SITING GUIDELINES FOR A DEEP BOREHOLE DISPOSAL FACILITY

Geoff A. Freeze[1], Bill W. Arnold[1], Patrick V. Brady[1], David C. Sassani[1], and Kristopher L. Kuhlman[1]

[1]*Sandia National Laboratories, Albuquerque, New Mexico, USA 87185; gafreez@sandia.gov*

This paper describes technical, logistical, and sociopolitical factors to be considered in the development of guidelines for siting a facility for deep borehole disposal of radioactive waste. Technical factors include geological, hydro-geochemical, and geophysical characteristics that are related to the suitability of the site for drilling and borehole construction, waste emplacement activities, waste isolation, and long-term safety of the deep borehole disposal system. Logistical factors to be considered during site selection include: the local or regional availability of drilling contractors (equipment, services, and materials) capable of drilling a large-diameter borehole to approximately 5 km depth; the legal and regulatory requirements associated with drilling, construction of surface facilities, waste handling and emplacement, and postclosure safety; and access to transportation systems. Social and political factors related to site selection 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 considerations are examined in the context of the siting process and guidelines for a deep borehole field test, designed to evaluate the feasibility of siting and operating a deep borehole disposal facility.

I. INTRODUCTION

Deep borehole disposal for the geologic isolation of spent nuclear fuel (SNF) and/or high-level radioactive waste (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 (up to 43 cm [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, 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 Figure 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 Figure 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.

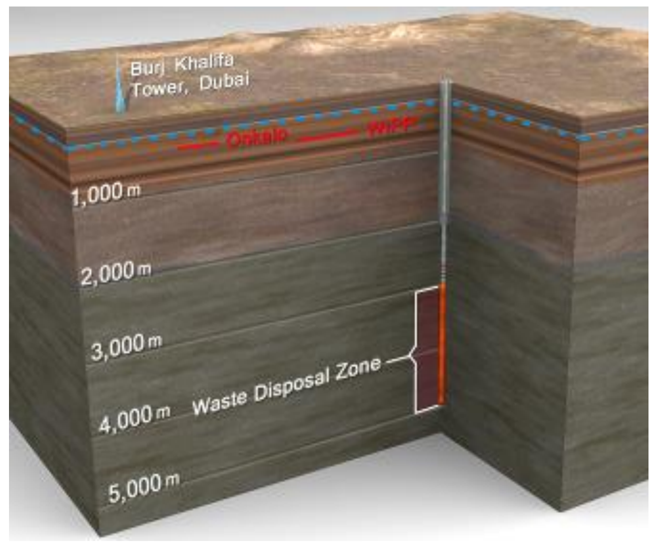

Figure 1. Generalized schematic of the deep borehole disposal concept.

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 UFDC deep borehole disposal studies[6,7] proposed waste canisters that contained commercial SNF. Specifically, the waste canister was designed to encapsulate a single pressurized water reactor (PWR) assembly, with canister design dimensions of 5 m length and 34 cm [13-3/8 in] diameter. This size waste canister would require a borehole with a bottom hole diameter of approximately 43 cm [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 research, development, and demonstration program addressing technologies relevant to deep borehole disposal of smaller DOE-managed waste forms"[10]. For example, the smallest DOE-managed waste forms, cesium and strontium capsules, are all less than 9 cm [3.5 in] in diameter[10], which could be emplaced in a borehole with a bottom hole diameter on the order of 22 cm [8.5 in].

In 2012, the Blue Ribbon Commission on America's Nuclear Future (BRC)[11] reviewed the prior research on deep borehole disposal, concluded that the concept may hold promise, and recommended further research, development, and demonstration to fully assess its potential. In 2013, consistent with the BRC recommendation, DOE[11] identified "developing a research and development plan for deep borehole disposal" as a key strategy objective. As part of this objective, UFDC has planned a deep borehole field test (DBFT)[14], without actual radioactive waste, to assess the viability of deep borehole disposal concept. The DBFT[14] includes site selection, site characterization, borehole and field test design, demonstration emplacement of canisters, and an assessment of viability of the concept.

