Siting Considerations for a Deep Borehole Disposal Facility – 15403

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ABSTRACT

This paper describes considerations for siting and designing a facility for deep borehole disposal of spent nuclear fuel (SNF) and/or high-level radioactive waste (HLW). Technical considerations include geological, hydrogeochemical, and geophysical characteristics that are related to the suitability of the site for deep drilling and borehole construction, waste emplacement activities, waste isolation (seals and surrounding geology), and long-term safety of the deep borehole disposal system. Logistical factors to be considered include: local or regional availability of drilling contractors (equipment, services, and materials) capable of drilling a large-diameter hole to approximately 5,000 m depth; construction of surface facilities and waste handling and emplacement equipment; legal and regulatory requirements associated with drilling, operation, and post-closure; and access to transportation systems. Social and political considerations include the distance from population centers and the support or opposition of local and state entities and other stakeholders to the facility and its operations. These technical, logistical, and sociopolitical factors are examined in the context of a consent-based siting process for a deep disposal borehole, which would be the first phase in developing an operating facility.

INTRODUCTION

Deep borehole disposal for the geologic isolation of SNF and/or HLW has been considered for many years [1, 2, 3, 4] beginning with evaluations by the US National Academy of Sciences in 1957 [5]. More recently, the U.S. Department of Energy (DOE) Used Nuclear Fuel Disposition Campaign (UFDC) has conducted research on generic deep geologic disposal options, including deep borehole disposal in crystalline basement rock [6, 7, 8, 9].

The deep borehole disposal design concept consists of drilling a large-diameter borehole (or array of boreholes) into crystalline basement rock to a depth of about 5,000 m, emplacing waste canisters in the lower (~2,000 m) disposal zone portion of the borehole, and sealing and plugging the upper portion of the borehole. Numerous factors suggest deep borehole disposal of SNF and HLW is viable and safe. Several lines of evidence indicate that groundwater at depths of several kilometers in crystalline basement rocks has (i) low velocity and long residence times, (ii) density-stratified high-salinity fluids that have limited potential for vertical flow and colloidal transport of radionuclides, and (iii) geochemically reducing conditions that stabilize low solubility phases and enhance the retardation of key radionuclides.

In 2012, the Blue Ribbon Commission on America's Nuclear Future (BRC) reviewed prior research on deep borehole disposal, concluded that the concept may hold promise, and recommended further research, development, and demonstration (RD&D) to fully assess its potential [10]. The BRC also recommended a consent-based approach to siting future nuclear waste management facilities. In 2013, consistent with BRC recommendations, the DOE identified developing a research and development plan for deep borehole disposal as a key strategy objective [11]. In accordance with the BRC recommendations and DOE strategy objective, UFDC is conducting RD&D activities to evaluate the feasibility of siting and operating a deep borehole disposal facility [9, 12].

DEEP BOREHOLE DISPOSAL CONCEPT

The deep borehole disposal design concept consists of drilling a large-diameter (up to 0.43 m (17 in)) borehole (or array of boreholes) into crystalline basement rock to a depth of about 5,000 m, emplacing waste canisters in the lower (~2,000 m) disposal zone portion of the borehole, and sealing and plugging the upper portion of the borehole with a combination of bentonite, cement plugs, and cement/crushed rock backfill. This design concept is expected to be achievable in crystalline rocks with currently available commercial drilling technology.

A generalized deep borehole disposal concept is illustrated in Fig. 1, showing that waste in a deep borehole disposal system is several times deeper than typical mined repositories. The typical maximum depth of fresh groundwater resources is also shown in Fig. 1, as indicated by the dashed blue line. Safety of the deep borehole disposal concept relies primarily on the great depth of burial, the isolation provided by the deep natural geological environment, and the integrity of the borehole seals.

