Collier (University of Sheffield, United Kingdom), Roland Pusch (Luleå University of Technology, Sweden)

QUESTIONS TO BE ADDRESSED:
In the context of DOE's plans to drill a 5 km deep hole in crystalline rock and dispose of sealed waste canisters between 3-5 km depth, while relying extensively on geology for containment as well as sealing of the disposal zone and upper 3 km of the borehole:

- What materials and processes have been developed for sealing, and used to seal, boreholes under representative conditions?
- What evidence is there for the long-term effectiveness of borehole seals?
- How can we predict the long-term performance of seals?
- What level of performance of a borehole seal is critical to the safety of deep borehole disposal?

5:15 p.m. **Public Comments**

5:35 p.m. **Adjourn Public Meeting**

Poster Session (Embassy Room)

Wednesday, October 21, 2015 (Ballroom)

8:00 a.m. **Call to Order and Introductory Statements**
Rod Ewing, Board Chairman
Mary Lou Zoback, Board Member

8:15 a.m. **U.S. Environmental Protection Agency Perspectives on Deep Borehole Disposal**
Dan Schultheisz, U.S. Environmental Protection Agency

9:00 a.m. **Panel #4 Hydrogeology at Depth: Anticipated Conditions and Characterizing the Conditions**
Moderator: Jean Bahr, Board Member
Panelists: Mark Person (New Mexico Tech), Mark Zoback (Stanford University), Kent Novakowski (Queen's University, Canada)

QUESTIONS TO BE ADDRESSED:
In the context of DOE's concept for borehole disposal using 5 km deep boreholes in crystalline rock, with disposal of sealed waste canisters between 3-5 km depth, relying extensively on geology for containment:

- What does the global experience tell us about subsurface conditions and hydraulic properties at 3-5 km in crystalline rock?
- What characterization techniques are best suited to determine in situ conditions and properties at depth prior to and after drilling?
- Will it be possible, within the relatively short time available for tests in the pilot hole, to adequately quantify hydraulic heads, gradients and permeability of fractures, fault zones and the rock matrix?
- How do the conditions at borehole depths compare with conditions at mined repository depths (~1 km) with respect to potential for transport from the disposal site to the accessible environment?

10:00 a.m. **Break**

10:15 a.m. **Panel #5 Geochemistry of Fluids at Depth: Anticipated Conditions and Characterizing the Conditions**
Moderator: Susan Brantley, Board Member
Panelists: D. Kirk Nordstrom (U.S. Geological Survey), Shaun Frape (University of Waterloo, Canada), Jennifer McIntosh (University of Arizona)

QUESTIONS TO BE ADDRESSED:
In the context of DOE's concept for borehole disposal using 5 km deep boreholes in crystalline rock, with disposal of sealed waste canisters between 3-5 km depth, and relying extensively on geology for containment:

- What does the global experience from geochemistry of fluids, fracture mineralogy, and fluid inclusions tell us about subsurface conditions and parameters at 3-5 km in crystalline rock?
- What characterization techniques are best suited to determine the geochemistry of fluids at depth?
- What are the implications of the expected saline and reducing groundwater conditions at 3-5 km for solubilities of minerals and retardation factors of radionuclides?

11:15 a.m. **Panel #6 Multiple Barriers: Waste Forms and Canister Materials**
Moderator: Rod Ewing, Board Chairman
Panelists: David Sassani (Sandia National Laboratories), Neil Hyatt (University of Sheffield, United Kingdom), Narasi Sridhar (DNV GL)

QUESTIONS TO BE ADDRESSED:
In the context of DOE's concept for borehole disposal using 5 km deep boreholes in crystalline rock, with disposal of sealed waste canisters between 3-5 km depth, and relying extensively on geology for containment as well as sealing of the disposal zone and upper 3 km of the borehole:

- How much reliance will be placed on engineered barrier components as compared to natural barriers?
- What waste form and package characteristics (e.g., resistance to corrosion, strength to withstand the column of waste above it, ability to be retrieved) are needed for deep borehole disposal?
- How well known are the characteristics of wastes (waste form per se, current packaging, potential future packaging) that are or might be disposed of in deep boreholes?

12:15 p.m. **Public Comments**

12:30 p.m. **Lunch Break (1 hour)**

1:30 p.m. **Panel #7 Efficacy of Deep Borehole Disposal and Risk Analysis**
Moderator: Rod Ewing, Board Chairman
Panelists: Peter Swift (Sandia National Laboratories), Bertil Grundfeldt (Kamakta Konsult AB, Sweden), Richard Garwin (IBM Fellow Emeritus)

QUESTIONS TO BE ADDRESSED:

- What are the advantages and disadvantages of deep borehole disposal relative to other disposal options?
- What is the projected post-closure dose from a deep borehole disposal program and how does it compare to projected doses from a conventional geologic repository for disposal of the same waste quantities and forms?
- What are the key uncertainties with the expected performance from a deep borehole disposal facility?
- What is the effect of sustained elevated temperatures on the performance of deep borehole disposal?
- How will the lack of international experience in implementing a deep borehole disposal program affect DOE's approach?