The remainder of this paper describes considerations for siting a facility for deep borehole disposal of radioactive waste. These considerations are examined in the context of the siting process for the DBFT. The siting process for the DBFT is likely to be less complex or controversial than for an actual disposal facility, but still may offer insights into siting that will be relevant to an actual facility. Also, many of the siting guidelines for the DBFT anticipate the needs for siting and operating a deep borehole disposal facility.

Section II summarizes the safety and viability factors supporting the deep borehole disposal concept. Section III presents general siting considerations for a deep borehole disposal facility. Section IV describes the siting process for the DBFT and outlines specific DBFT siting guidelines, based on the general siting considerations presented in Section III. Section V provides a summary.

II. SAFETY AND VIABILITY OF DEEP BOREHOLE DISPOSAL

A number of factors suggest that the deep borehole disposal concept may provide a technically feasible and cost-effective alternative for the safe disposal of SNF, HLW, and/or some DOE-managed waste forms. These include[7,13]:

- 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 upward 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)

Several of these safety and viability elements are dependent on site characteristics, and provide a basis for the deep borehole disposal siting considerations and guidelines outlined in the following sections.

III. 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.[11,15] 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[16]. 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.[11,15]

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[12]. The implementation of a consent-based process is facility and location specific, and the process should prioritize which of the siting considerations are most relevant to that particular situation.

Associated with the siting process is the development of a set of basic initial siting guidelines. The purpose of specifying siting guidelines is to enhance the likelihood of safe development, operations, and post-closure performance of a radioactive waste disposal system. Siting guidelines 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[15]. In cases where there are multiple volunteer communities and/or candidate sites, the siting guidelines provide a basis for evaluation and comparison of the relative merits.

Specific to deep borehole disposal, siting guidelines should encompass considerations 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. These general considerations broadly reflect the deep borehole disposal safety and viability elements identified in Section II. Deep borehole siting guidelines should include potentially disqualifying factors – to identify sites that are clearly unsuitable or inappropriate. Examples of unfavorable features may include: upward hydraulic 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, which can be used to develop specific guidelines, include technical, logistical, and sociopolitical factors. These considerations are discussed in the following subsections. The translation of these siting considerations to more specific siting guidelines is described in Section IV.

III.A. Technical Factors

Technical considerations include geological, hydrogeochemical, and geophysical conditions potentially relevant to successfully completing a deep borehole field test and demonstrating 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 known or suspected structural complexity, such as major faults, shear zones, or rift basins, should be avoided. Large plutons of felsic intrusive rocks are generally less foliated and heterogeneous than metamorphic rocks, and are more desirable.
- 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 be related 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, Figure 2 shows a GIS-compiled map of depth to crystalline basement.

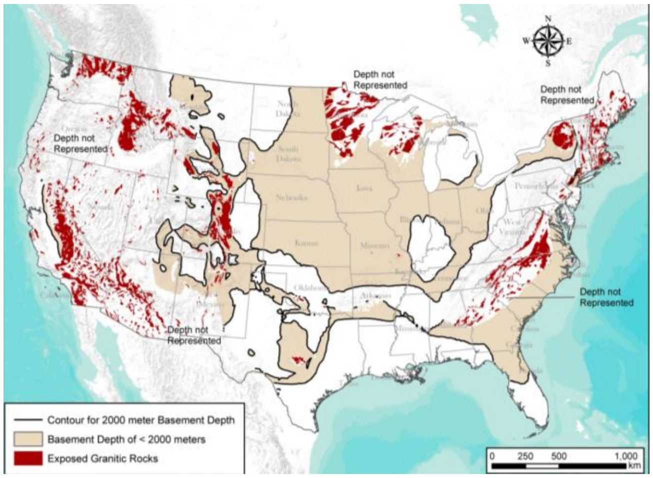

Figure 2. Depth to crystalline basement in the continental US[17].