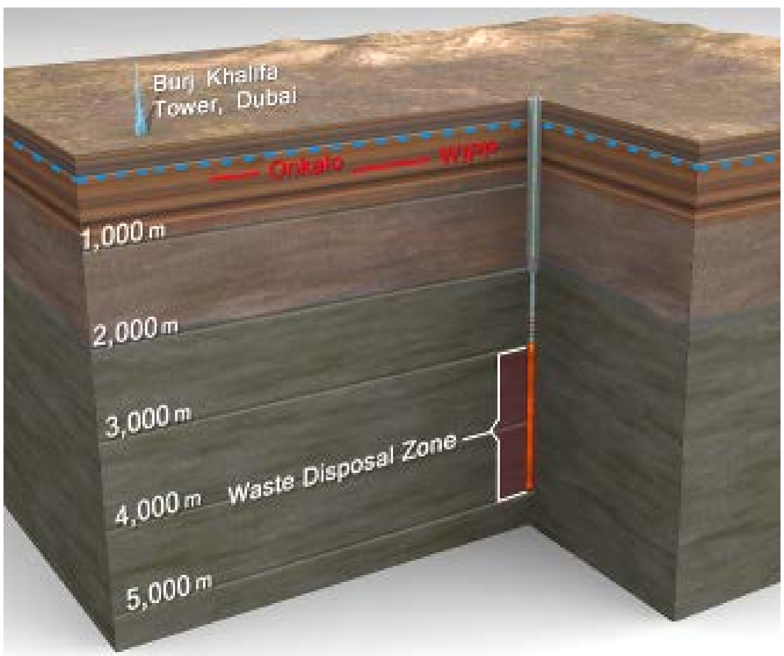

Fig. 1. Generalized schematic of the deep borehole disposal concept.

Several design alternatives exist that satisfy this basic concept, dependent on a variety of factors, most notably the size and characteristics of the waste form and packaging. Initial deep borehole disposal studies [6] proposed waste canisters that contained commercial SNF. Specifically, the waste canister was designed to encapsulate a single PWR assembly, with canister design dimensions of 5 m length and 0.34 m (13-3/8 in) diameter. This size waste canister would require a borehole with a bottom hole diameter of approximately 0.43 m (17 in). More efficient loading of SNF could be achieved by dismantling the PWR assemblies and consolidating individual fuel rods into the same size (or smaller) canisters, with consideration given to avoiding conditions conducive to nuclear criticality. More recently, DOE has recommended "a focused RD&D program addressing technologies relevant to deep borehole disposal of smaller DOE-managed waste forms" [13]. For example, the smallest DOE-managed waste forms, cesium and strontium capsules, are all less than 0.09 m (3.5 in) in diameter [13], which could be emplaced in a borehole with a bottom hole diameter on the order of 0.22 m (8.5 in).

Borehole Design

For the purposes of examining siting considerations, a reference borehole design was selected from [7] with a bottom hole diameter of 0.43 m (17 in), although a smaller-diameter borehole would not significantly impact the siting considerations. This design, shown in Fig. 2, provides an achievable, internally consistent system for waste disposal that meets regulatory requirements for operational and public safety [7].