2:30 p.m.	**Break**
2:45 p.m.	**Key Observations from Panels** One panelist from each panel summarizes the panel's key points based on what has been presented at the workshop (5 minutes each and Board questions)
4:00 p.m.	**Closing Speaker** Andrew Griffith, Associate Deputy Assistant Secretary for Fuel Cycle Technologies, U.S. Department of Energy QUESTIONS TO BE ADDRESSED: What does DOE need to do to make its deep borehole disposal research program a success? What external factors (e.g., lack of applicable regulations) and current waste storage site factors (e.g., need to build bulk packaging facility for calcine waste or timing of removal of cesium and strontium capsules from pool storage) impact the timeframe for implementation of deep borehole option? What other activities must DOE complete to determine whether deep borehole disposal is a viable option?
4:45 p.m.	**Public Comments**
5:00 p.m.	**Adjourn Public Meeting**

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Appendix B: Bibliography on Deep Borehole Disposal of Radioactive Waste

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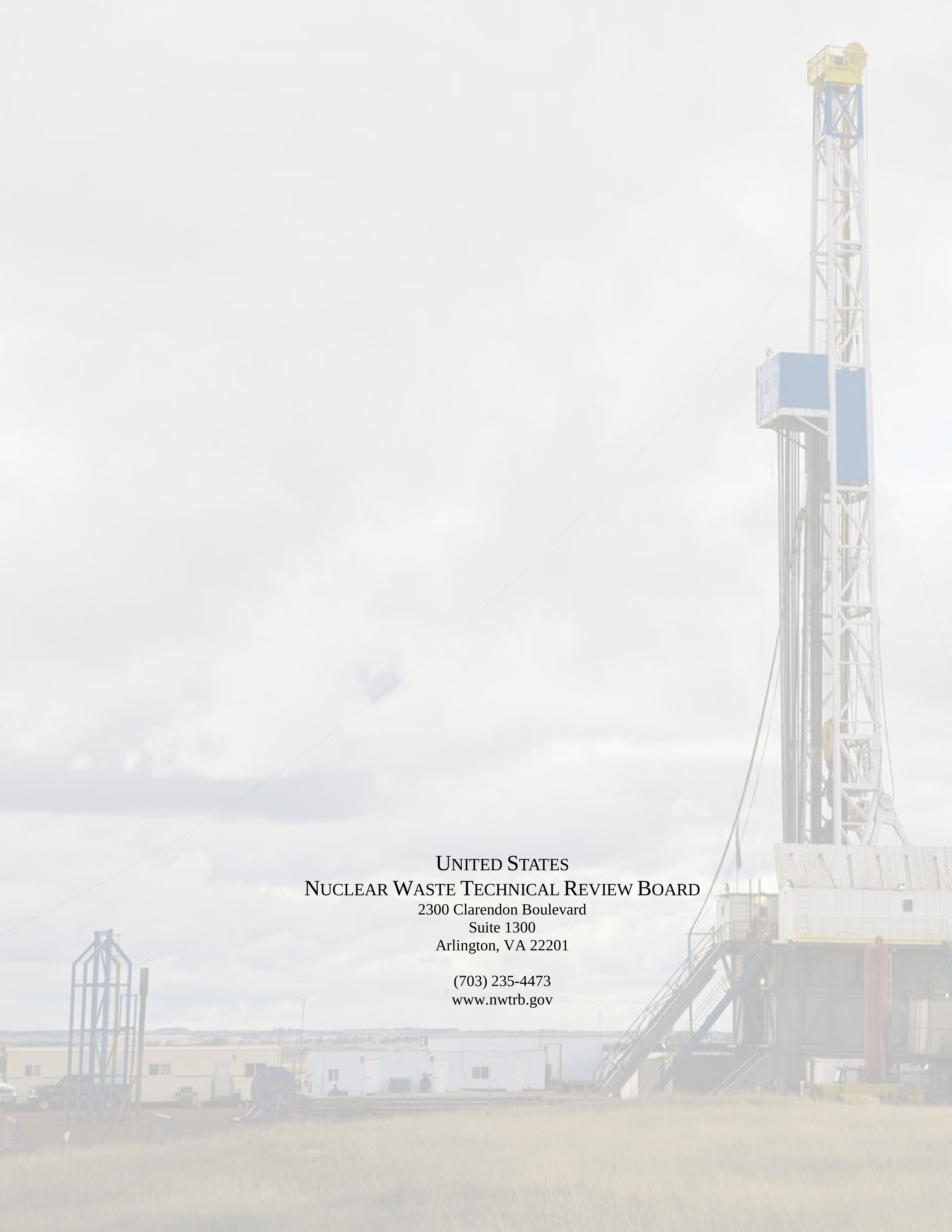

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