III.B. Logistical Factors

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

- Regulations and permitting – Legal and regulatory requirements associated with preclosure operations (i.e., drilling, construction of surface facilities, and waste handling and emplacement) should be achievable. The regulatory environment is different in different states and for Federal versus private land. In addition, existing regulations for postclosure safety in mined geologic repositories (i.e., 10 CFR 60 and 40 CFR 191) would need to be updated to be applicable to deep borehole disposal[9].
- 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 5,000 m depth should be locally or regionally available.
- Site area – There should be sufficient area for drilling, construction of surface facilities, 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. Transportation costs could vary considerably depending on the disposal site location relative to waste storage or nuclear power plant locations.

III.C. 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.

The sociopolitical climate can be enhanced through early engagement with local and regional stakeholders; engagement with scientific communities (e.g., state geological surveys and state university faculty) provides local and regional geoscientific knowledge.

IV. SITING GUIDELINES FOR DEEP BOREHOLE DISPOSAL

As noted in Section I, DOE has initiated a deep borehole field test to assess the viability of deep borehole disposal concept. As a first step in the DBFT, DOE issued a Request for Information (RFI)[18] to "seek interest in, and input from, States, local communities, individuals, private groups, academia, or any other stakeholders willing to host a Deep Borehole Field Test". The RFI[18] contained a set of preferred guidelines for a site for the DBFT, based on the more general deep borehole disposal siting considerations outlined in Section III. These preferred guidelines for the DBFT site are listed below – ordered to correspond to the siting considerations listed in Section III:

- Less than 2 km depth to crystalline basement
- No known major crystalline basement shear zones or major tectonic features
- Less than 2% probability within 50 years of peak ground acceleration greater than 0.16 g from a seismic event (generally indicative of area of tectonic stability)
- Distance to Quaternary age volcanism greater than 10 km
- Distance to Quaternary age faulting greater than 10 km
- Distance greater than about 100 km to topographic slope of greater than 1º to avoid deep groundwater circulation
- Geothermal heat flux less than 75 mW/m^2
- Low density of petroleum drilling
- Not at or proximate to a strategic petroleum reserve site
- Not near an urban area

- Site area greater than 1 km^2 (so that there is ample area for drilling operations)
- Lack of known existing surface or subsurface anthropogenic radioactive contamination

The RFI[18] stated that interested responders should discuss how any proposed host site meets the above preferred location guidelines and state and local government approval requirements. The RFI also identified, separate from the siting guidelines, potential technical and economic benefits. Specifically, it stated that "A community hosting the DBFT may benefit by gaining a more thorough understanding of the local subsurface geologic and hydrologic characteristics that may permit better community management of local resources. Economic and scientific aspects of the DBFT also may benefit the local community, policy decision makers and regulators, local and state government, universities, and other regional stakeholders in such other subsurface technical areas such as geothermal energy production, fossil energy production, and carbon sequestration amongst others." [18]

Collectively, the siting guidelines and associated statements in the DBFT RFI capture the key siting considerations outlined in Section III for a deep borehole disposal facility. Although the RFI was "issued solely to request information that may be used by DOE to develop and issue an RFP"[18], the solicitation of interest from potential host communities is a first step in early stakeholder engagement. It is expected that, as interested potential host communities respond to the RFI and/or a subsequent RFP, there will be a process to evaluate proposed sites against the siting guidelines.