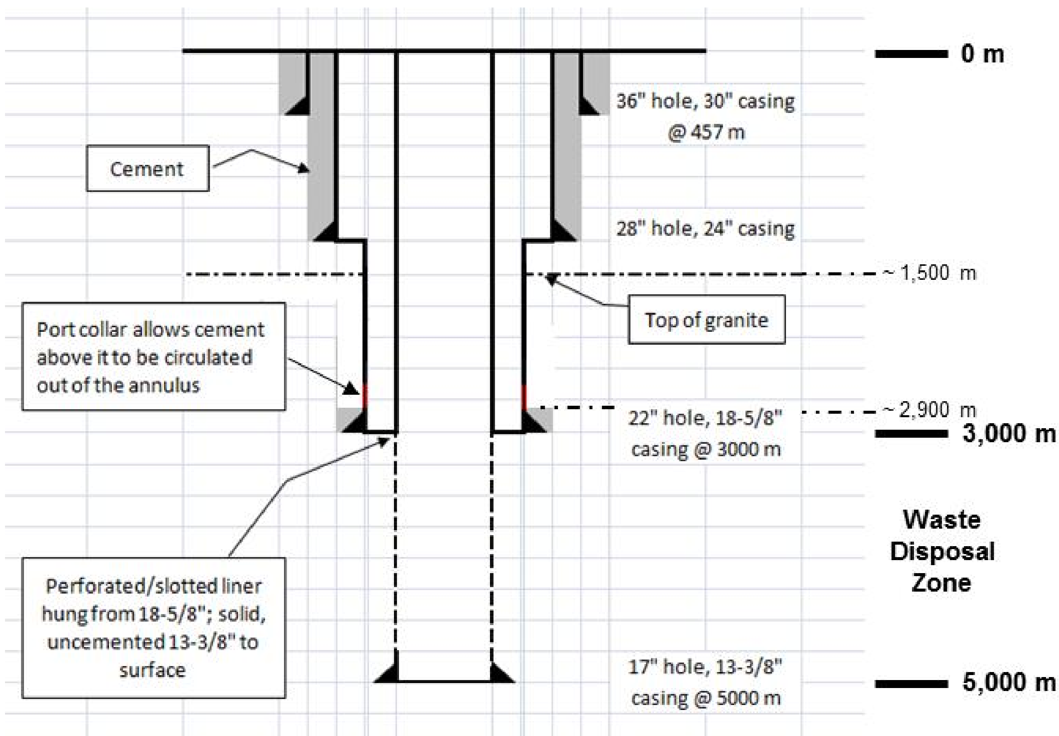

Fig. 2. Reference borehole design.

The reference design [7] includes drilling of progressively smaller diameter sections down to about 5,000 m depth, with the top of the crystalline basement rock encountered somewhere between 1,500 m and 2,000 m depth. In each section down to 3,000 m depth, casing will be installed and cemented to the borehole wall. An exception is from the top of the crystalline (about 1,500 m depth in Fig. 2) to the depth of the port collar just above the waste disposal zone (about 2,900 m in Fig. 2), where the casing will not be cemented to facilitate later removal as part of the sealing process. From the surface down to 3,000 m depth, a guidance liner will be installed inside the casing. This guidance liner provides a smooth constant-diameter pathway above the waste disposal zone for canister emplacement that minimizes the potential for stuck canisters. The guidance liner will be removed after all the canisters are emplaced. From 3,000 m to 5,000 m depth, in the waste disposal zone, a slotted or perforated liner will be installed. The perforated liner will be left in place after waste emplacement.

Waste Canister Emplacement

Prior to emplacement, loaded waste canisters will be transported to the site by tractor trailer (or rail) using shipping casks. For the reference design, surface handling of the shipping casks and loaded waste canisters, and emplacement of the waste canisters using a specially designed emplacement rig, will be as described in [7]. A synthetic oil-based mud with a high bentonite concentration will be present in the disposal zone, forming a grout around the waste canisters. The perforated liner in the disposal zone will prevent the build-up of fluid pressure during emplacement due to canister-heat-induced thermal expansion and after emplacement once the waste canisters have been grouted and sealed. The waste canisters are designed to retain their integrity until after the borehole is sealed, but are not depended upon to provide any barrier to post-closure radionuclide releases or migration. Additional details of surface handling and emplacement are beyond the scope of this paper, and multiple options are viable. However, engineering feasibility and operational safety has been demonstrated for surface handling and borehole emplacement of waste canisters during the Spent Fuel Test – Climax at the Nevada Test Site in 1986 [14], and will be evaluated as part of a deep borehole field test initiated in 2014 [12].

Sealing

Following waste emplacement, the casing will be removed from the top of the crystalline rock (about 1,500 m depth) to the port collar (about 2,900 m depth) to create a zone where sealing materials can directly contact the surrounding host rock. The reference seals design, shown in Fig. 3, consists of an upper seal zone in the cased portion above 1,500 m depth and a lower seal zone from 1,500 m to 3,000 m depth that is uncased (except for 100 m above the waste disposal zone and below the port collar).

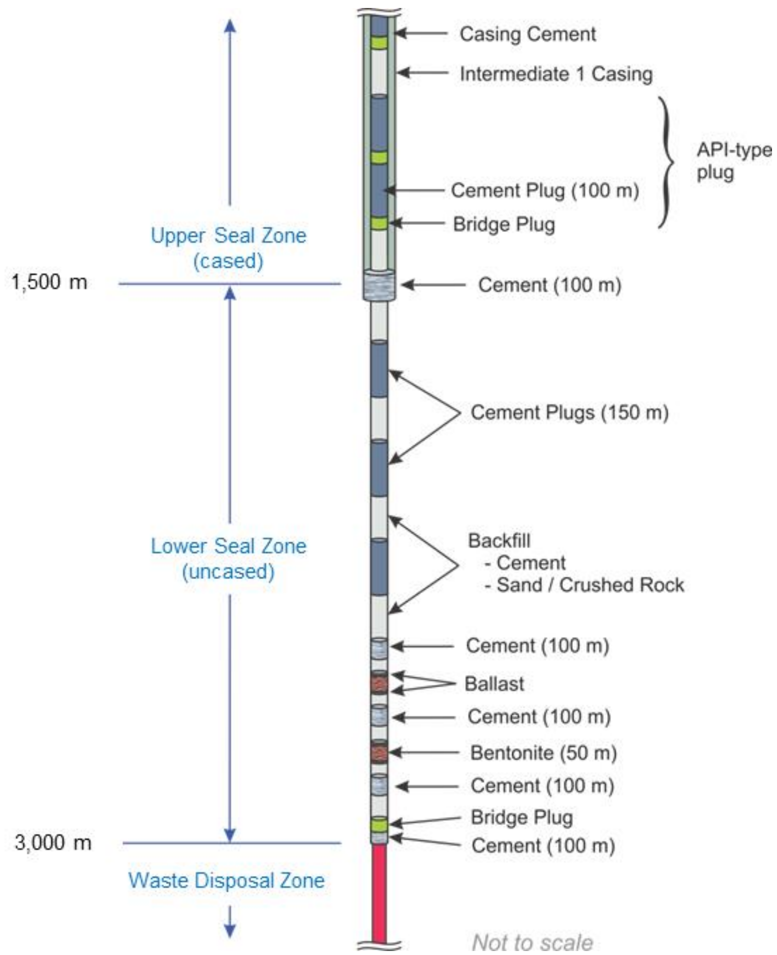

Fig. 3. Reference seal design.

At the bottom of the lower seal zone in the 100-m thick cased section between the top of the waste disposal zone and the port collar will be a cement seal. The cement is designed to provide both sealing and some thermal insulation to the borehole above and will be topped by a bridge plug. Overlying the bridge plug, the uncased portion of the lower seal zone will consist of an alternating series of cement, backfill (finely crushed rock or silica sand), and compacted bentonite seal segments topped by cement plugs higher up in the lower seal zone (Fig. 3). The lack of casing will allow the cement and bentonite to directly penetrate to some degree into the fractures of a possible disturbed rock zone surrounding the borehole, creating a more robust seal.

In the upper seal zone, the cased borehole will be plugged predominantly with cement or cement mixed with sand or crushed rock backfill (Fig. 3). The upper seal zone will also include one or more American Petroleum Institute (API) recommended bridge plugs.

Safety and Viability Considerations

Several factors suggest that the deep borehole disposal concept may provide a technically feasible and cost-effective alternative for safe disposal of some DOE-managed waste forms [7, 15]:

- Drilling and casing a large diameter borehole to 5,000 m depth in crystalline basement rock is achievable with existing drilling technology at acceptable cost
- Waste emplacement is deep – between 3,000 and 5,000 m depth in crystalline basement rock with at least 1,000 m of crystalline rock overlying the waste disposal zone.
- Borehole and casing can be designed to provide a high level of assurance that waste canisters can be emplaced at the desired depth, with minimal probability of canisters becoming stuck during emplacement.
- Crystalline basement rocks within 2,000 m of the surface are common in many stable continental regions
- Deep crystalline rocks have low permeability and lack large-scale, high-permeability structural features that extend to the surface or shallow subsurface at many locations
- Deep fluids in the crystalline basement have very long residence times and have been isolated from shallow groundwater on geologic time scales
- Deep groundwater is highly saline and geochemically reducing, which limits the solubility and enhances the sorption of many radionuclides in the waste
- Density stratification of saline groundwater underlying fresh groundwater would oppose thermally induced groundwater convection
- Waste canisters can be engineered to maintain structural integrity and provide a high level of assurance that no leakage of radioactive materials will occur during loading, transportation, handling, and emplacement.
- Borehole seals can be engineered to maintain their physical integrity as permeability barriers, at least over the time scale of thermally-induced groundwater flow (due to decay heat from the waste forms)