With regard to siting for an operating deep borehole disposal facility, actual disposal of nuclear waste would be a much more controversial activity from a social and political perspective than siting the DBFT. Site selection for a disposal program would involve a more extensive stakeholder outreach program and more complex political engagement than locating the DBFT. Site selection for a deep borehole disposal facility would also involve consideration of waste transportation costs and infrastructure, which could vary considerably depending on the disposal site location relative to waste storage or nuclear power plant locations. A deep borehole disposal facility would also require a larger site and a longer-term commitment than the DBFT, which would be important considerations in the site selection process.[8]

V. SUMMARY AND CONCLUSIONS

This paper describes the initiation of a siting process for a deep borehole field test, designed to evaluate the feasibility of siting and operating a deep borehole disposal facility. A set of guidelines for siting the DBFT were developed, starting from a broader set of safety and viability elements and general considerations for siting a deep borehole disposal facility for radioactive waste. The siting guidelines for the DBFT, outlined in an RFI for potential host communities, include technical, logistical, and sociopolitical factors.

The technical and logistical guidelines for the DBFT are similar to those that would be expected for a deep borehole disposal facility: sufficient depth to relatively homogeneous crystalline basement, absence of recent seismic or volcanic activity, absence of significant thermal gradients or upward hydraulic gradients, low natural resources potential, distant from population centers.

The issuance of the RFI to solicit interest from potential host communities addresses some initial sociopolitical considerations. However, these considerations should continue to be addressed as the site evaluations, site selection, and DBFT implementation proceed.

Furthermore, while stakeholder consent is a part of the DBFT siting process, the siting of an operating deep borehole disposal facility would involve a much more complex, controversial, and longer-term stakeholder engagement than the DBFT, which would be important considerations in the site selection process. Nonetheless, the DBFT siting process may still offer insights into siting that will be relevant to an actual facility.

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 paper is Sandia publication SAND2014-20111C.

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. *The Very Deep Hole Concept: Evaluation of an Alternative for Nuclear Waste Disposal*. LBL-7089, Lawrence Berkeley Laboratory, Berkeley, CA (1979).
2. WOODWARD-CLYDE CONSULTANTS. *Very Deep Hole Systems Engineering Studies*. ONWI-226, Office of Nuclear Waste Isolation, Columbus, OH (1983).
3. C. JUHLIN and M. SANDSTEDT. *Storage of Nuclear Waste in Very Deep Boreholes: Feasibility Study and Assessment of Economic Potential*. SKB

89-39, Svensk Kärnbränslehantering AB, Stockholm Sweden (1989).

4. NIREX. *A Review of the Deep Borehole Disposal Concept*. Report N/108, Nirex Ltd., U.K. (2004).
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. *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. (1957).
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, *Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2009–4401, Sandia National Laboratories, Albuquerque, NM (2009).
7. B. W. ARNOLD, P. V. BRADY, S. J. BAUER, C. HERRICK, S. PYE, and J. FINGER, *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2011–6749, Sandia National Laboratories, Albuquerque, NM (2011).
8. DOE. *Research, Development, and Demonstration Roadmap for Deep Borehole Disposal.* FCRD-USED-2012-000269, US Department of Energy Used Fuel Disposition Campaign, Washington, D.C. (2012).
9. DOE. *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. (2013).
10. DOE. *Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel.* US Department of Energy, Washington, D.C. (2014).
11. BRC. *Report to the Secretary of Energy*, Blue Ribbon Commission on America's Nuclear Future, Washington, D.C. (2012).
12. DOE. *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste.* US Department of Energy, Washington, D.C. (2013).
13. B.W. ARNOLD, W.P. GARDNER, and P.V. BRADY. *Hydrogeology of Deep Borehole Disposal for High-Level Radioactive Waste*. SAND2014-18615C, Presentation at Geological Society of America Annual Meeting, Vancouver, Canada (2014).
14. SNL. *Project Plan: Deep Borehole Field Test*. SAND2014-18559R, FCRD-UFD-2014-000592, Rev 0, Sandia National Laboratories, Albuquerque, NM (2014).
15. 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).
16. 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).
17. 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).
18. DOE. *Request for Information (RFI) – Deep Borehole Field Test.* Solicitation Number DE-SOL-0007705, US Department of Energy Idaho Operations Office, Idaho Falls, ID (2014).