SITING CONSIDERATIONS FOR DEEP BOREHOLE DISPOSAL

Siting of storage or disposal facilities has proven in several countries, including the US, to be the most contentious part of a radioactive waste management program [10, 16]. Most of these failed efforts resulted from top-down, federally-mandated siting decisions, made over the objections of local authorities. Even when public participation mechanisms (e.g., public hearings and public comment processes) were established following the expression of public opposition, those efforts did not result in successful siting of a facility [17]. As a result, siting efforts (e.g., potential repository locations in Finland, Sweden, and Canada) are moving in the direction of earlier and more meaningful public involvement and decision-making, in order to garner acceptance for building radioactive waste facilities [10, 16].

Promising experiences in other countries indicate that a consent-based process, developed through engagement with states, tribes, local governments, key stakeholders, and the public, offers a greater probability of success than a top down approach to siting [11]. A consent-based siting process covers a broad range of technical, logistical, and sociopolitical considerations. Clearly, the implementation of a consent-based process is facility and location specific, and the process must prioritize which of the considerations are most relevant to that particular situation.

Specific to deep borehole disposal, siting should consider factors that maximize the probability of successfully (i) drilling and completing a deep large-diameter borehole at a site with favorable geologic, hydrogeochemical, and geophysical conditions, (ii) building and maintaining the associated infrastructure, (iii) conducting surface handling, emplacement, and sealing operations, and (iv) demonstrating long-term post-closure safety. Consideration of these factors should enhance the likelihood of safe development, operations, and post-closure performance of a radioactive waste disposal system. Siting considerations provide a means to determine relatively quickly whether a site meets basic suitability requirements, and can inform decisions for proceeding to more detailed site investigation and site characterization studies [16]. In cases where there are multiple volunteer communities and/or candidate sites, the siting factors can provide a basis for evaluation and comparison of the relative merits.

Deep borehole siting considerations should include potentially disqualifying factors – to identify sites that are clearly unsuitable or inappropriate. Examples of unfavorable features may include: upward vertical fluid potential gradients, presence of economically exploitable natural resources at depth, presence of a high-permeability connection from the waste disposal zone to the shallow subsurface, and significant probability of future volcanic activity.

General considerations for deep borehole disposal siting relate back to the design concepts and safety and viability considerations discussed in the previous section. These siting considerations include technical, logistical, and sociopolitical factors, as discussed in the following subsections.

Technical Factors

Technical considerations include geological, hydrogeochemical, and geophysical conditions potentially relevant to the siting, operation, and post-closure safety for a deep borehole disposal system. These include [8, 9]:

- Depth to crystalline basement – A depth less than 2,000 m allows for a 2,000 m disposal zone overlain by at least 1,000 m of seals within the crystalline basement.
- Crystalline basement geology – Areas with regionally homogeneous structure and lithology (e.g., plutonic or felsic intrusive rocks) tend to be less likely to have major faults or shear zones, well-connected fracture systems, or recent tectonic activity or seismicity.
- Horizontal stress – A large differential in horizontal stress at depth can be an indicator of potential difficulties in drilling a vertical hole and of borehole instability (e.g., extensive borehole breakouts and/or an enhanced disturbed rock zone around the borehole).

- Seismicity – Seismic hazard could increase risk during drilling and emplacement. Seismic hazard is also a general indicator of tectonic activity, potential fault movement, and structural complexity.
- Volcanism – Quaternary-age faulting and volcanism is an indicator for potential future tectonic activity or volcanism.
- Topographic relief and hydraulic gradient – Hydraulic gradients in the deep subsurface are generally related to regional variations in topography and can lead to the potential for upward flow in regional discharge areas. However, deep groundwater can be isolated and stagnant in some hydrogeologic settings, in spite of topographic effects.
- Geochemical environment – High salinity and geochemically-reducing conditions tend to reduce radionuclide mobility.
- Geothermal gradient – High geothermal heat flux can lead to the potential for upward hydraulic gradients and is also related to the potential for geothermal drilling.
- Natural resources potential – Petroleum and mineral resources exploration and/or production could lead to human intrusion into the deep borehole and/or impact the release of radionuclides to the overlying sediments.

Evaluation of many of these factors can be accomplished on a preliminary, regional basis with existing data. An accurate compilation of relevant data can be made using a geographical information system (GIS) database. As an example, Fig. 4 shows a GIS-compiled map of depth to crystalline basement.

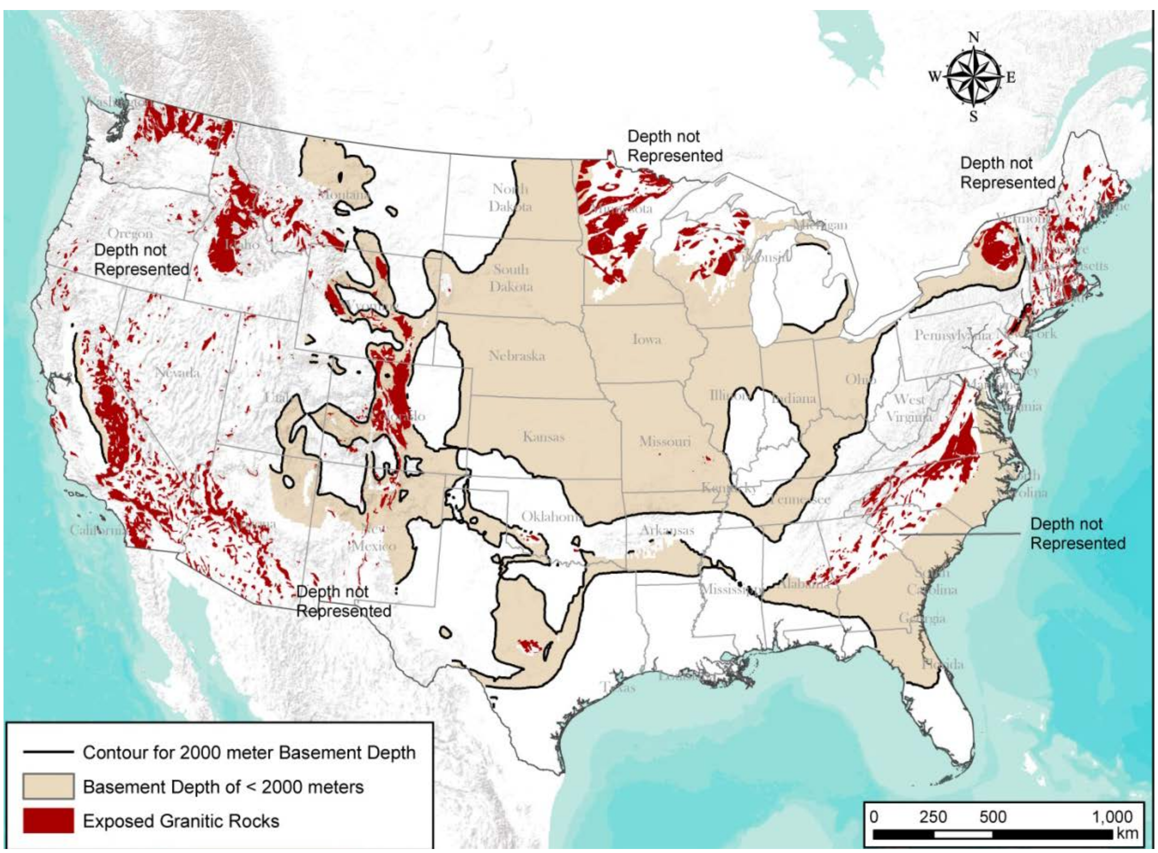

Fig. 4. Depth to crystalline basement in the continental US[18].

Logistical Factors

Logistical considerations include factors relevant to successfully completing the construction and engineering operations associated with a deep borehole disposal facility. These include:

- Availability of drilling contractors and support services – To reduce operational costs, drilling contractors (equipment, services, and materials) capable of drilling a large-diameter hole to approximately 5,000 m depth should be locally or regionally available.
- Regulations and permitting – Legal and regulatory requirements associated with drilling, construction of surface facilities, and waste handling and emplacement must be achievable. The regulatory environment is different in different states and for Federal versus private land.
- Site area – There should be sufficient area for drilling, construction of surface facilities, and surface waste handling and downhole emplacement operations.
- Site access – There should be reasonable access to roadways and/or railways for transportation of waste and other materials. Waste transportation costs could vary considerably depending on the disposal site location relative to waste storage or nuclear power plant locations.

Sociopolitical Factors

Social and political considerations include factors relevant to public opinion and acceptance. These include [9]:

- Proximity to population centers.
- Opinion (e.g., support or opposition) of state and local entities and other stakeholders towards nuclear facilities.
- Willingness to participate in a consent-based process.

The sociopolitical climate can be enhanced through implementation of a consent-based process. Additionally, early engagement with local and regional stakeholders is helpful, and engagement with scientific communities (e.g., state geological surveys and state university faculty) provides local and regional geoscientific knowledge. An ongoing stakeholder outreach and political engagement program is necessary.

SUMMARY AND CONCLUSIONS

This paper describes the basis for a set of general considerations for siting a deep borehole disposal facility for SNF and/or HLW. These siting considerations include technical, logistical, and sociopolitical factors.

Technical considerations encompass geological, hydrogeochemical, and geophysical characteristics that are related to the suitability of the site for deep drilling and borehole construction, waste emplacement activities, waste isolation (seals and surrounding geology), and long-term safety of the deep borehole disposal system. Technical factors for siting include: sufficient depth to crystalline basement, absence of recent seismic or volcanic activity, absence of significant thermal gradients or upward hydraulic gradients, and low natural resources potential.

Logistical factors to be considered for siting include: local or regional availability of drilling contractors (equipment, services, and materials) capable of drilling a large-diameter hole to approximately 5,000 m

depth; construction of surface facilities and waste handling and emplacement equipment; legal and regulatory requirements associated with drilling, operation, and post-closure; and access to transportation systems.
Social and political considerations for siting include the distance from population centers and the support or opposition of local and state entities and other stakeholders to the facility and its operations. These sociopolitical factors must continue to be addressed as the construction, operations, and site closure phases proceed.

Finally, the safety and viability of the deep borehole disposal concept relies primarily on the great depth of burial, the isolation provided by the deep natural geological environment, and the integrity of the borehole seals. Demonstrating confidence in these safety factors is vital to siting and public acceptance. In that regard, RD&D associated with the deep borehole field test [12] may contribute to confidence in the following areas:

- Demonstration of drilling technology and borehole construction to about 5,000 m depth with sufficient diameter for cost effective waste disposal
- Verification of deep geological, geochemical, and hydrological conditions at a representative location
- Evaluation of canister, waste, and seals materials at representative temperature, pressure, salinity, and geochemical conditions
- Development and testing of engineering methods for waste canister emplacement and borehole seals deployment

REFERENCES

1. M. T. O'BRIEN, L. H. COHEN, T. N. NARASIMHAN, T. L. SIMKIN, H. A. WOLLENBERG, W. F. BRACE, S. GREEN, and H. P. PRATT (1979). *The Very Deep Hole Concept: Evaluation of an Alternative for Nuclear Waste Disposal*. LBL-7089, Lawrence Berkeley Laboratory, Berkeley, CA.
2. WOODWARD-CLYDE CONSULTANTS (1983). *Very Deep Hole Systems Engineering Studies*. ONWI-226, Office of Nuclear Waste Isolation, Columbus, OH.
3. C. JUHLIN and M. SANDSTEDT (1989). *Storage of Nuclear Waste in Very Deep Boreholes: Feasibility Study and Assessment of Economic Potential*. SKB 89-39, Svensk Kärnbränslehantering AB, Stockholm Sweden.
4. NIREX (2004). *A Review of the Deep Borehole Disposal Concept*. Report N/108, Nirex Ltd., U.K.
5. H. H. HESS, J. N. ADKINS, W. B. HEROY, W. E. BENSON, M. K. HUBBERT, J. C. FRYE, R. J. RUSSELL, and C. V. THEIS (1957). *The Disposal of Radioactive Waste on Land, Report of the Committee on Waste Disposal of the Division of Earth Sciences*. Pub. 519, National Academy of Sciences - National Research Council, Washington, D.C.
6. P. V. BRADY, B. W. ARNOLD, G. A. FREEZE, P. N. SWIFT, S. J. BAUER, J. L. KANNEY, R. P. RECHARD, and J. S. STEIN (2009). *Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2009–4401, Sandia National Laboratories, Albuquerque, NM.
7. B. W. ARNOLD, P. V. BRADY, S. J. BAUER, C. HERRICK, S. PYE, and J. FINGER (2011). *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2011–6749, Sandia National Laboratories, Albuquerque, NM.
8. DOE (2012). *Research, Development, and Demonstration Roadmap for Deep Borehole Disposal*. FCRD-USED-2012-000269, US Department of Energy Used Fuel Disposition Campaign, Washington, D.C.

9. DOE (2013). *Deep Borehole Disposal Research: Demonstration Site Selection Guidelines, Borehole Seals Design, and RD&D Needs.* FCRD-USED-2013-000409, US Department of Energy Used Fuel Disposition Campaign, Washington, D.C.
10. BRC (2012). *Report to the Secretary of Energy*, Blue Ribbon Commission on America's Nuclear Future, Washington, D.C.
11. DOE (2013). *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste.* US Department of Energy, Washington, D.C.
12. SNL (2014). *Project Plan: Deep Borehole Field Test.* SAND2014-18559R, FCRD-UFD-2014-000592, Rev 0, Sandia National Laboratories, Albuquerque, NM.
13. DOE (2014). *Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel.* US Department of Energy, Washington, D.C.
14. W.C. PATRICK (1986). *Spent Fuel Test – Climax: An Evaluation of the Technical Feasibility of Geologic Storage of Spent Nuclear Fuel in Granite – Final Report.* UCRL-53702, Lawrence Livermore National Laboratory, Livermore, CA.
15. B.W. ARNOLD, W.P. GARDNER, and P.V. BRADY (2014). *Hydrogeology of Deep Borehole Disposal for High-Level Radioactive Waste*. SAND2014-18615C, Presentation at Geological Society of America Annual Meeting, Vancouver, Canada.
16. R.P. RECHARD, B. GOLDSTEIN, H. GREENBURG, J.A. BLINK, W.G. HALSEY, M. SUTTON, F.V. PERRY, S. LEVY, T.A. COTTON, J.T. CARTER, and A. O'NEAL DELLEY. *System-Wide Integration and Site Selection Concepts for Future Disposition Options for UNF and HLW.* FCRD-USED-2011-000335, US Department of Energy Used Fuel Disposition Campaign, Washington, D.C. (2011).
17. H.C. JENKINS-SMITH, C.L. SILVA, K. GUPTA, J. RIPBERGER, R.P. RECHARD, R. ROGERS, M. PENDLETON, and L. PRICE. *Summary of Approaches for Consent-Based Siting of Radioactive Waste Management Facilities: Evidence-Based Considerations and Case Studies.* FCRD-NFST-2013-000113, US Department of Energy, Nuclear Fuel Storage and Transportation Planning Project, Washington, D.C. (2013).
18. F.V. PERRY, R.E. KELLEY, P.F. DOBSON, and J.E. HOUSEWORTH. Regional Geology: *A GIS Database for Alternative Host Rocks and Potential Siting Guidelines*. LA-UR-14-20368, FCRD-UFD-2014-000068, Los Alamos National Laboratory, Los Alamos, NM (2014).

ACKNOWLEDGEMENTS

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This work is supported by DOE Office of Nuclear Energy, Office of Used Nuclear Fuel Disposition. This paper is Sandia publication SAND2015-0001C.